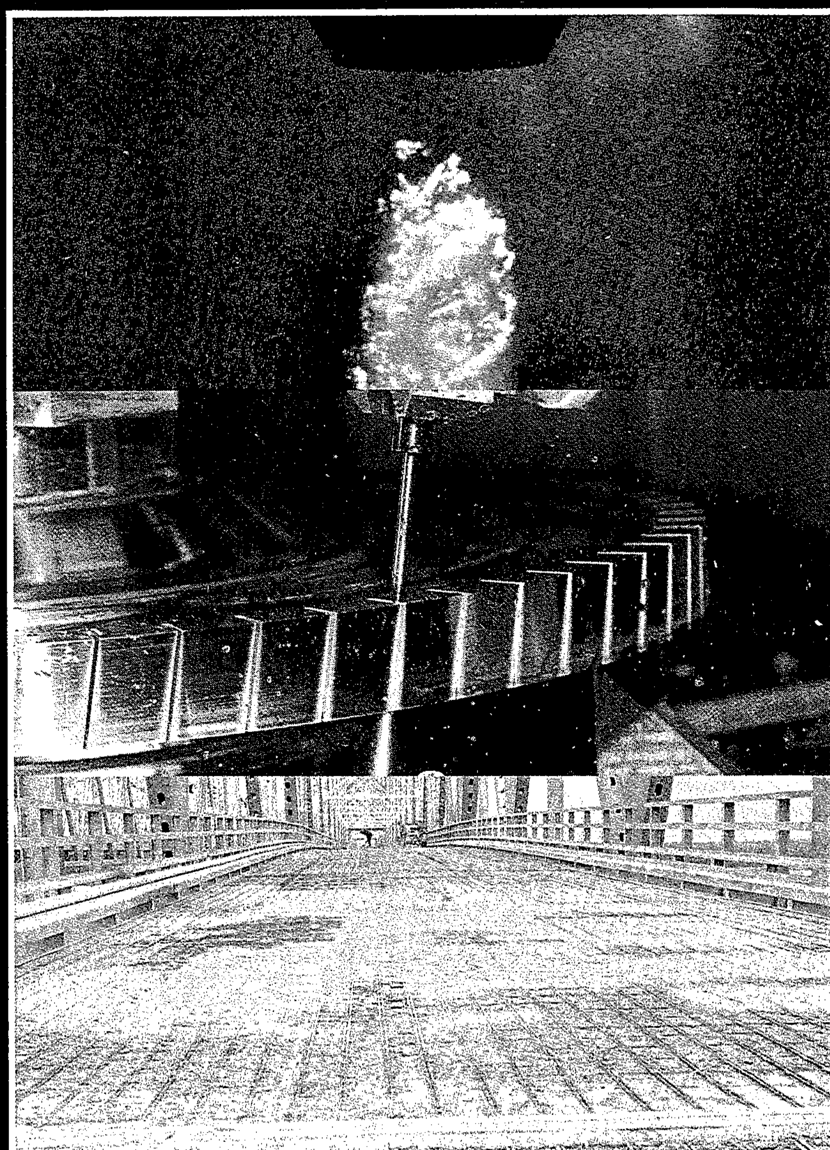
Proceedings
of the
7th American Water Jet Conference

Volume II



Edited by Mohamed Hashish

August 28-31, 1993
Seattle, Washington

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Cover: The three photographs shown on the cover reflect the three main sessions presented at the conference: technology developments, manufacturing, and contractors' applications. The top picture shows the development of cavitation bubbles in a submerged waterjet *(photograph courtesy of National Research Council of Canada)*. The middle picture shows an abrasive-waterjet machining slots in an aircraft component *(photograph courtesy of General Electric Aircraft Engines)*. The bottom picture shows a bridge deck scarified using a waterjet *(photograph courtesy of Flow International Corporation)*. In the background is the Space Needle, which is a landmark in Seattle.

Proceedings of the 7th American Water Jet Conference

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FOREWORD

The mission of the Water Jet Technology Association is to advance the state of the art of water jet technology. Water jet technology has made significant contributions to industry productivity, and the pace of improvement is accelerating. One method of advancing the art is to provide a forum where innovative people engaged in water jet technology can meet and discuss new insights and applications. The publication of a record of these discussions encourages others to use their ingenuity to gain more insight into water jet technology and to explore new applications of the technology. The present volume is the seventh in a series of published proceedings dating back to 1981. We proudly offer the Proceedings of the 7th American Water Jet Conference as evidence that water jet technology is a vibrant technology with a bright future. We expect that many readers will be inspired to investigate water jet technology. We trust that they will find more applications for this exciting technology and thereby increase the effectiveness and productivity of society.

GEORGE A. SAVANICK, Ph.D.
President
Water Jet Technology Association

Since 1972, when the 1st International Symposium on Jet Cutting Technology was held in the U.K., the water jet technology has rapidly spread worldwide and with it the appetite for more knowledge, as evidenced by the fact that there are more conferences in the field than ever before and the founding of a new *International Journal on Water Jet Technology*. I am confident that this Conference, like the ones before, will make it possible to share the knowledge gained around the world, as indicated by the large number of papers from many countries presented and included in this publication.

The success of the Conference is due to sharing of the work by many individuals in the Organizing Committee, the Conference Administrators and the International Advisors. However, this "Foreword" will be incomplete without special gratitude to Dr. Mohamed Hashish, the Conference Chairman, and his associates Dr. Andrew Conn, Prof. Thomas Kim, Prof. Thomas Labus and Prof. Mamidala Ramulu, the Conference Co-Chairmen.

I am indeed fortunate, privileged and honored to write this "Foreword." I am sure you will go home, like I always do, better informed and better equipped to pursue and enhance the areas of your interest in water jet technology. I sincerely thank you for enriching the Conference by your presence and I wish you all the best in your future endeavors.

MOHAN M. VIJAY, Ph.D.
Chairman of the Board
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PREFACE

The proceedings for the 7th American Water Jet Conference is being presented in two volumes due to the record number of papers received - 71. These papers were presented in three main sessions at the conference: a general technology session that was held concurrently with two workshop sessions on manufacturing and contractors' applications.

The papers in this proceedings reflect the great advances that have been made in waterjet technology over the past 20 years. In the 1970s, major advances were related to waterjet tool and process developments primarily for mining, construction, rock cutting, cleaning, and a few manufacturing applications. A conference proceedings in the 1970s typically contained an average of 35 papers. In the 1980s, most advances that occurred were related to the introduction of the abrasive-waterjet technology. The number of papers presented at jet cutting conferences jumped noticeably to about 50 papers per conference, and the word "machining" started to replace the word "cutting" in many papers, due to the fact that the main applications for abrasive-waterjets were found in manufacturing where more accurate material removal was required. The increased number of papers may also have been due to the increased number of applications for both waterjets and AWJs.

In the 1990s, especially with this conference, we have observed another major jump, but we are not able to attribute it to a single factor. It is my opinion that the technological advances in the 1990s will not be singular and will be realized with the development of abrasive suspension jets, low-cost high-pressure direct drive pumps, and 3-D machining systems for the average size machine shop. Both nuclear and demilitarization applications will grow significantly in the 1990s, requiring further developments in nonabrasive jetting techniques. The need for these developments and for the continuing evolution of existing technologies to enable reliable and widespread use is more important to the growth of jet cutting technology than is the seeking of alternative approaches.

The success of this conference belongs to every participant. I would like to thank the authors for their technical contributions and for making these proceedings possible. A special thanks goes to those authors who are not proficient in English but yet elected to write and share their findings with us. The great professional and tireless efforts by David Birenbaum & Associates in organizing this conference have been most critical to its success. I would especially like to express my gratitude to Mark Birenbaum, Ken Carroll, LeAnn Hampton, Rhonda Stevens, and Jan Tubbs. I would also like to acknowledge the help and guidance of the conference co-chairmen: Dr. Andy Conn, Dr. M. Ramulu, Professor Thomas Kim, and Professor Thomas Labus. The assistance of Dr. Pawan Singh, Dr. Ed Ting, and Dr. Mohan Vijay was most useful in developing the subject index. Thanks are also due Kristie Hammond and Christa Ramey at QUEST for their assistance on this project. Finally, I must express my continuing gratitude to my wife, Nadia, for her ongoing patience and understanding.

MOHAMED HASHISH, Ph.D.
Editor & Conference Chairman

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ADVANCED MACHINING AND FUTURE NEEDS

MISCELLANEOUS PAPERS

The following papers contain valuable contributions to jet cutting technology. The editor sincerely thanks the authors for their efforts in preparing the papers in English, which is not their mother tongue. Accordingly, they have been scanned and slightly edited to improve their readability.

LATE SUBMISSIONS

7th American Water Jet Conference
August 28-31, 1993: Seattle, Washington
Paper 33

APPLICATION OF WATER JET ENERGY IN THE BOREHOLE MINING

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ABSTRACT

The conceptual idea of the water-jet energy application in the Borehole Mining was a subject of several articles of the former Proceedings of the WJTE conferences. The development of this technology is visible but still not successful. This paper present the results of our field experiments in the shallow borehole located in brown coal deposit, including our comments, discussions and conclusions. We submit also the scope of work related to the mining, mechanical and hydraulic engineering indispensable for further development of both the HBM and the Blast – HBM technology. We would like to inspirate the worldwide scientists to discuss, to criticize and to correct our working hypothesis and experimental operations.

Organized and Sponsored by the Water Jet Technology Association.

1. INTRODUCTION

The application of the water jet energy in mining engineering was known and practised long ago as hydro-mechanization process acting in underground and open-cast mining.

Since last several years the mining scientists have been trying to apply the water jet energy for a new mining branch named the Hydraulic Borehole Mining (HBM). This quite new branch of mining invented and developed by the scientists from the U.S. Bureau of Mines recently became the subject of intensive research work, studies and experiments.

The Polish Mining Institute participating in this development have carried out several theoretical studies and field experiments, which results were presented in this paper.

The HBM technology can be apply for soft and middle hard minerals. Recently we have concentrated our efforts on the application of water jet energy for hardrock mineral exploatation. This new application known as the Blast – HBM would be a subject of our further research work and field experiments.

2. RESULTS OF FIELD EXPERIMENTS

The principle of the Borehole Mining technology has been described in several articles including A. W. J. C. Proceedings as well as in other worldwide publications. The main information on this method are illustrated in Fig. 1.

The Polish Mining Institute has carried out many theoretical studies and research work and some field experiments on the brown coal deposits first in a narrow trench and next in a shallow borehole. Fig. 2.

In both experiments were employed following basic equipment:

- high-pressure water pump with a head ca 8.0 MPa and the flow rate 3.5 m^3/min.
- high-pressure water pump for the over-size fragmentation with a head 6.0 MPa and the flow rate ca 2.5 m^3/min.
- compressor with air pressure ca 3.0 MPa and capacity ca 6.0 m^3/min.

The mining device (pipe column) lower into the borehole was operated by manpower. Several control and measurement equipment has been used. The experiment carried out in the narrow trench has given a lot of practical information used in the shallow borehole trial, where all operations are invisible.

During the trials in the shallow borehole dia 800 mm and 21 m in depth illustrated in Fig. 3 we have searched for the optimum size of the parameters as well as for the relations between them.

Finally we have settled:

- optimum dia. of the nozzles is 15 to 18 mm,

- optimum traverse speed of the jet across the rock-face was ranging between 25 to 50 cm/sec,
- optimum size of increment in the coal amounts 20 to 25 cm.

In consequence of several trials we have concluded as follows:

- The brown-coal cutting by water jet was successful and the maximum cutting radius was 5.5 to 6.5 m in distance.
- The down-hole crushing of the brown-coal oversizes by means of water jet was quite successful but movable nozzles would be more effective.
- The submerged water jet cutting was possible but for a small distance, not more then 0.7 to 1.0 m. The water jet cutting in the compressed air environment with pressure 3 to 5 bar was possible, not harmful and may be very useful. This problem needs more trials and theoretical studies.

Basing on all above mentioned experiments in the trench and in the borehole we have indicated the following essential problems, which need more studies, discussions and field experiments:

1 – Further extension of the cutting range.
2 – Roof-supporting in the excavated cave.
3 – Down-hole crushing while the material is hard.
4 – Remote control of the invisible, underground process.

In this article we would like to outline and initially discuss all these problems but the solution and practical application need much financial engagement, which at present have been not available.

3. THE PROBLEMS

3.1. Cutting range extension

The rock-cutting examples described in many articles published in previous A. W. J. Conferences Proceedings were concerned mainly to the short distance between the nozzle and the rock, usually below 0.5 m. Application of water jet in mining requires substantial increasing of the cutting range, not lese then 5 to 12 m. The lower size of cutting radius gave rather small amount of product, therefore the operation would be not effective.

We could expect that increasing of water pressure and flow rate will produce bigger cutting radius but in a limited range only. Thus, we have designed extended arms, holding the nozzles and continuously approaching them to the rock-face. We have solved it in many variants one of them is illustrated in Fig. 4 where we have doubled the cutting range.

This simple solution seems to be very useful and promising. In needs a specific mechanical design, adjusted to the bore-hole conditions and rock properties. We also expect to use the abrasive particles added to the water jet according to the instructions indicated in many articles presented in the Proceedings of A. W. J. Conferences.

3.2. Roof-support problem

From the mining point of view we can solve this problem in several ways, adjusting the solution to the local rock-properties.

While the roof-formation are not fractured, we can successfully apply the roof support by means of compressed air, water or other fluid medium. While we continuosely press the compressed air into the excavated cave the pressure produces the force, which supports the roof of the cave. Knowing the geomechanical parameters of the roof-formations we can determine the air pressure needed for roof-support.

We know that the size of arch-pressure insides the rock does not result from the total thickness of rock-formations but it depends on the arch of ellipsoid only. The rise of arch in the middle hard rock is approximately 10 to 15 m, and the bulk density amounts to 2500 kg/m^3

The air pressure needed for this conditions will be approximately:

$$p = 9.81 f \gamma = 9.81 \cdot 12 \cdot 2500$$

$$p = 300 \text{ kPa} = 0.3 \text{ MPa} = \text{ca } 3.0 \text{ bar}$$

In order to improve the safety conditions it may be increased to 5.0 bar. This compressed air acting upwards will support the roof and acting downwards will press on the slurry surface in the cave, improving the air-lift operation.

This kind roof supporting has not been examined in practice till now, therefore it was only a hypothesis. It requires the sophisticated research work and field experiments.

The other roof-supporting system mainly by the mining measures have been elaborated in conceptual mining studies and they need more design and experimental works. The program for this research work has been prepared but their performances would require a lot of financial means.

3.3. Down-hole crushing system

The rock-material cutted by water jets is falling down partly as fine and partly as big lumps, which are to be crushed All these oversizes are submerged in the slurry and they approach to the bottom by gravity where they are to be crushed.

In our field testing performed in the brown-coal deposit we have successively crushed the oversizes by means of water jets generated by the pump with a head below 5.5 bar.

The greater number of lumps have been crushed in 3–5 min and the fine grains of coal were suitable to be hydro-transported in the pipe of 211 mm dia. up to the surface. Location of the crushing jet-nozzles are illustrated in Fig. 3. However, movable water-jets would be more effective.

Basing on our field experiments we can say, that the problem of down-holecrushing for such minerals like brown-coal has been definitely solved. Now, there is a very serious problem how to solve the down-hole crushing system, while the cutting material is hard and very hard. This problem is just under consideration and we expect to solve it and to put it in successful pilot-operation soon.

3.4. Airlifting of the slurry up

The water mixed with the fine grains of cutted material is to be airlifted from the bottom of the cave by pipe p to the surface. The successful air-lift operation is possible while the slurry level is not less than 1/2 of the borehole depth. From the mining point of view we prefer to hold the slurry level below the jet-cutting level. In such a situation the air-lift could not work.

The pumping the slurry by jet-pumps would be possible but with a very low efficiency and to the limited depth of the borehole i.e. below 80 m. When we have started during our experiment to press the air into the cave we have succeeded with this problem. The compressed air pressing on the slurry surface inside the cave helped us to lift the slurry up. This is very simple but very effective solution.

3.5 Remote control of the invisible process

All mining operations as rock cutting, oversize fragmentation, sucking and airlifting of the slurry are executed in underground cave, hance they are not visible.

All these operations must be remote controlled including:

- continuous measurement of slurry level inside the cave,
- density of slurry inside the cave,
- pressure of compressed air inside the cave,
- measurement of the radius of excavated cave by sonic sounder or other way.

We have to employ the appropriate measurement equipment as well as we shall try to apply some television control equipment, too.

This equipment will facilitate our operations and indicate necessary correction of the process.

4. BLAST – HBM METHOD FOR HARD-ROCK EXCAVATION

The HBM method is suitable and useful for soft and semi-hard minerals only. Nowadays, the intensive efforts of several scientists are focused on the adjustment of the HBM method to hard and very hard-rocks excavation.

The most essential problem is the rough cracking and fracturing of undisturbed soil covered by overburden by means of explosives or other blasting materials as for example the plasma or electric energy expansion. The down-hole fragmentation will be essential point of this technology. The further proceeding will be adapted from the HBM method.

Our working team has carried out several variants of the Blast – HBM method. The concept of one of them is illustrated in Fig. 5, where the roof of the excavated cave is supported by the muck (blasted material). This simple solution seems to be most practical and realistic.

The further development of the Blast – HBM method needs much scientific work and expensive field experiments.

This program requires the concerned sponsor, which will be willing to cover the adequate expenses.

5. PERSPECTIVE FOR THE HBM AND BLAST – HBM METHODS

Both methods can be apply in the specific geological conditions, particularly over-there, where conventional methods (underground and open cast) ones are not successful. The HAM method requires big thickness of coal seam or massive orebody but they can be apply for low grade ore, overflooded deposits as well as for all occurrences, which can not be taken by conventional methods in economical way. The production rate from our borehole unit estimated for 100÷120 t/h, i.e. about 2.000 t/d. A mine with 10–15 working units will produce 4÷5 Mt/y. This quantity could be compared with conventional mines.

6. CONCLUSIONS

The hydraulic bore-hole mining basin on the water jet energy application has a chance to prove to be successful but it still needs much efforts, scientific research work and field testing.

Existing world recession in mining will constrain many investors to look for a new mining technology offering the lower costs, small investment and environmental compatibilities.

The worldwide mining institutes should concentrate their joint efforts on this subject, looking for additional funds needed for continuation of the related research work and field testing. The financial contribution of mining investors would help on this way.

We do realise that the HBM and Blast – HBM methods are extremely difficult problem and as the pioneer research work require multilateral point of view. Therefore, the remarks, suggestions and critical words of various worldwide scientists would be very appreciated. The success is still very far but it will be reached. We do believe.

7. ACKNOWLEDGEMENT

The authors wish to express their appreciations and thanks to Mr George A. Savanick from the U.S. Bureau of Mines for his presentation of scientific reports from the field testing and research work.

The scientific paper published in the Proceeding of the XV World Mining Congress by Mr Peter G. Chamberlain and Mr James J. Olson both from the U.S. Bureau of Mines have encouraged us to further continuation of and effort on this field.

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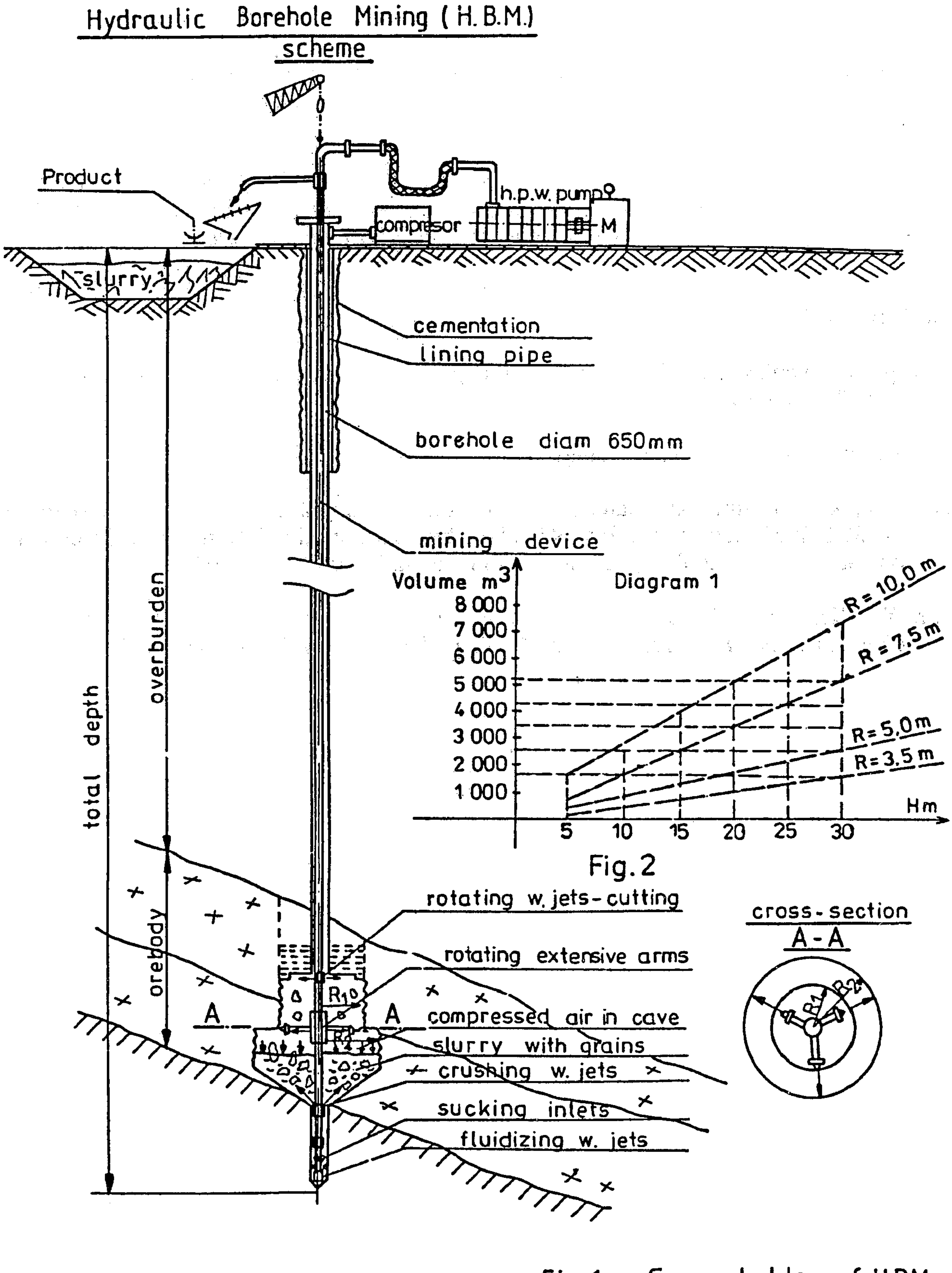

Fig. 1. General Idea of H.B.M.

Experimental Borehole in Brown Coal

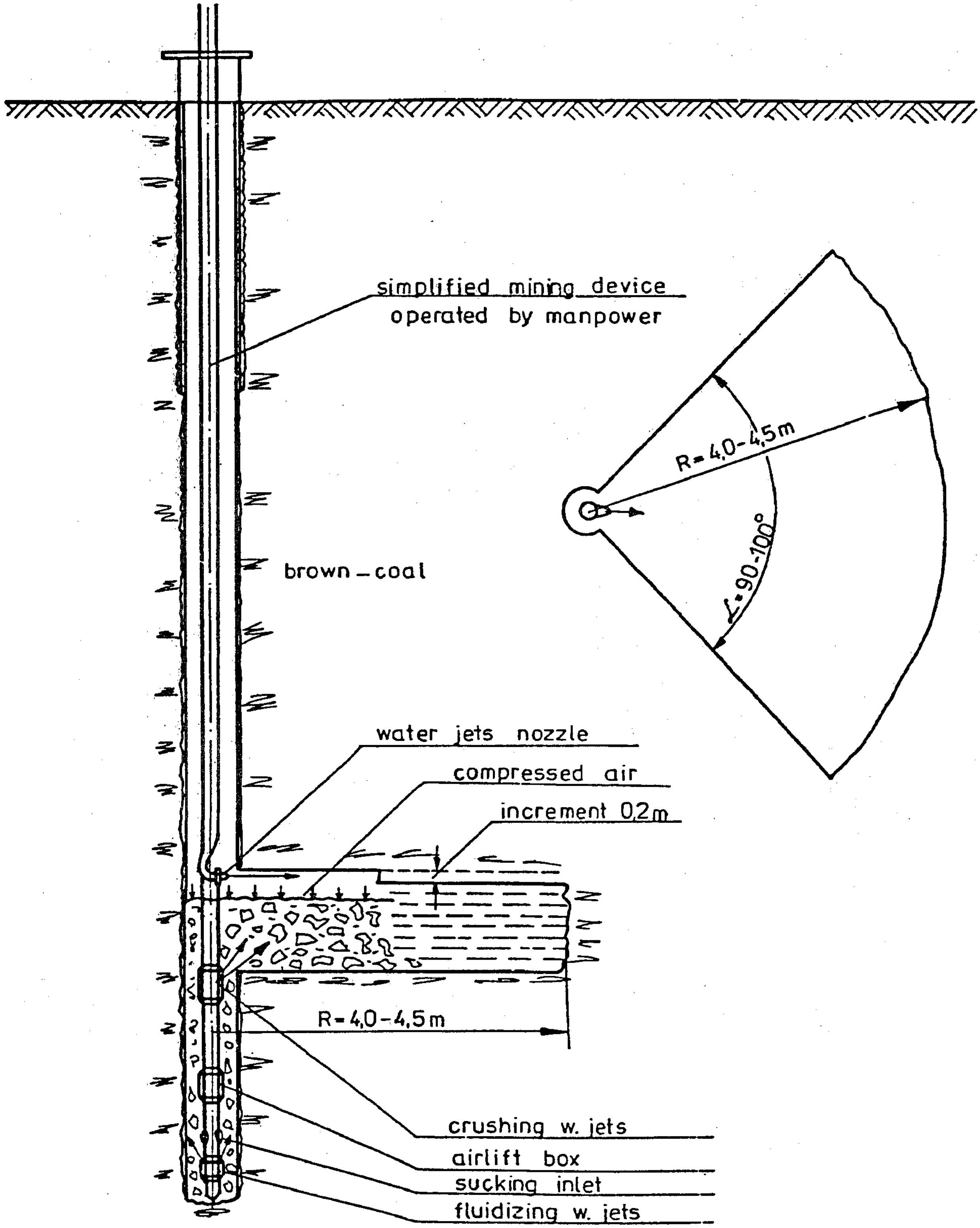

Fig.3 Experimental (bore-hole)

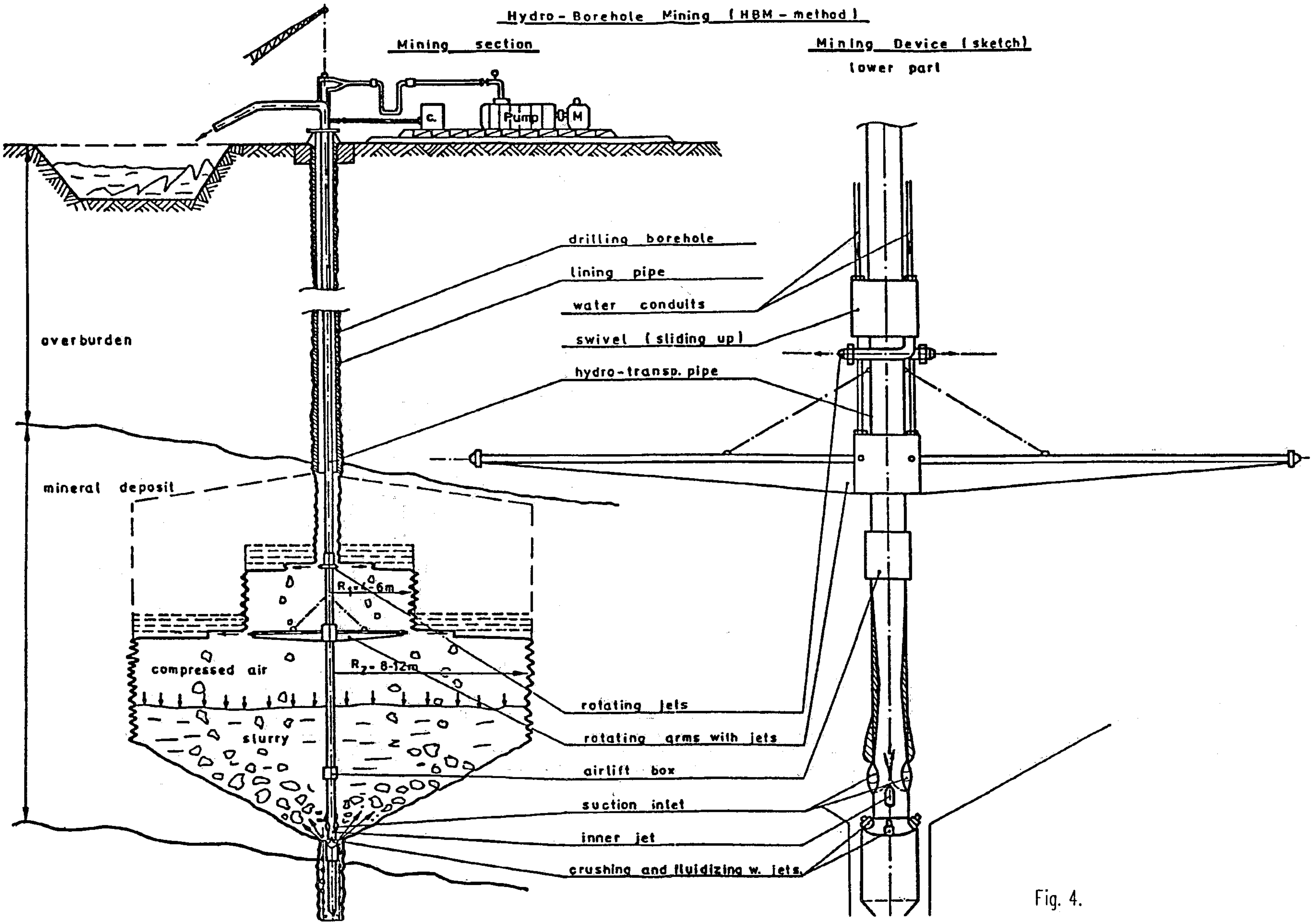
Hydro-Borehole Mining (HBM-method)
Mining section
Mining Device (sketch)
lower part
C.
Pump
M
overburden
mineral deposit
compressed air
slurry
$R_1 = 4-6m$
$R_2 = 8-12m$
drilling borehole
lining pipe
water conduits
swivel (sliding up)
hydro-transp. pipe
rotating jets
rotating arms with jets
airlift box
suction intet
inner jet
crushing and fluidizing w. jets.

Fig. 4.

Blast. H.B.M. method - conceptional scheme

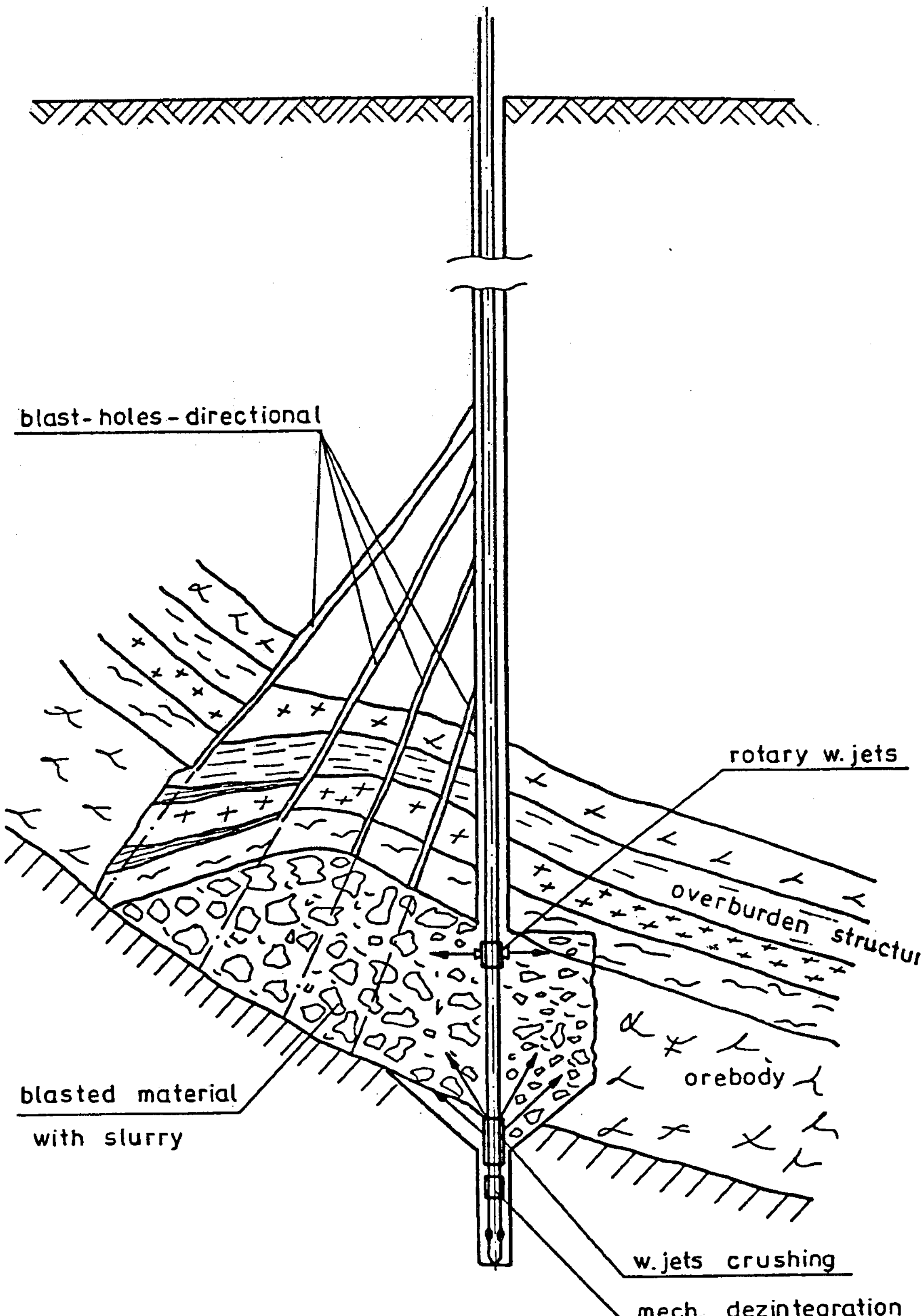

Fig.5. Blast-H.B.M. concept.

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Paper 34

BOREHOLE MINING OF GOLD FROM FROZEN PLACERS

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ABSTRACT

The U.S. Bureau of Mines (USBM) has designed, built and field tested a borehole mining system for mining gold from placers in Alaskan permafrost. This system, which uses two borehole mining tools operating in concert in two adjacent boreholes, is superior to conventional single borehole mining systems when applied to mining gold. Single borehole mining is unsuccessful because gold settles before the slurry enters the downhole pump. The USBM system overcomes the settling problem. After water jets cut a connection between boreholes, the water jet of one miner is operated simultaneously with the slurry pump of the other miner. The gold particles do not settle because they are pushed by the jet into the inlet of the pump. This two-borehole mining system was used to mine gold from a frozen placer under 12.2 m (40 ft) of overburden at the Voytilla mine, 43 km (27 miles) northwest of Delta Junction, Alaska.

1. INTRODUCTION

This document describes the extension of the borehole mining technique to the remote extraction of gold from frozen gravels in Alaska. This description includes an outline of the design of a borehole miner specially suited for borehole gold mining, the results of laboratory testing, and an account of a field test conducted at Tenderfoot Creek near Delta Junction, Alaska in the summer of 1992.

Borehole mining, also known as slurry mining, is a process whereby a tool incorporating a water-jet cutting system and a downhole slurry pump, is used to mine minerals through boreholes drilled from the surface to buried mineralized rock. Water jets from the mining tool erode the ore to form a slurry. The slurry flows into the inlet of a pump at the base of the tool. The material is lifted to the surface in a slurry ideally suited for pipeline transfer to a mill or processing plant.

Borehole mining offers a number of important advantages over conventional open pit and underground mining methods, and it can mine mineral deposits that presently are not mined because of technical or economic considerations. Since mining is done remotely from the surface, there is no need to drive development headings in the deposits, which permits almost immediate production of ore. In contrast, conventional mining methods may require years of preparation before production and return on investment can be expected. In borehole mining the fragmentation and transportation systems are incorporated into a single machine that is remotely operated from the surface, thus eliminating health and safety problems inherent to underground mining. The environmental disturbance is minimal and short term; no overburden is removed, and subsidence can be avoided by backfilling. Borehole mining is selective and can extract deposits that are small or erratically mineralized, thereby broadening the resource base. This selectivity allows the ore to be extracted without disturbing the country rock, thereby avoiding dilution. Crushing and grinding costs are minimal because the ore is reduced to a fine size by the jet. Tailings from the processing plant can be pumped into the mined-out caverns to control subsidence and solve waste disposal problems. Reviews of the history and the state of the art have been published "Abramov et al., (1992) and Savanick et al., (1992),...." At present, borehole mining is active in Kasakhstan, Russia, and the Ukraine. There are no known commercial borehole mining operations in the United States.

2. BOREHOLE MINING OF FROZEN PLACERS

Mining of the frozen placer deposits in Alaska has greatly diminished because of economic reasons. The shallower deposits that can be dredged are exhausted. Remaining deposits are buried under 15 to 60 meters (50-200 ft) of overburden. The older dredges are not capable of operating in the deeper deposits and the capital cost of new dredges cannot be justified because of the small size of the individual deposits.

The Bureau of Mines instituted a study to determine the economic feasibility of applying borehole mining to the extraction of deeply buried frozen placers. Research conducted in 1990 by the Bureau included building and testing a borehole miner modeled after its earlier borehole miner used to mine coal, sandstone, oil sands and phosphate through a single borehole. This research, as well as research conducted in 1985 by Hawley Resource Group Inc. "Retherford et al., (1985)...," indicated that a conventional, single borehole miner probably would not be effective as a placer gold miner because gold would settle in the mining cavity created at the base of the borehole and not enter into the downhole slurry pump. This indicated the need to provide a highly turbulent regime in the cavity to maintain heavy particle suspension, and a high velocity at the intake of the pump to induce the gold particles to enter the pump. Another problem is the presence of oversize materials (greater than about 13 cm or 5 inches) that will not enter the pump, causing the development of a bed of oversized cobbles and boulders on the floor of the cavity. This bed might trap gold particles, which typically are less than a millimeter in diameter, making their removal difficult. This suggested designing the slurry pump to transport cobbles as large as possible, and/or developing a multihole system which allows a high pressure jet in one borehole to force gravels and fines around large cobbles and boulders into a second "sump" borehole.

These problems were addressed in the design of the Bureau of Mines borehole gold mining system, which is a method of borehole mining through two or more boreholes. In multiple borehole mining, a water jet cuts a horizontal connection between one borehole and an adjacent borehole containing a slurry pump. The cutting jet is directed toward the intake of the slurry pump thereby creating a high velocity, turbulent regime at the pump intake. This method may also be extrapolated to allow mining from an array of boreholes drilled strategically in a frozen gravel deposit. The balance of this paper is taken up with a description of the design, laboratory testing and field testing of a two-borehole mining system.

3. DESIGN OF A TWO-BOREHOLE MINING SYSTEM

A field-ready prototype Borehole Placer Miner has been produced and successfully field tested in a frozen placer deposit in Alaska. The borehole mining machinery used is shown schematically in figure 1. Two identical borehole miners are placed in boreholes approximately 7.6 m (25 ft) apart. Each borehole miner is in the form of an assembly of pipes functioning as a water jetting system and a slurry pumping system as shown in figure 2.

The pipe assembly consists of three pressurized feed pipes nested inside a 25.4 cm (10 inch) diameter pipe which acts both as a housing and as a slurry exit pathway. Two of the three nested pipes join at the base of the tool where they feed into a 8-cm-diameter (3 inch) elbow which changes the direction of the jet pump feedwater from vertical downward to vertical upward. This water is then accelerated through a 6.35-cm-diameter (2.5-inch) nozzle which drives a jet pump used as a downhole slurry pump. The third of the nested pipes feeds a cutting jet nozzle. This 90° elbow-type nozzle was designed based on data published by "Rouse et al., (1951)..," and is especially suited to down-the-hole applications because of its compact geometry. The nozzle and feed pipe can rotate 90° in a horizontal plane and can move 1 meter (3 feet) vertically starting at a point near the jet pump inlet. The cutting jet nozzle movements are independent of the position of the slurry pump which is typically stationary at the base of the borehole. The 25.4-cm-diameter (10 inch) pipe extends from the outlet of the jet pump and thus provides a convenient pathway for the exiting slurry.

The borehole miner works as follows: An Ingersoll-Rand model HMTA-7 pump feeds 1500 l/m (400 gpm)[1] of water at 5500 kPa (800 psi) through the high pressure feed pipe terminated with a 1.91 cm (0.75 inch) nozzle. The jet thus created impacts on and disaggregates the frozen gravel. The resulting slurry is drawn into the inlet of a jet pump (figure 3) by the entrainment effect caused by forcing 5700 l/m (1500 gpm) of water at 1380 kPa (200 psi) from a Goulds model 3405 pump, through a 6.35 cm (2.5-inch) nozzle into a 15.2-cm-diameter (6-inch) mixing throat. The slurry is mixed with the driving jet and subsequently pressurized in the diffuser section of the jet pump. The output of this slurry pump then flows vertically alongside the nested pipes inside the 25.4 cm-diameter (10 inch) pipe until it exits into a sluicing system at the surface.

The mining sequence is as follows: Each of two borehole miners cuts a long, horizontal passage approximately 0.1 m^2 (1 ft^2) in cross section, in the direction of the other miner until the two passages meet. Then the water jet cutter of one miner is operated simultaneously with the slurry pump of the other miner. This cutting jet is directed toward the inlet of the slurry pump of the other miner. Thus, the water jet forces the slurry toward the inlet of the other miner with high velocity and turbulence. This keeps the gold in suspension while the slurry is induced to flow into the inlet of the slurry pump and is lifted to the surface (figure 4). The nozzle may be rotated in the horizontal plane and adjusted vertically to enlarge the cavity. The jetting/pumping sequence is alternated between the two boreholes until the horizon of interest is mined out.

4. LABORATORY TESTING

Several laboratory prototypes were built and tested leading to the design, fabrication and testing of the field equipment described above. These machines were tested in two types of test facilities. The first type of test facility consists of simulated frozen placer deposits as large as 8.5 x 2.4 x 1.5 m deep (28 x 8 x 5 ft). An example is the large rectangular box shown in figure 5. The deposits were saturated with water and allowed to freeze outside in the Minnesota winter to a solid mass. Thermocouples were inserted throughout the frozen gravels to monitor temperature. The target temperature (-4° C or 25° F), water content (10% moisture), and particle size distribution were chosen to approximate that of the frozen gravel in the Fox Tunnel near Fairbanks, Alaska. The deposits were seeded with lead or gold to help determine heavy metal recovery.

The second type of laboratory test facility allows for year-around borehole mining tests in frozen material. It consists of a large holding tank from which, at right angles, a long (up to 9.1 m [30 ft]) conduit can be attached. The conduit consists of 208 l (55-gallon) drums of frozen gravel without lids or bottoms, which are placed horizontally next to each other and fastened together. The borehole mining tool is set into an artificial borehole in the holding tank, with the high pressure water jet directed along the longitudinal axis of the barrels of frozen material (figure 6).

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[1]All pressures cited in this report were measured at the outlet of the pump. Flow rates cited are approximations based on nozzle size and pressure measured at the pump outlet.

4.1 Jet Cutting Tests

Preliminary tests using a variety of cutting jets ranging from 1200 l/m at 6900 kPa to 2600 l/m at 690 kPa (320 gpm at 1000 psi to 700 gpm at 100 psi) yielded disaggregation rates between 2.3-4.6 m^3/hr (3 and 6 yd^3/hr) of gravel frozen at -12° C to -1° C (10° F to 30° F). These tests indicated that the cutting rate was strongly dependent on both the feedwater temperature and the temperature of the frozen material. Two test sequences were, therefore, carried out to isolate these dependencies.

In the first test sequence, the feedwater temperature was held constant and the temperature of the frozen material varied. The test results are shown in figure 7 which indicates that, if the temperature of the jet is held constant, the removal rate decreases with decreasing sample temperature and increases dramatically as the sample temperature approaches 0° C (32° F).

The second set of tests involved a wide range of feedwater temperatures. These were achieved by solar heating to achieve the warmer temperatures and the addition of large amounts of ice to the supply water to cool the water to as low as 1° C (34° F) measured at the nozzle. The test results are shown in figure 8. These results are particularly revealing. Note that the removal rate falls practically to zero as the feedwater temperature approaches 0° C (32° F). This indicates that the removal process for this 6700 kPa (950 psi) jet is one of melting and that little or no mechanical fragmentation takes place.

It appears that there are two distinct melting processes in operation during the mining process. The first, which we call overmelting, is a slower process caused by the effect of ambient air and water on the entire cavity periphery. It affects a thin skin of material on the entire surface of the cavity. The second is a rapid localized melting likely enhanced by convective heating, the effect of jet impact pressure on the local melting point, and the instantaneous removal of thawed material. This second melting process appears to be the dominant factor in removing material and enlarging the cavity, especially over short time periods such as in the mining process. Figure 8 which plots the mining rate as a function of the feedwater temperature at the nozzle (of the water jet cutter used both in the laboratory experiments and the field trial in Alaska), suggests that maximum material disaggregation rates of about 9.1 metric tons/hr (10 tph) would be expected from the present system using the 7-10° C (45-50° F) pond water typically available.

Jet cutting tests also indicated that the most effective way to cut a connection between boreholes with the equipment available was to use a nozzle operating at 6900 kPa, 1200 l/m (1000 psi, 320 gpm). Such a jet punches a 4.6 m (15 ft) long horizontal passage in -3° C (26° F) gravel in about 10 minutes using 7° C (45° F) feedwater.

Experiments showed that lower-pressure, higher-volume jets cut slower but are more energy efficient in slurrifying gravels. A likely explanation for this is that as the cutting time and flow rate increase, more heat is transferred to the cavity periphery resulting in more "overmelting." Thus, after the high-pressure jet cuts the interconnection between boreholes, the pressure should optimally be decreased while the jet is used to sweep the slurrified ore into the jet pump in the other borehole. Using this method of operation in the lab, -3° C (26° F) gravels were mined at a rate of approximately 4.5 metric tons/hr (5 tph) from boreholes 8.2 m (27 ft) apart, using 4.5° C (40° F) jetting water. Seeded gold particles and lead shot were also recovered and captured in a sluicing system.

4.2 Slurry Pumping Tests

Disaggregated gold ore from permanently frozen gravels contains large cobbles. In order to lift as much material to the surface as possible while keeping operational costs low, a system was needed which would maximize the size of the removed material while minimizing borehole size. It was determined that jet pumps could achieve this. Typically, jet pumps are used to transport relatively small solid particles. A theoretical model was developed which would allow estimation of the performance of jet pumps in pumping up to 15.2 cm-diameter (6-inch) cobbles, such as those shown in figure 9.

Using this theoretical model as a design basis, two laboratory-scale jet pumps were built and tested. The first was a 15.2 cm (6-inch) jet pump built to be powered by an Ingersoll-Rand model HMTA-7 pump at 4100 kPa and 1700 l/m (600 psi and 450 gpm). Tests revealed that this pump performed as predicted by the model. It was capable of lifting slurrified gravels containing 12.5 cm-diameter (5-inch) cobbles at a rate of 20 metric tons/hr (22 tph) through a height of 12.2 m (40 ft). When this pump was powered by a BMI model PP113, two-stage centrifugal pump at 1100 kPa and 3400 l/m (165 psi and 500 gpm), it lifted 12.2 cm (5 inch) gravels 7.3 m (24 ft) vertically at a rate of 7.3 metric tons/hr (8 tph). A smaller 10.2 cm (4-inch) jet pump powered by the BMI drive pump lifted 7.6 cm (3-inch) gravels through a height of 12.2 m (40 ft) at a rate of 9.1 metric tons/hr (10 tph).

Results from the laboratory testing of these jet pumps were used to verify the theoretical model. The model, in turn, was used to predict the performance of a larger jet pump that would be required for field testing, but which required a higher volume driving jet than was available in the laboratory.

The pumps tested in the laboratory were not suitable for field application because they could not achieve high enough lifts with large 10.2-15.2 cm (4-6 inch) throat sizes. The lifts were limited not only by flow rate and nozzle pressure, but also because they use coherent jets directed along the center line of the 10.2-15.2 cm diameter throats. These coherent jets, powered by available pumps which operated between 1150-3000 l/m (300 and 800 gpm), were limited to maximum diameters of less than 5.1 cm (2 inches). Such jets fill only a small portion of the large area of the 10.2-15.2 cm throats and, therefore, the momentum transfer process is not optimized. It was determined using the theoretical model that a 6.35 cm-diameter (2.5 inch) nozzle operating at 5700 l/m and 1400 kPa (1500 gpm and 200 psi), would provide a combination of throat area coverage and driving momentum to lift 15.2 cm (6-inch) gravels to a height of approximately 15 m (50 ft). Therefore the borehole mining tool used in Alaska and depicted in figure 1 incorporated a 6.35 cm (2.5-inch) jet pump nozzle, supplied by a Goulds model 3405 pump at 5700 l/m (1500 gpm), 1400 kPa (200 psi).

5. FIELD TESTING THE BOREHOLE PLACER MINER

Field testing of the two-hole borehole mining concept was done at a mine on Tenderfoot Creek, 43 km (27 miles) northwest of Delta Junction, Alaska under terms of a Memorandum of Agreement with Voytilla Mining Ventures. The gold-bearing gravel at the test site is about 30.5 cm (1 ft) thick and occurs immediately adjacent to bedrock under approximately 12.2 m (40 ft) of overburden.

Two 35.6 cm (14-inch) boreholes were drilled 7.6 m (25 ft) apart and 13.1 m (43 ft) deep, into which were inserted 30.5 cm (12-inch) casings to a depth of 11.3 m (37 ft) (figure 10). The borehole miners were 28.7 cm (11.3 inches) in diameter to fit into the casing. An auxiliary third hole, located midway between the two production holes, was lined with 22.2 cm (8-3/4-inch) casing.

After the holes were drilled and cased, the borehole miners were lowered in 3 m (10-ft) sections into the holes. The first section was lowered and suspended from the lip of the larger 30.5 cm (12-inch) casing by small hanger brackets. The subsequent section was lifted into place using a winch on a drilling rig, and threaded into the hanging section. The hangers were then removed and the connected sections were lowered another 3 m (10 ft) and hung again on the lip of the casing. This process was repeated until the bottom of the borehole miner reached the bedrock interface.

The field trial of the Borehole Place miner utilized three boreholes and took place in two phases. Single borehole mining was performed in one of the production holes whereas two-hole borehole mining was performed between one production hole and the auxiliary hole. In the single borehole mining experiments the only force inducing the gold to flow into the downhole slurry pump was the pump suction. For the two-borehole tests, single borehole mining was performed in one of the production holes until a connection was cut in the "pay zone" that connected this production hole with the auxiliary hole 4 m (13 ft) distant (figure 11). Then a cutting jet with a 1.6 cm (0.62 inch) nozzle was lowered into the auxiliary hole and directed toward the borehole miner in the production hole. This jet was operated at pressures from 690 to 5700 kPa (100 to 800 psi) and rotated in the horizontal plane in order to flush material into the sump of the production hole. The jet pump in the production hole was operated for the duration of the run.

Gold was produced in both of these phases but the two-borehole arrangement produced three times as much gold as single borehole mining (Table 1). Table 1 shows the difference in gold production between single and two-borehole mining tests. Note that only about 1.8 cubic meters (2 cubic yards) of material were excavated from the 30.5 cm (1 ft) gold-bearing zone at the interface between the frozen gravel and the bedrock, thus the total amount of gold produced was small.

Surface subsidence and clogging of the borehole miner with cobbles were the main problems encountered during field testing. These problems will have to be corrected before borehole gold mining can be considered technically feasible.

Surface subsidence occurred in the form of a cylinder 1.2 m (4 ft) in diameter and about 1.8 m (6-ft) deep around the casing of the production holes. The subsidence was a process resulting from both the drilling method and the permafrost quality. The permafrost was melted 7.1 m (23 ft) from the surface, and due to the use of water in the drilling process, the borehole was drilled substantially larger than the casing. This allowed thawed material at the 7.1 m (23 ft) level to fall through the annulus around the casing into the mining cavity at the bottom of the borehole leaving a void at the 7.1 m (23 ft) level.

Surface material then subsided into this void. To prevent this problem in the future, holes might be drilled using air circulation in lieu of water, and/or be drilled the same diameter as the casing and the casing hammered into place. This would insure a tight fit between the casing and the borehole wall, thereby leaving no space for surface material to fall down into the borehole mining cavity. Working in a deposit frozen near to the surface would also alleviate this problem.

Clogging of the slurry output line with cobbles was the most serious problem encountered. It occurred in all of the field tests and was the reason for the termination of each of the field tests. The slurry pumping system is capable of passing a 15.2 cm-diameter (6 inch) cobble and many of these were lifted to the surface. The problem occurred when an elliptical shaped rock with one dimension smaller than 15.2 cm (6 inches) and another dimension larger than 15.2 cm (6 inches) entered the pump and then rotated and became wedged in the conduits of the tool. The problem was compounded when attempts to backflush by closing the slurry exit caused gravels in the vertical column to sink and congregate inside the column. This problem will be addressed in future designs by limiting the inlet size of the pump to preclude the possibility of such oversize materials entering the slurry system. In addition, a laboratory prototype borehole miner is being built which uses auxiliary jets and/or a rock breaker to free the jet pump inlet, while maintaining the full lift power of the jet pump to prevent cobbles from sinking inside the vertical section of the borehole miner.

6. CONCLUSIONS

1. Borehole mining of gold is more effective if a two-borehole system is used instead of the conventional single borehole system. Settling of gold is impeded through the action of a high discharge jet directed from one borehole to an adjacent borehole in which a downhole slurry pump is pumping material to the surface.

2. A tight seal must be maintained between the casing and the borehole wall in order to avoid subsidence caused by surface material falling between the casing and the wall of the borehole. This is particularly important where the deposit is thawed near the surface.

3. Rocks which have one dimension small enough to enter the slurry inlet but are larger in other dimensions can rotate and become wedged in the throat and/or the slurry outlet line. The jet pump inlet must be designed to prevent this, while still maximizing the diameter of material pumped.

4. More data are needed to determine the optimum jet characteristics for the disaggregation of frozen gravels, particularly for the advancement of horizontal headings to connect the boreholes.

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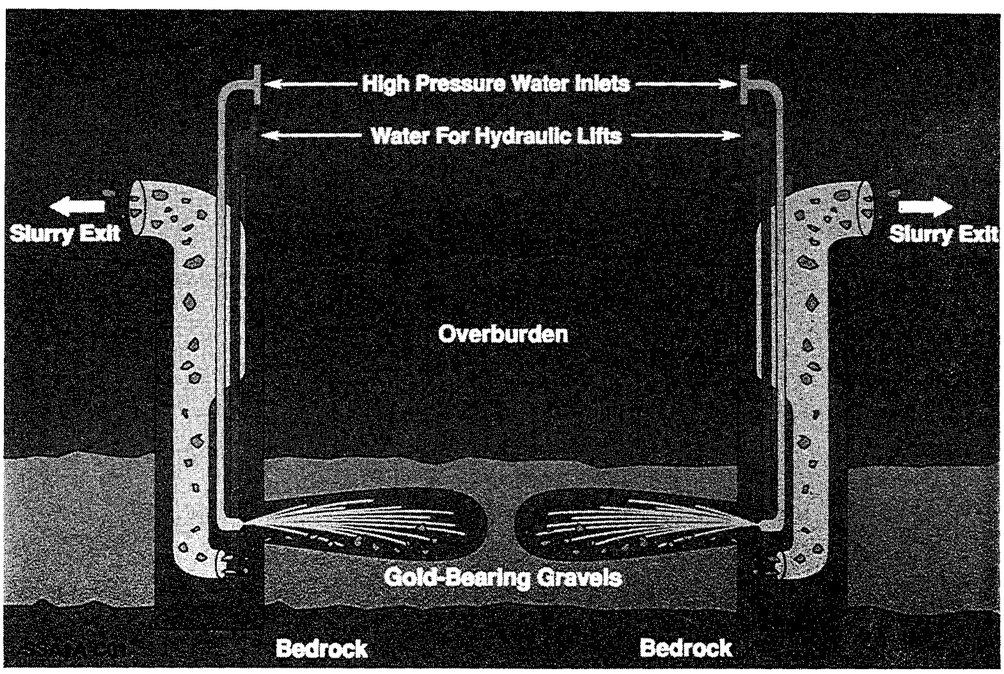

Figure 1. Two-borehole mining system cutting a connection between boreholes.

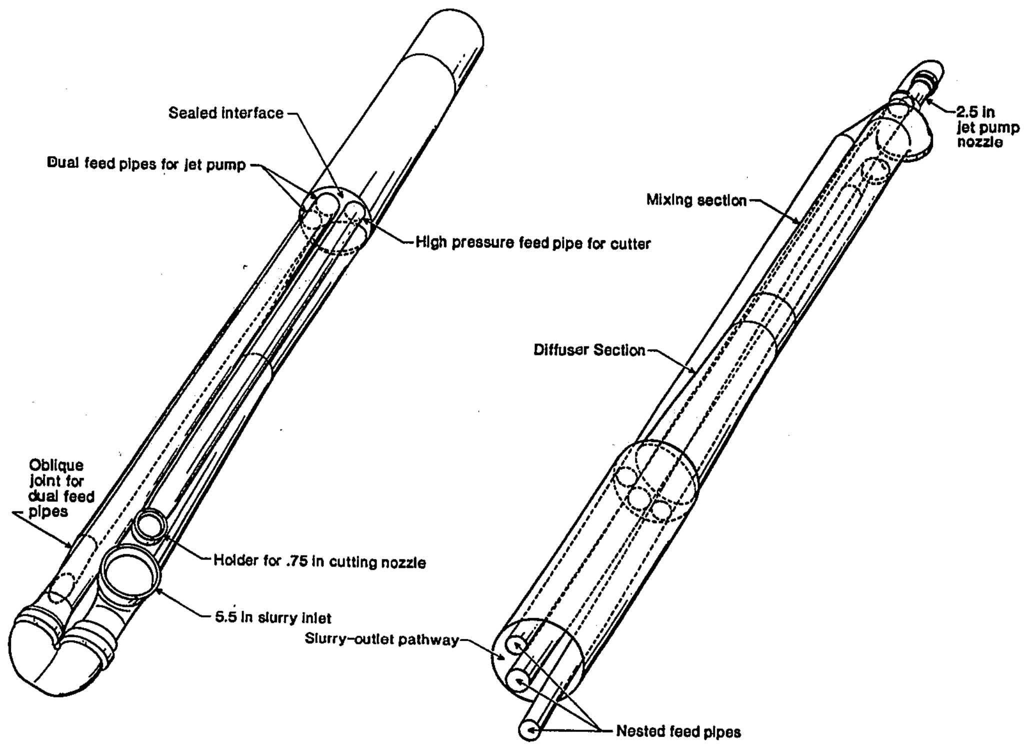

Figure 2. Schematic drawing of the Borehole Gold Miner.

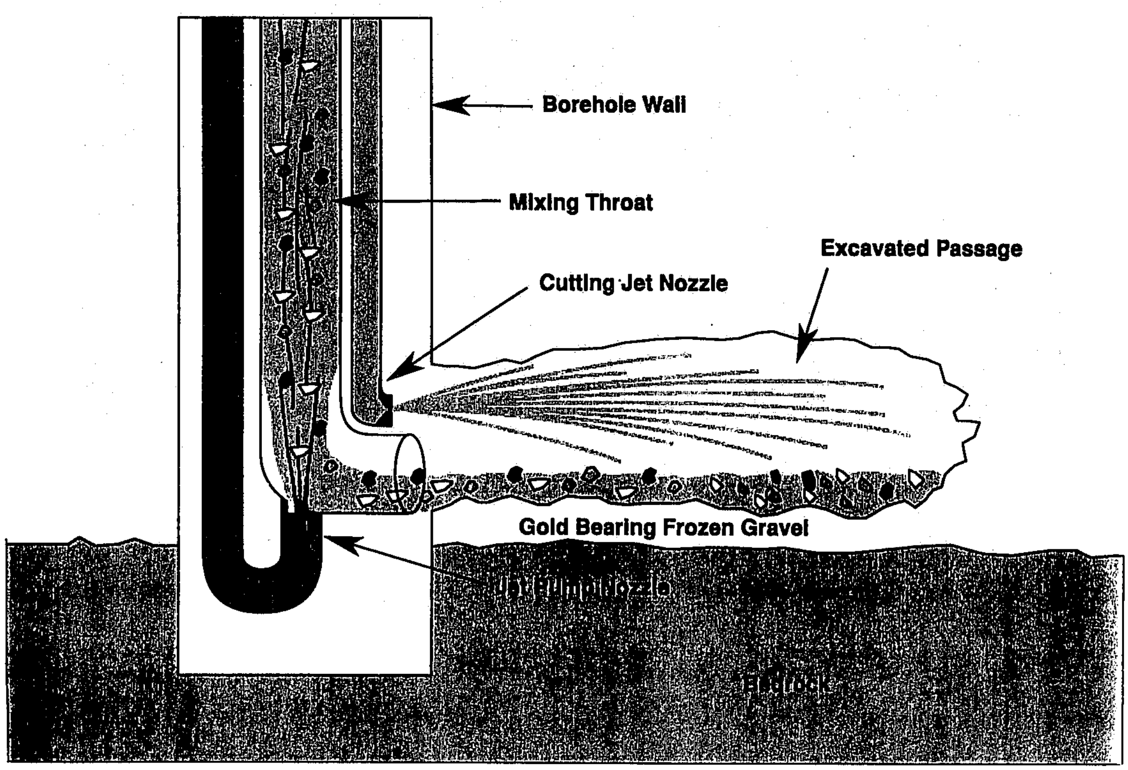

Figure 3. Schematic diagram of the jet pump and the jetting nozzle at the base of the borehole miner.

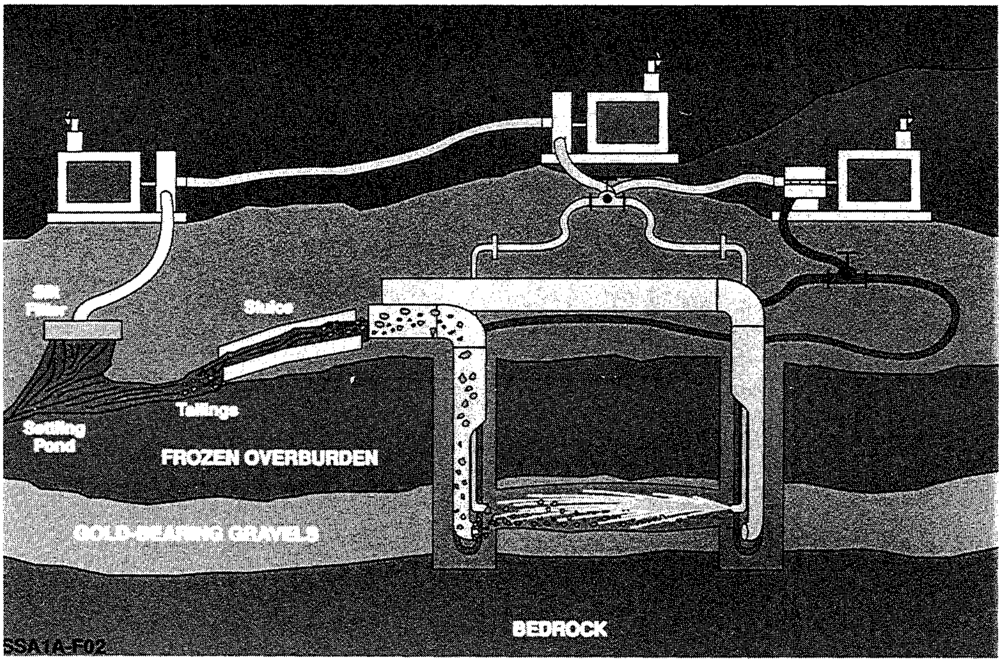

Figure 4. The two-borehole mining system jetting in one borehole and pumping in another.

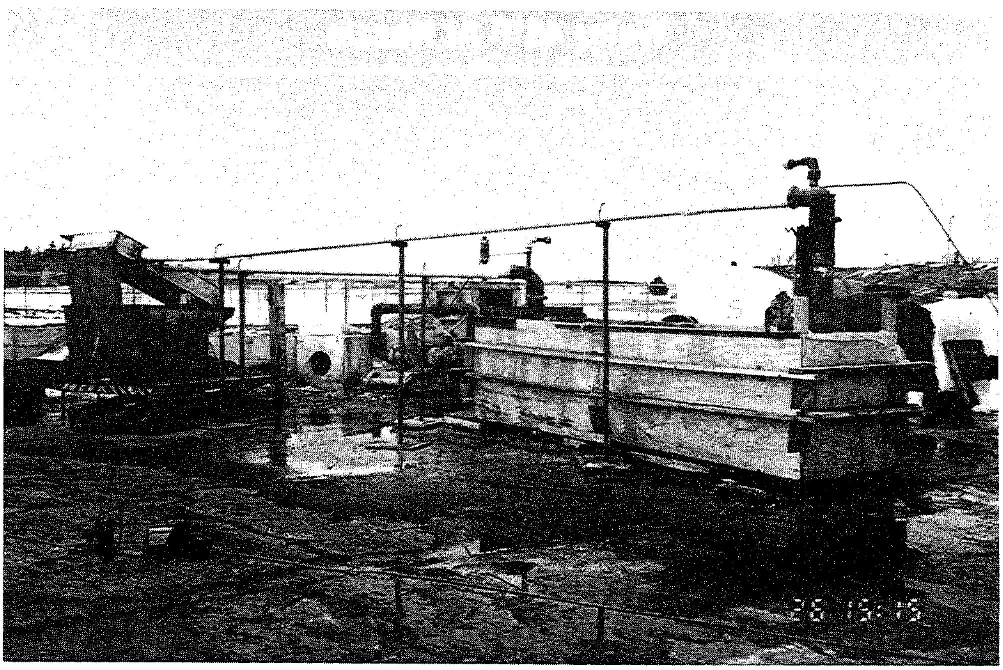

Figure 5. Borehole miners in frozen gravel in the laboratory.

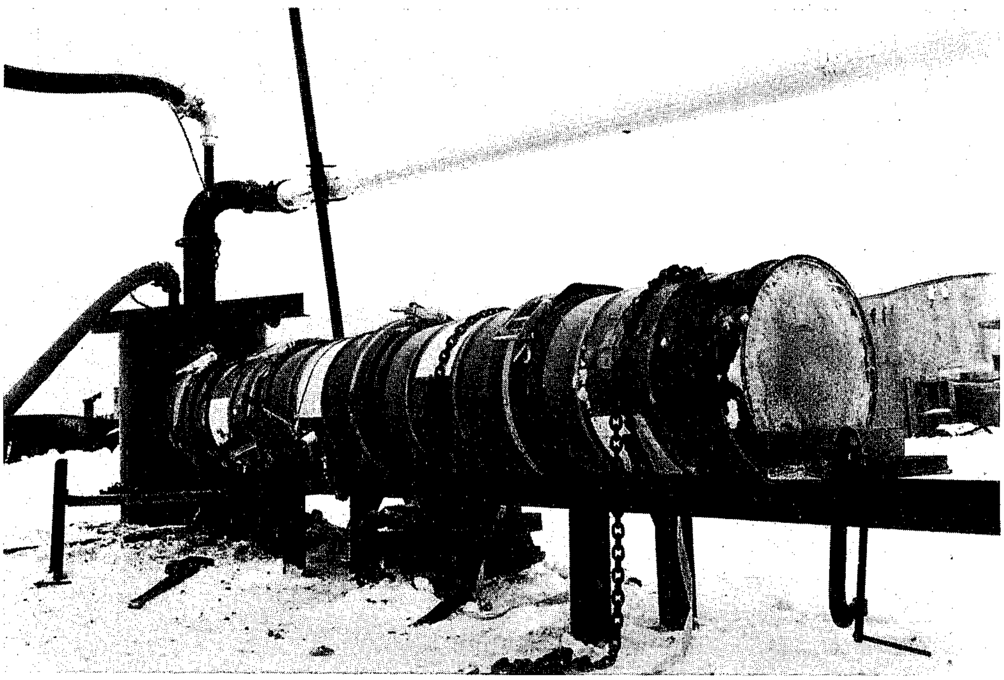

Figure 6. Facility for jet cutting of long holes in frozen gravels.

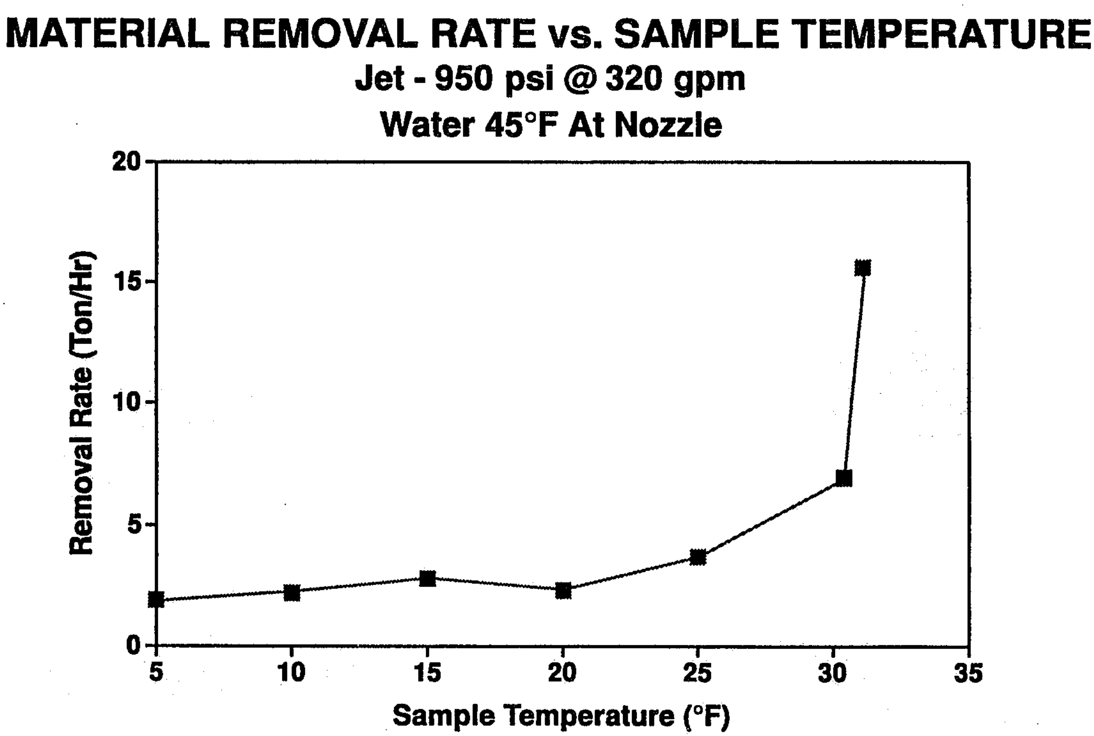

Figure 7. Graph of the rate of removal of frozen gravel as a function of sample temperature, the feedwater temperature held constant.

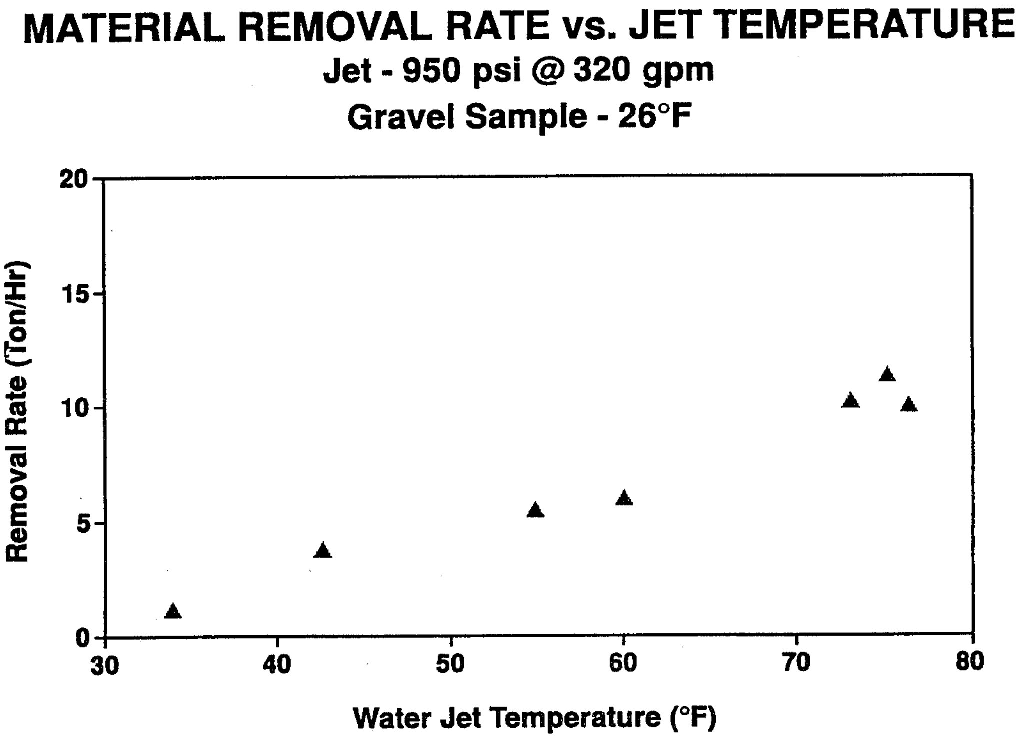

Figure 8. Graph of the rate of removal of frozen gravel as a function of the temperature of the jetting water, the sample temperature held constant.

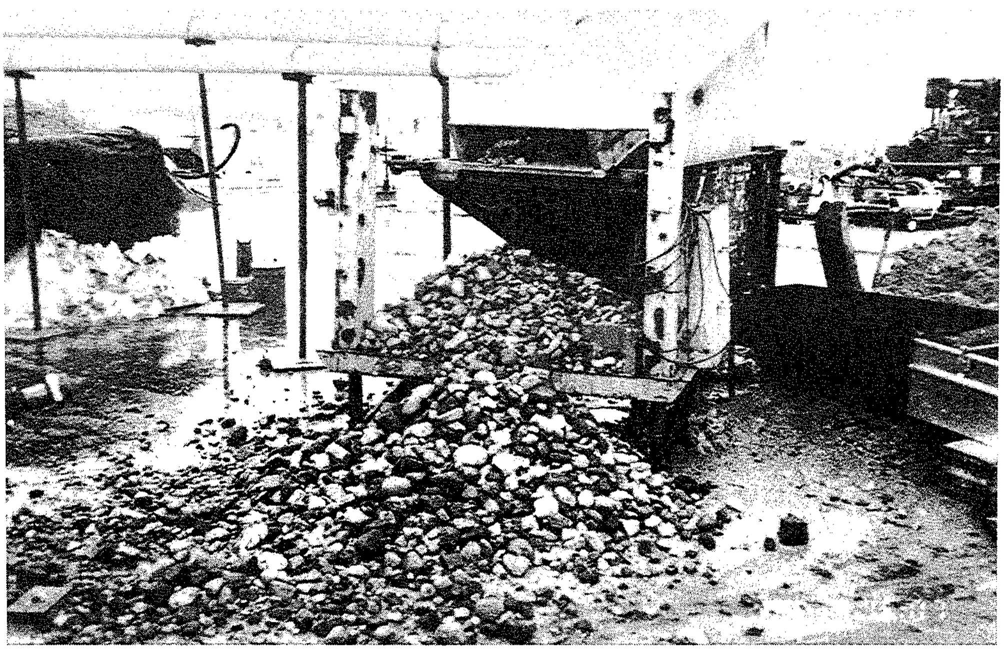

Figure 9. Screened cobbles pumped in laboratory tests.

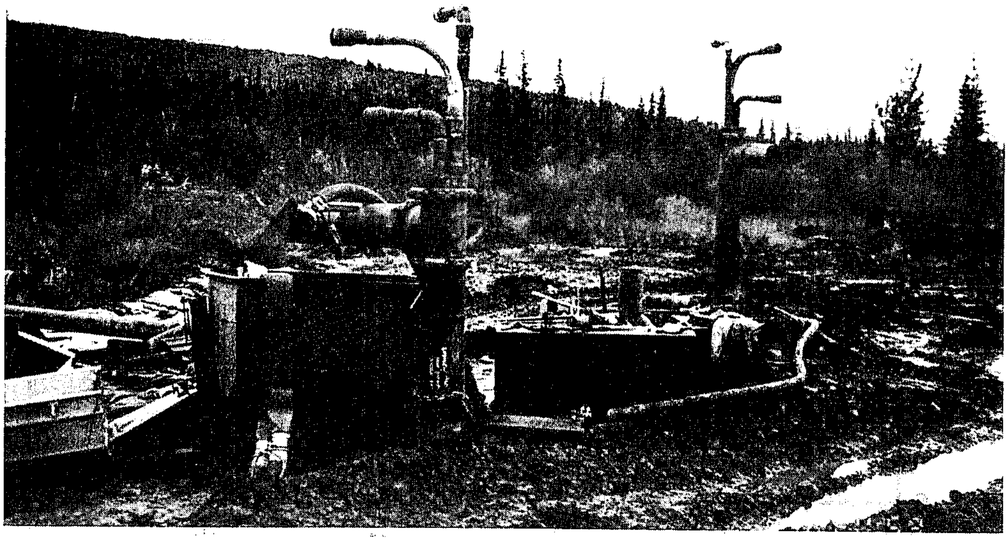

Figure 10. Borehole miners in place at Tenderfoot Creek, Alaska.

Figure 11. Borehole mining at Tenderfoot Creek, Alaska.

Table 1. -- Comparison of gold in one and two-borehole mining

	Gold Recovered
Single Borehole Mining	1.09 grams
Two Borehole Mining	3.65 grams

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CERTAIN CHOSEN PROBLEMS OF HYDROMECHANICAL MINING WITH DISK TOOLS

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ABSTRACT

This paper presents the results of a preliminary examination on the use of high–pressure water jets for assisting excavation with disk cutters. Based on data generated in earlier work where disk cutters and high pressure water jets were separately used to cut rock, this study is of the optimum working parameters required of a combined system and a prediction of the anticipated results. The basic assumptions made for the combined system have been preliminarily verified, using a test–stand especially developed for this research effort.

Organized and Sponsored by the Water Jet Technology Association.

1. INTRODUCTION

A problem of tunnelling and roadheading in Polish mining becomes more complicated with a decreasing of mining and geological condition accessible deposits. One can hit upon the rocks much more cohesive during the mining of first workings on deeper deposits. Thus from the operational point of view these working cross–sections have to be respectively larger. In consequences the new mining technology is necessary. One of such operational trends is a searching of new hydromechanical mining methods. The example of it is the combined system using a symmetric disk with an assistance of two high–pressure water jest. The paper presents the investigations on optimum working parameters of rock cutting with the assistance of water jets as well as a description of foreseen effects.

2. PENETRATION OF DISK CUTTER EDGE SHAPE INTO ROCK

From the point of view of mechanics the problem of destruction of space structure of cohesive rocks, concerned as an elastic and brittle medium, can be taken under consideration as contact questions between the body of rock and disk cutter edge shape. When the cutter is vertically penetrating into rock it generates a destruction area, which can be described by the following component elements (Fig.1):

1 – decay zone

2 – zone of side rock chips

3 – boundary surface of side shearing

4 – zone of original fractures of penetrating rock

A penetration of cutter edge has been described by a few mathematical models. For the analysis of hydromechanical mining with disk cutter the Dutta's model (Dutta, 1972) has been accepted as the most convenient, and next its generalization by Marianowski (Marianowski, 1980). Dutta's model was based on assumption that rock aggregated materials zone, which was below the cutter edge was a triangular cross–section with an angle of inclination θ (Fig.2). It allowed for calculation of this zone influence in a mathematical interpretation of the process.

The Marianowski's model, describing a periodical mechanism of concentrated zone formation and lateral chip splitting off during a tool penetration, additionally assumed the value of chip angle ψ for crater surface was the same as not crater surface. Basing on stroke ratio process of lateral rock chip formation along certain surfaces of the lowest resistance, fulfilling the Coulomb's and Mohre's criteria one can define, according to the Dutta's model, this force which is necessary to penetrate of the cutter edge shape into body of rock by the following equation:

$$P_d = K_1 \cdot h_1 \tag{1}$$

where:

$$K_1 = \frac{2R_c\,(1 - \sin\varphi)\sin\theta'}{1 - \sin(\theta' + \varphi)} \tag{2}$$

$$\theta' = \frac{\pi}{4} - \frac{\varphi}{2} + \theta$$

φ – internal rock wear angle

h_1 – cutter edge penetration depth

It is possible to define the angle of side rock chip ψ for a disk cutter edge by the following formula:

$$\psi = \frac{1}{2}\left(\frac{\pi}{4} + \theta_f - \frac{\varphi}{2}\right) \tag{3}$$

where:

θ_f – aggregate rock wear angle against body of rock.

Assuming the Marianowski's model where the angle of rock fracture is independent of state of rock surface on what the cutter edge is working (Fig.2) it can assume that:

$$F = K \cdot d_1 \tag{4}$$

$$F = k \cdot h_1 \tag{5}$$

where:

K – rock fracture constant

$$k = K \tan\beta \tan\left(\frac{\pi}{4} + \frac{\varphi}{2}\right) \tag{6}$$

hence we can obtain:

$$d_1 = \frac{k}{K} \cdot h_1 \tag{7}$$

Having d_1 and ψ values for given rock it is possible to define the breadth of groove space W (Fig.2) on rock according to the formula:

$$W = 2 \cdot \frac{d_1}{\tan\psi} \tag{8}$$

After substitution to the (8) formula (3), (6) and (7) dependencies we finally obtain:

$$W = 2 \cdot \frac{h_1 \tan\beta \tan\left(\frac{\pi}{4} + \frac{\varphi}{2}\right)}{\tan\left[\frac{1}{2}\left(\frac{\pi}{4} + \theta_f - \frac{\varphi}{2}\right)\right]} \tag{9}$$

It would be an initial value for a definition of disk cutter against assisting high–pressure water jets.

3. HIGH–PRESSURE WATER JET ASSISTANCE OF DISK CUTTER OPERATION.

For excavation of certain volume of rock with disk cutter it must be accomplished the definite number of runs of this tool in the aim to rock crushing. Successive running of disk cutter ought to be in such a distance that at the minimum amount of energy use could obtain the maximum effect. The distance so called cutter spacing depends on excavated rock kind and depth of cutting of rocks (Fig.3c) (Bureau of Mines Report, 1974). In this case called optimum spacing we obtain a full material removing between the grooves. In larger distance between the grooves there is no rock removing there is only a parallel contact on a surface of rock. That is the critical spacing (Fig.3b). An exceeding of this distance causes that the neighboring grooves are independent so they are opening ones (Fig.3a). An introduction of high–pressure jet between neighboring grooves for rock surface cutting will enable an enlargement of these grooves giving the full material removing. The new cut as an uncovered plane will diminish the rock and increase the mining effect. Taking under consideration (9) dependence on breadth of groove space W on rock body it has been assume the critical spacing was equal to W. Our assumed two jet cuts with high–pressure jets, symmetrically to the disk cutter work axe in a spacing B equal to:

$$B = \frac{1}{2} W + b \tag{10}$$

where:

W – breach breadth

b – cut breadth

A constant depth of cut g was assumed for cutting assistance with tree different grooves of disk cutter h_1. The presented investigations were carried out for disk cutter excavation with the disk cutter of D = 400 mm diameter, disk cutter edge angle equal to 2β = 90°, rock strength σ = 16 MPa and circumference cutting of ∅ = 0.50 m diameter and with a test–stand rotation table with tested rock ω = 11 1/min. We admitted the cutter penetration h_1 respectively: 10; 12.5 and 15 mm.

On the basis of earlier tests with the high–pressure water jet for assisted cutting they were used: the *Saphintec* type nozzles of d = 0.8 mm diameter and jet pressure p = 650 bar. This jet with given working parameters could erode the grooves of g = 13–14 mm depth (Fig.4) and cut breadth b = 3.4 mm.

It also assumed the surface of a breach would have a shape of double trapezoid (Fig.5).

From the earlier given dependencies and taking for the cutting rock φ = 28.5°; θ = 30°; θ_f = 24° and K = 0.12 in Table 1 the theoretical values of P_d force, W cut breadth, d_1 cut depth and V mined rock volume for disk cutting have been accepted, however in Table 2 the values of 2B cut breadth and V volume of mined rock with high–pressure jet cutting assistance. A verification of these assumptions was carried out on the test–stand for the elementary cutters.

4. INVESTIGATIONS OF DISK CUTTERS MINING.

Test of disk cutter mining and assisted cutting using high–pressure water jets were carried out on a laboratory stand for elementary tools (Fig.6). These tests were carried on the identical concrete samples of ∅ = 1200 mm diameter, h = 150 mm height and σ = 16 MPa compressive strength (Fig.7).

The disk cutter operation was carried out on tool of D = 400 mm diameter and 2β = 90° disk cutter edge angle. Thanks the generated stress of tested cutter on sample the penetration depth was h_1 and respectively 10; 12.5 and 15 mm and one made a cut along the whole sample circumference of ∅ = 0.50 m diameter and of the table speed with the cutting sample of ω = 11 1/min. The test–stand especially developed for these investigations was shown in Fig. 8.

During the mining process the P_d pressure force, P_b side force and P_s adjacent force having influence on the dick have been registered. The measurement way for one of series of these measurements was shown in Fig. 9. For further calculations the medium values of these forces have been done. In Fig. 10 there is the picture of one of these samples after testing study.

Table 3 presents the real values of P_d, P_b, P_s forces; W cut breadth; d_1 cut depth; V cutting rock volume and E_j elementary cutting energy during disk cutter mining. Comparing the theoretical values of Table 1 with analogical ones of Table 3 we can find a convergence of P_d and W values however the difference occurs in the comparison of d_1 and V values. The difference is diminution according to the increase of disk cutter penetration.

5. INVESTIGATION OF DISK CUTTER MINING WITH THE ASSISTANCE OF HIGH–PRESSURE WATER JET CUTTING.

Test of disk cutter mining with the assistance of high–pressure water jets were carried out on the same concrete samples and working parameters as for unassisted ones. These samples were cut by the combine system of both: disk cutters and water jets. The jets were placed before the cutting tool symmetrically to its axe in a B distance calculated from the formula (10) and distance from surface $l = 20$ mm using the nozzle of *Saphintec* type with $d = 0.8$ mm diameter at pressure of $p = 650$ bar.

These jets cut two grooves. In Fig. 11 there is a picture of the developed test–stand. During the operation the same values were registered as in the case without water jets assistance. The measurement way for of the series was shown in Fig. 12.

Thanks application of high–pressure water jet assistance the total decay of rock has been achieved between two grooves (Fig.13).

On Table 4 the real values of the same sizes like for cutting by the disk tool only, have been given and additionally crushing depths hw1 and h_{w2} on the cut edges (as in Fig. 5).

Comparing the obtained values with the analogical values of Table 2 and 3 one can find the convergence of the theoretical and testing data. As an effect of application of high–pressure water jet assistance is a diminution of P_d force value from 10 to 25%. That is the force which has the most important influence on cutting process. There is also an enlarged V volume of mined rock from 195 to 215% with E_j elementary summary energy comparable or lowest than energy required to disk cutters mining.

Comparing, however, these obtained effects for the same cut depths generated by the high–pressure water jet $g = 13$ to 14 mm for three different depths of h1 disk cutter penetration the best results were for h_1 depths comparable or greater from g cut depths.

It was additionally performed a series of tests with the disk cutter penetration of $h_1 = 12.5$ mm and with cutter spacing 2B as following:15; 30 and 45 mm greater. The purpose of them was to check up how the clearing of made grooves would flow into a cutting effect.

On Table 5 the real values of the same sizes as before were presented, except of 2B value replaced by W1 size. That is the real size of executed cutting.

Analyzing the obtained values we came to the conclusion that with the greater spacing of excavated grooves from the axe of disk cutting tool the result of cutting process was decreasing. The limit spacing when the total crushing of rock occurred across the whole breadth of groove was a distance of 15 mm greater (15%) from calculated 2B value. Increasing this spacing of 30 mm (30%) from the external groove side during the cutting, the hw1 crushing depth was obtained equal to 0 with the comparable crushing breadth of spacing of grooves. At the greatest groove spacing, when 2B = 135 mm, only the inner part of the groove there were crushed rocks (Fig.14). The measurement way for this series of tests was shown in Fig. 15.

6. CONCLUSIONS.

1. Applying high–pressure water jet assistance with the disk cutter one achieved the V volume of mined rock increase from 185 to 215% with the E_j elementary cutting energy equal or lower of 10% than in mechanical rock cutting;
2. The depth of assisted water jet cutting g ought to be comparable to h_1 disk cutter penetration depth;
3. The best effects of cutting one can obtain if the groove spacing caused by the assisted cutting do not exceed 2B value, calculated for h_1 disk cutter penetration depth;
4. The cutting speed can be increased by implementation of the above described combine systems, with assisted high–pressure water jets into mechanical system, with the same energy consumption.

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Table 1

h_1 [mm]	10	12.5	15
P_d [T]	5.624	7.382	10.353
W [mm]	64.9	81.1	97.4
d_1 [mm]	16.5	20.6	24.7
V [$m^3 \cdot 10^{-3}$]	0.839	1.317	1.887

Table 2

h_1 [mm]	10	12.5	15
2B [mm]	71.5	87.9	104.2
V [$m^3 \cdot 10^{-3}$]	1.689	2.327	3.097

Table 3

h_1 [mm]	10	12.5	15
P_d [T]	5.72	6.74	9.94
P_b [T]	1.59	1.84	2.6
P_s [kN]	1.78	1.11	2.15
W [mm]	57.8	80	89.6
d_1 [mm]	13.6	17.3	22.8
V [$m^3 \cdot 10^{-3}$]	0.593	1.065	1.604
E_j [$J/m^3 \cdot 10^8$]	1.485	1.092	1.007

Table 4

h_1 [mm]	10	12.5	15
P_d [T]	4.53	5.87	7.61
P_b [T]	0.55	0.80	2.54
P_s [kN]	0.98	1.65	0.99
2B [mm]	73.6	88.5	106.9
d_1 [mm]	13.8	18.1	20.1
h_{w1} [mm]	8.9	11.5	12.8
h_{w2} [mm]	9.0	12.7	13.6
V [$m^3 \cdot 10^{-3}$]	1.288	2.228	2.910
E_j [$J/m^3 \cdot 10^8$]	1.530	0.994	0.890

Table 5

2B [mm]	105	120	135
P_d [T]	5.96	5.99	6.36
P_b [T]	2.56	0.97	1.58
P_s [kN]	1.46	1.55	1.45
W_1 [mm]	106.1	116.8	96.2
d_1 [mm]	16.4	17.5	16.3
h_{w1} [mm]	10.0	0.0	0.0
h_{w2} [mm]	10.2	11.2	10.3
V [$m^3 \cdot 10^{-3}$]	2.223	2.031	1.805
E_j [$J/m^3 \cdot 10^8$]	1.189	1.320	1.390

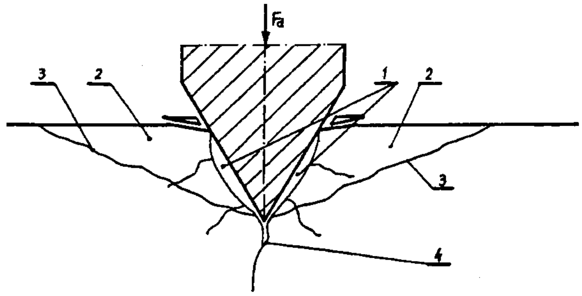

Fig. 1. Destruction area of rock with the disk cutter edge.

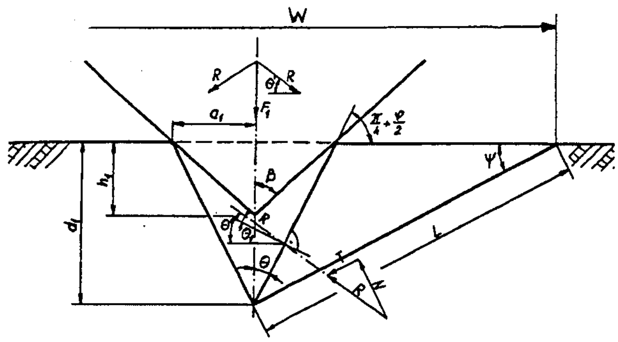

Fig. 2. The Dutta's model of disk cutting.

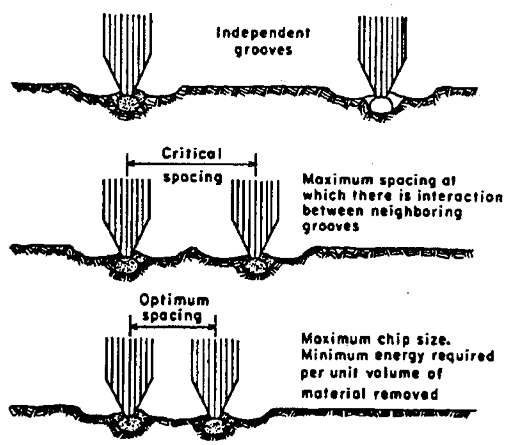

Fig. 3. Optimum and critical cutter spacings

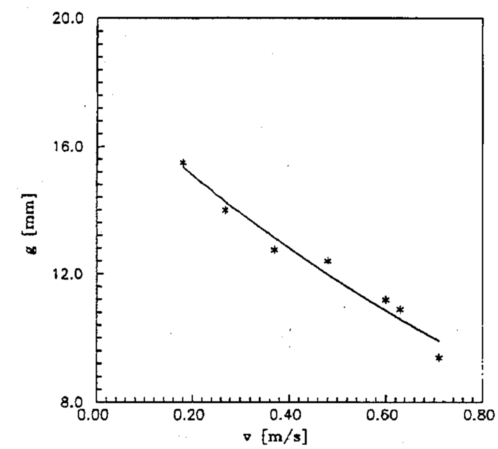

Fig. 4. Cutting depth depending on running velocity of the nozzle in relation to the sample.

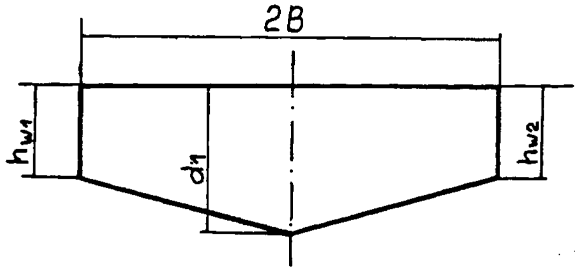

Fig.5. Scheme of breach surface.

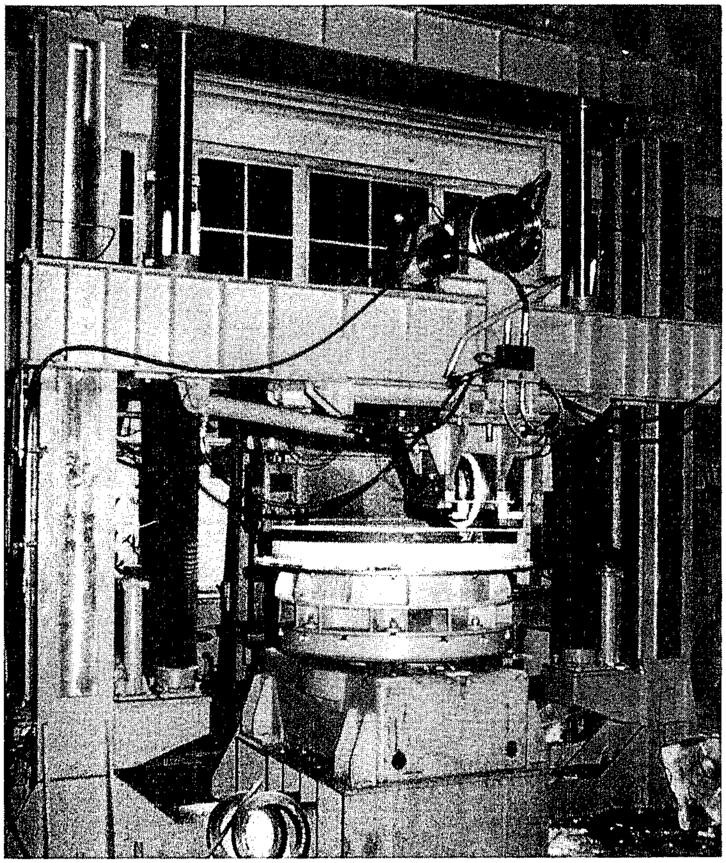

Fig. 6. The test-stand for elementary tools.

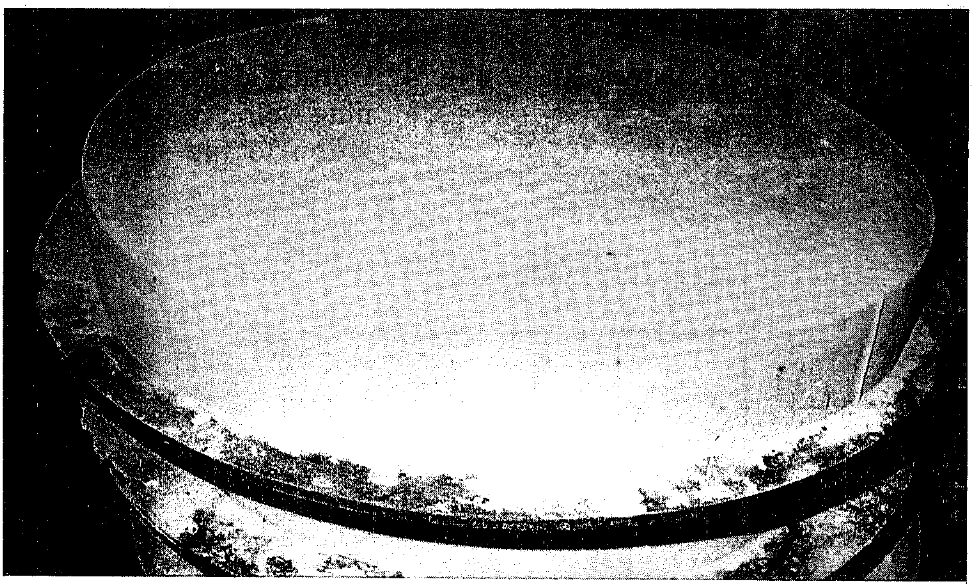

Fig. 7. Concret samples.

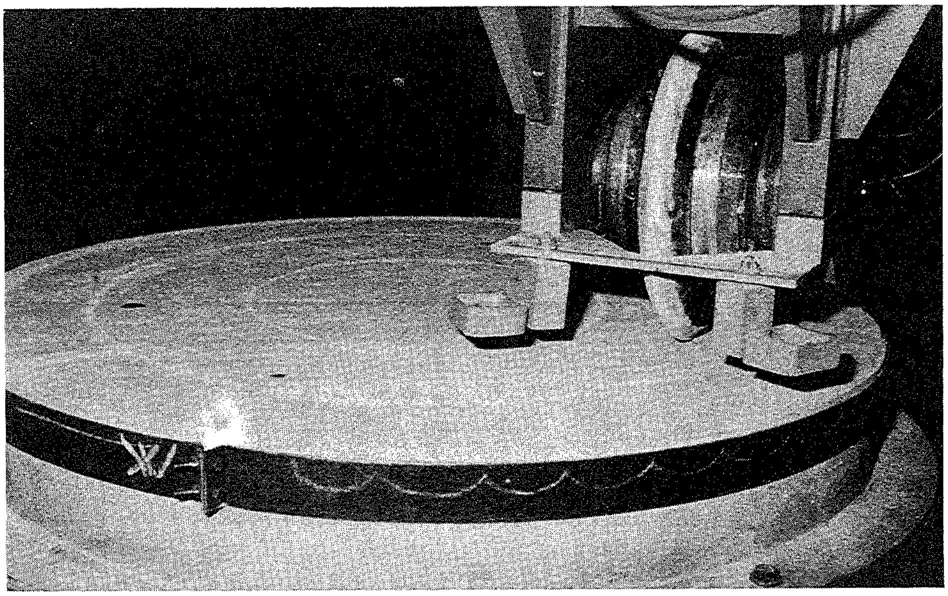

Fig. 8. The test-stand for investigations with disk cutters.

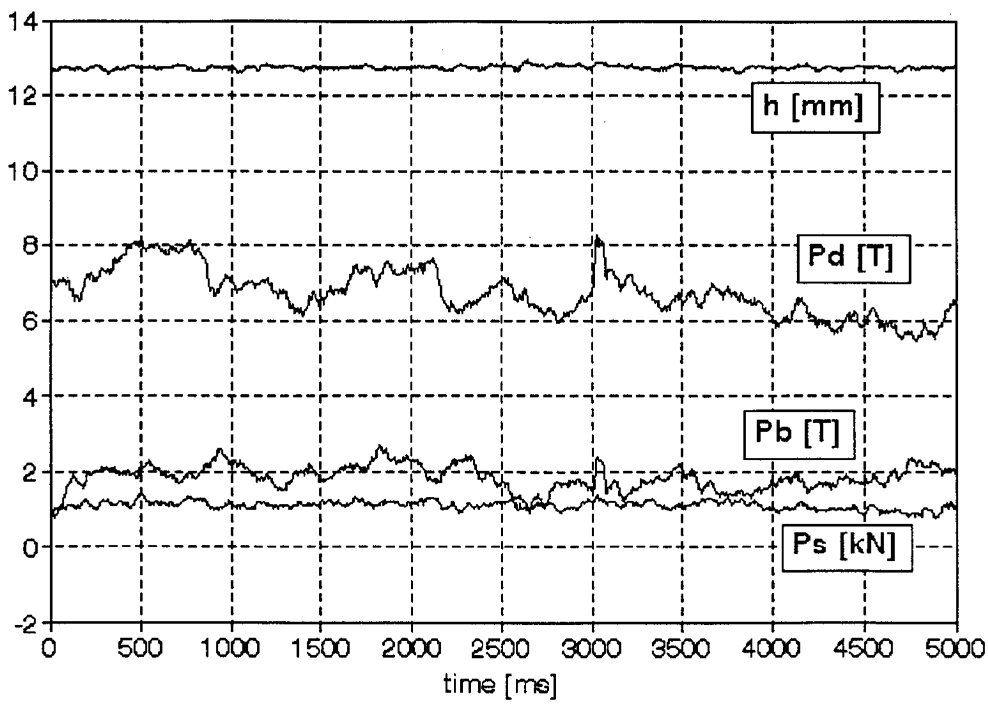

Fig. 9. Measurement way for one of series with disk cutting.

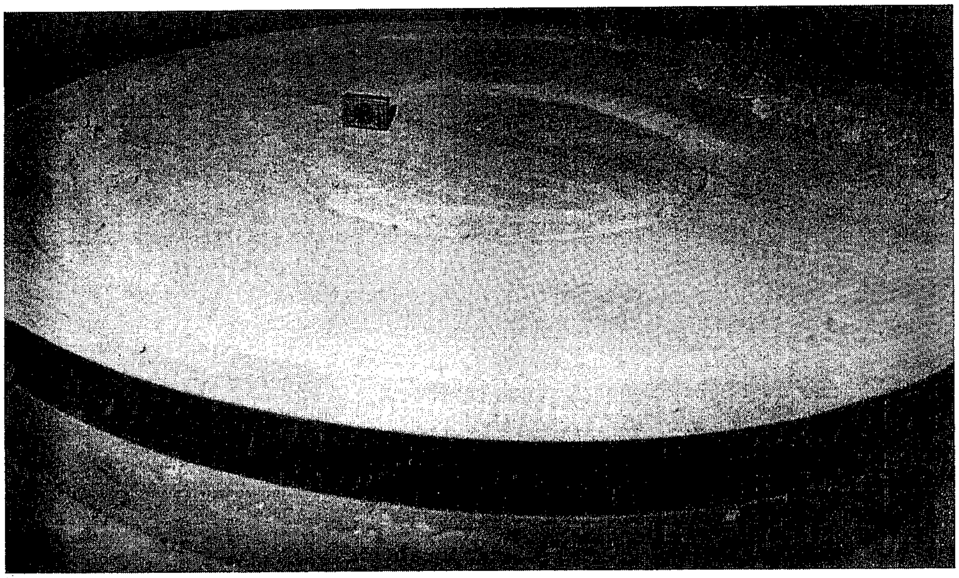

Fig. 10. One of the samples after mining process with disk cutters.

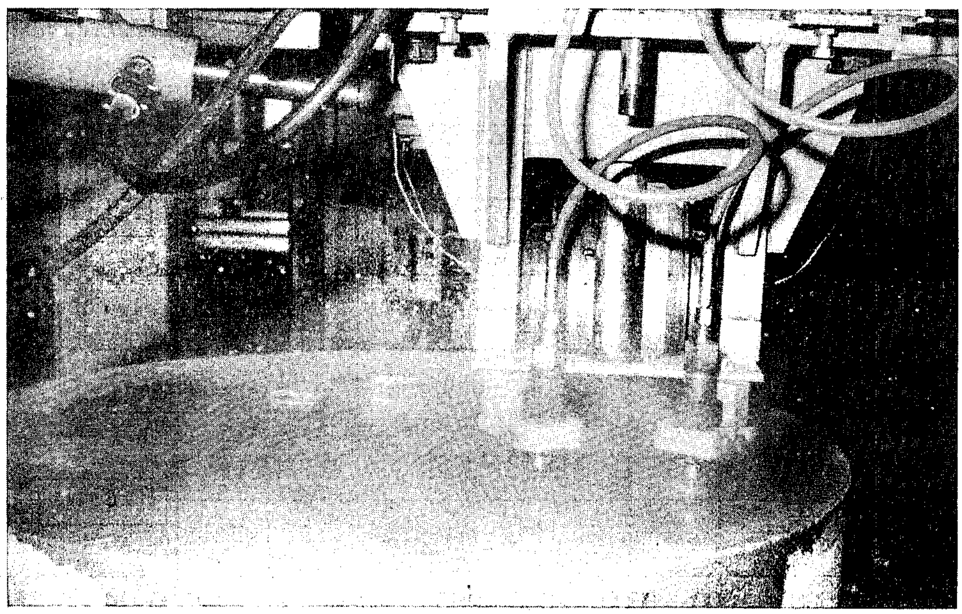

Fig. 11. The test-stand for investigations with a disk cutter with the assistance of high-pressure water jets.

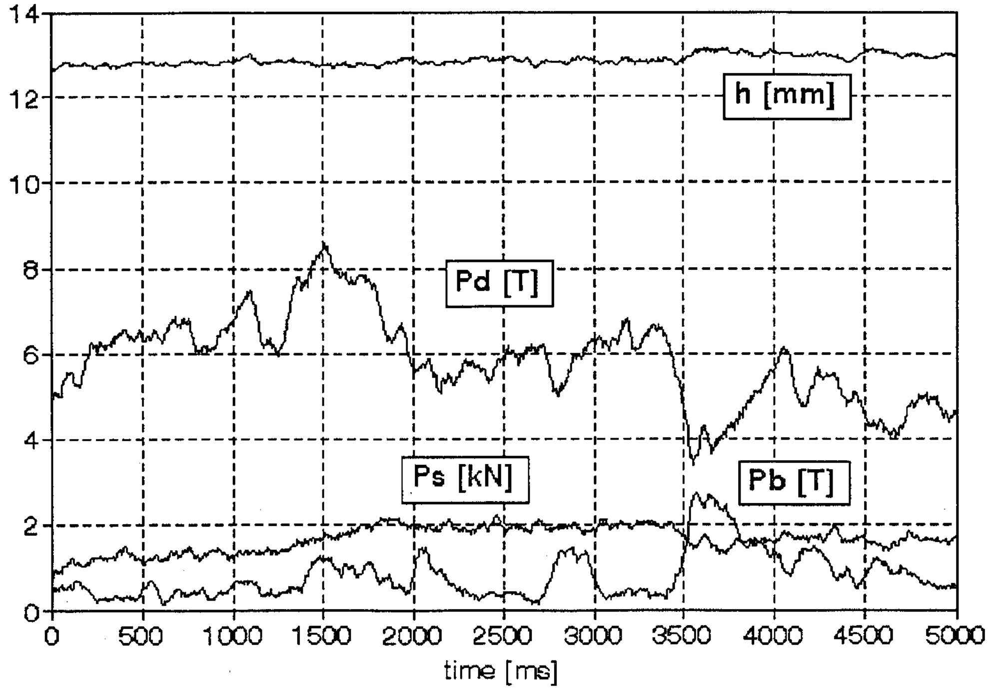

Fig. 12. Measurement way for one of series with mechanical mining process with the assistance of high-pressure water jets.

Fig. 13. One of the samples after mining process with a disk cutter and the assistance of high-pressure water jets.

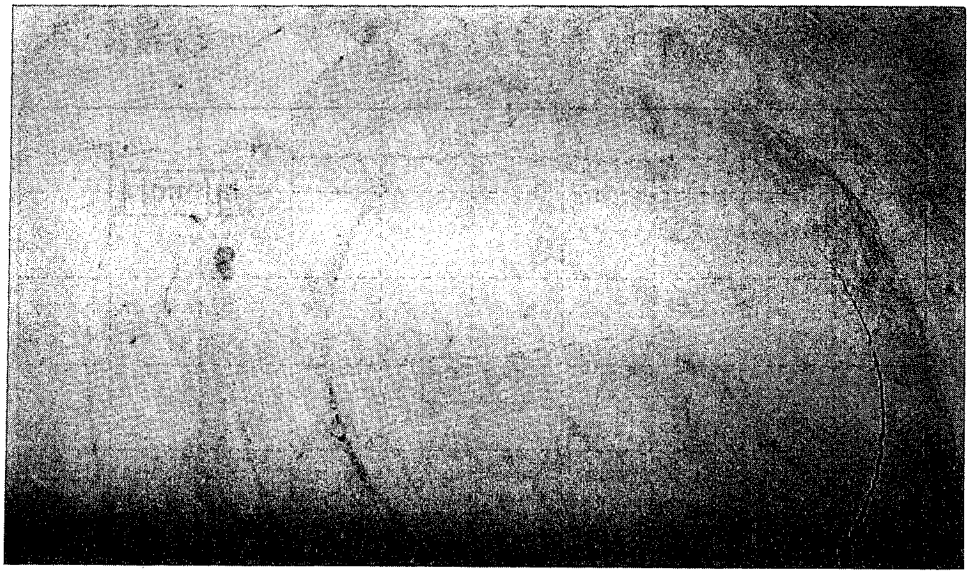

Fig. 14. One of the samples after mining process with a disk cutter with the assistance of high-pressure water jets and the greatest groove spacing.

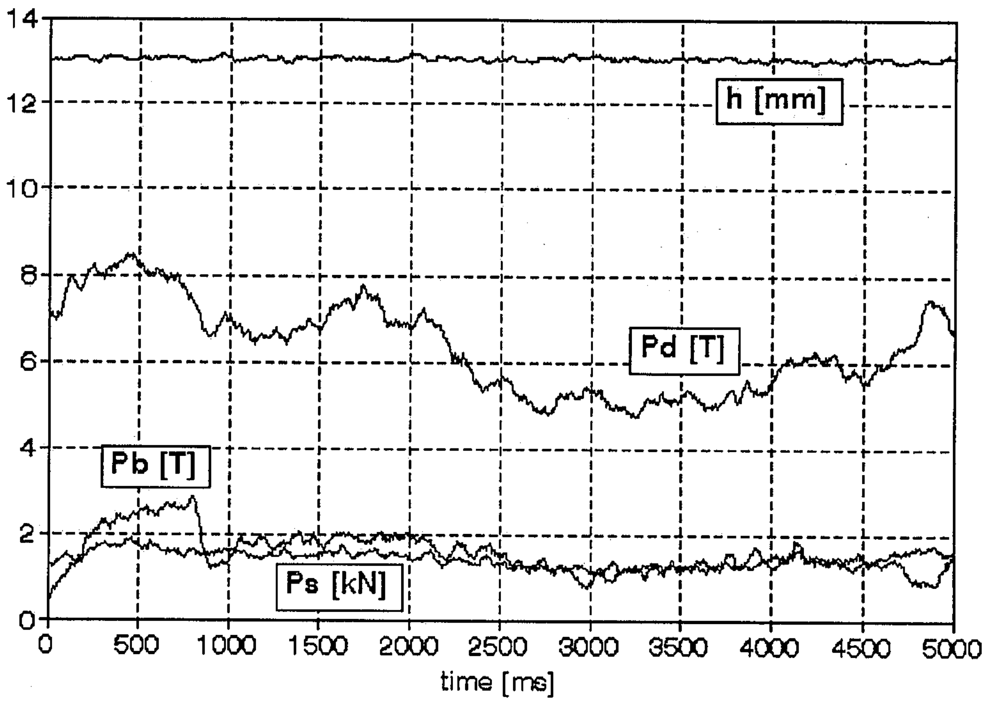

Fig. 15. Measurement way for the series with mechanical mining process with the assistance of high-pressure water jets and the greatest groove spacing.

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Paper 36

STUDIES ON CATASTROPHE MECHANISM OF SELF-CONTROLLED HYDRO-PICK CUTTING ROCK

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ABSTRACT

The possibility of increasing the self-Controlled hydro-pick breaking rock volume was discussed. The leaping phenomenon in cutting process was studied with the method of catastrophe theory. Analysis and test results prove that the static water pressure can be applyed to enhance rock breaking volume.

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1. INTRODUCTION

The assistance cutting method of water jet cutting at a position of 1 to 2 mm ahead of pick tip has been studied for many years[1]~[3]. For this type of cutting, it is necessary to apply high water pressure in order to reduce the cutting force and to achieve faster pick cutting velocity because of the great distance from the nozzle to the rock surface. So the water pressure is generally greater than 100 MPa.

Based on the problems of water jet assisted cutting, we have made a proposal to reduce the stand-off distance. The pick tip is designed as a nozzle used for cutting as well as water flushing. This type of tool is caled the self-controlled hydro-pick (SCHP). The SCHP cutting mechanism is different from that of water jet assisted cutting. The function of water jet is not for pre-cutting of kerf, and for propagation of cracks in rock produced by SCHP in a form of hydraulic wedge.

This method is called combination cutting method which makes full use of the charactor of rock that the tensile strength is by far lower than the compressive strength. So the water pressure required by combination cutting method is by for lower than assistance cutting method[4]~[6].

Based on the studies of combination cutting method, this paper will further discuss the possibility of increasing SCHP breaking rock volume

2. CATASTROPHE PHENOMENON IN ROCK CUTTLNG PROCESS

There is not a linear relation between the penetration of pick and the cutting force. In the initial stage of rock breaking, the penetration increases correspondingly with the cutting force. When the cutting force is at some critical value, the penetration will leap forward suddenly.

The leaping phenomenon in the process of rock breaking is a typical catastrophe phenomenon which can be described as the sudden change of the system state resulted from the contimuous change of some factors.

The building of catastrophe model depends on the knowlege of rock breaking essential relation. The compressing test results of marble specimen as shown in Fig. 3 can be simulated with a exponential function:

$$F_2 = G_0 s e^{-s/s_0} \tag{1}$$

in which

F_2: rock resistance

s: driven displacement of the interface

s_0: displacement at peak rock resistance

G_0: initial stiffness

Parameters G_0 and s_0 as shown in Fig. 4 can be drawn up from test data. The force F_1 of loading system is equal to the rock resistance F_2 only in the condition of static equilibrium:

$$F_1 = k(w - s) \tag{2}$$

k: stiffness of the elastic loading system

w: driving displacement of the loading system

The total potential V of the model can be described as

$$V = \frac{1}{2}k(w-s)^2 + s_0 G_0 [s_0 - (s+s_0)e^{-s/s_0}] \tag{3}$$

The equilibrium curved surface **M** is saticfied with $\frac{dv}{ds} = 0$:

$$k(w-s) = sG_0 e^{-s/s_0}, \tag{4}$$

and the strange point set **N** with $\frac{d^2v}{ds^2} = 0$:

$$k + G_0(1 - \frac{s}{s_0})e^{-s/s_0} = 0 \tag{5}$$

The set **N** is irrelevant to the driving displacement w, so the catastrophe conditions of the rock breaking system only depend on its charactors of the system itself.

3. CATASTROPHE ANALYSIS

The equilibriam curved surface **M** can be developed at branch point s_c of the set N:**N**:

$$G_0 s_c e^{-s_c/s_0} - k(w - S_c)$$
$$+ [G_0(1 - \frac{s_c}{s_0}e^{-s_c/s_0} + k](s - s_c)$$
$$+ [\frac{G_0}{2s_0}(-2 + \frac{s_c}{s_0})e^{-s_c/s_0}](s - s_c)^2$$

$$+ \left[\frac{G_o}{6\, s_o^{\,2}}\left(3 - \frac{s_c}{s_o}\right)e^{-s_c/s_o}\right](s - s_c)^3$$

$$= 0, \tag{6}$$

and translated into standard catastrophe form:

$$x^3 + px + g = 0 \tag{7}$$

in which

$$x = \frac{s - s_c}{2s_0} \tag{8}$$

$$p = \frac{3}{2}(\lambda - 1) \tag{9}$$

$$q = \frac{3}{2}(1 - \lambda\zeta) \tag{10}$$

$$\lambda = \frac{k}{G_0 e^{-2}} \tag{11}$$

$$\zeta = \frac{w - s_c}{2s_0} \tag{12}$$

Is is thus obvious that the system state parameter x is complelely dominated by the parameters λ and ζ.

According to catastrophe theory,[7], the catastrophe condition is

$$p < 0 \tag{13}$$

or

$$\lambda < 1 \tag{14}$$

or

$$k < G_0 e^{-2} \tag{15}$$

That is to say, the stiffness of loading system must be lower than that of rock.

4. APPLICATION

The above analysis results show that the leaping phenomenon can be enhanced by increasing energy release rate of loading system. This principle is applyed to design the SCHP as shown is Fig. 6.

The test results show that the rock breaking volume of the SCHP increases about 34% than that of common pick under the conditions of water pressure 40 MPa, rock compressive strength 110 MPa and cutting depth 18 mm.

5. CONCLUSION

In the system of pick combined with water jet, the static water pressure can be applyed to reduce the stiffness of loading system in order to increase rock breaking volume.

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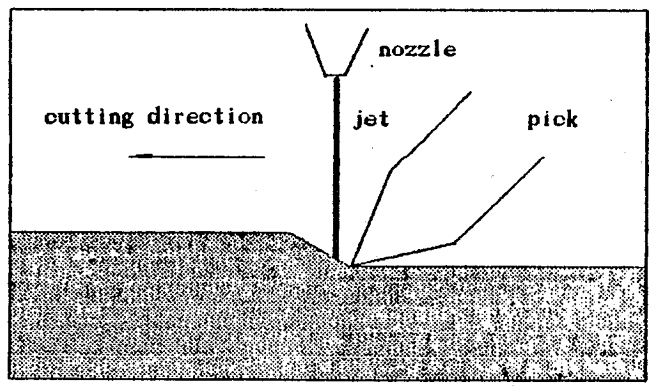

Fig. 1 Assitance Cutting Method

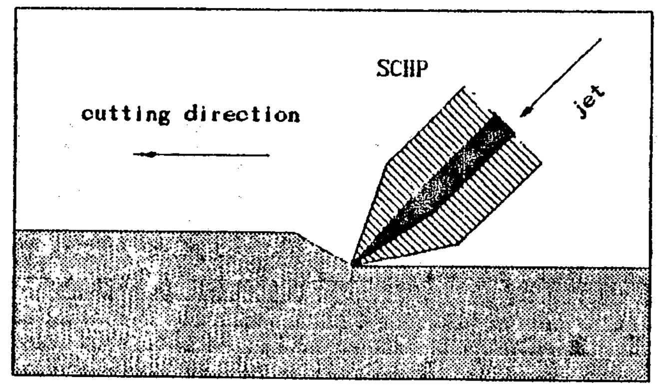

Fig. 2 Combination Cutting Method

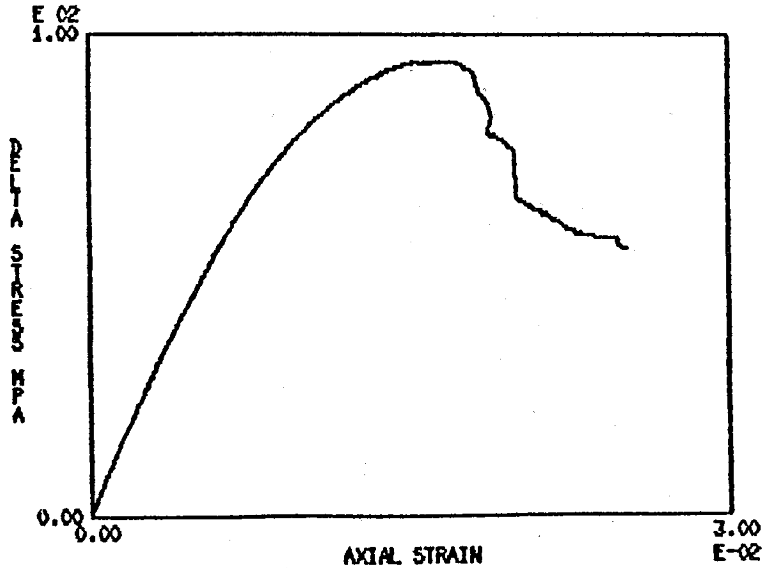

Fig. 3 Experimental Curve

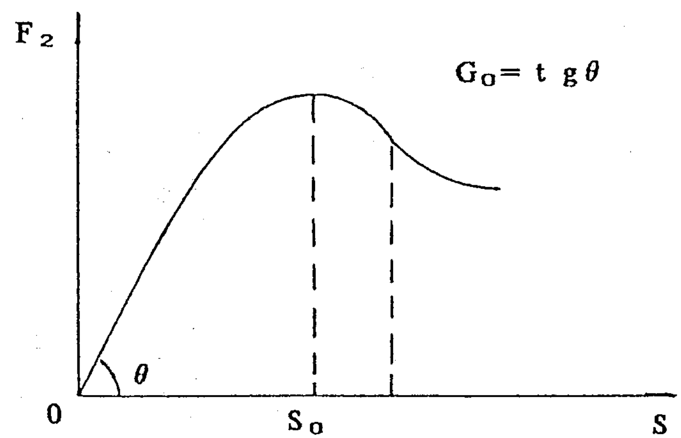

Fig. 4 Simulated Curve

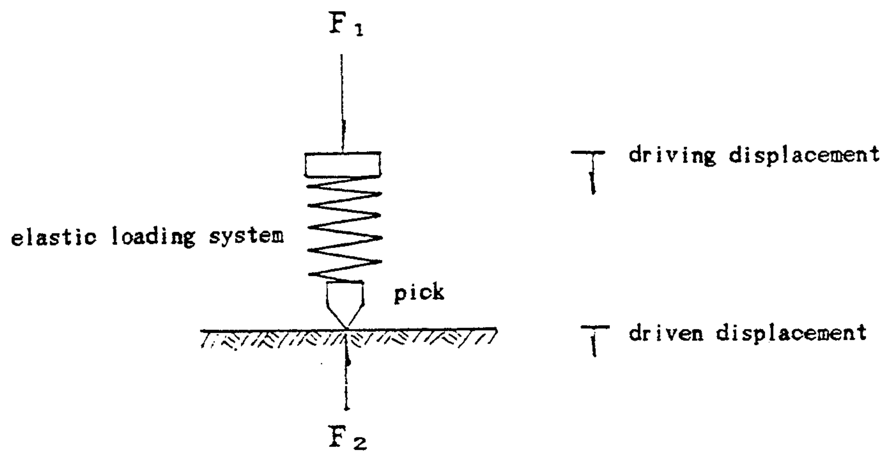

Fig. 5 Mechanical Model Of Cutting System

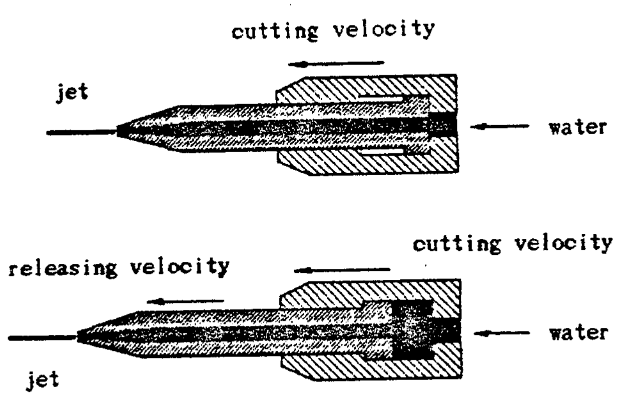

Fig. 6 Static Water Potential Energy Releasing Principle

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Paper 37

JET-ASSISTED MECHANICAL DRILLING OF OIL AND GAS WELLS

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ABSTRACT

A newly developed system for drilling oil and gas wells takes advantage of ultrahigh-pressures up to 235 MPa. A small portion of the downhole mud flow is pressurized and conducted to the drill bit through a dual conduit drill string. This allows a high velocity jet of drilling mud at the bit to be directed at the bottom of the hole. The jet(s) assists the mechanical action of the bit to achieve penetration rates 2-3 times conventional rates. As a result of faster penetration rates, the cost and time required to drill an oil or gas well can be significantly reduced.

Equipment on the surface includes ultrahigh-pressure pumps, an isolator (for pressurizing mud), surface piping, kelly hoses, a dual passage swivel, and dual conduit kelly. The drill string and associated downhole tools include all the elements found in conventional rotary drilling: drill pipe, drill collars, stabilizers, various specialty subs, and drill bits. To achieve acceptable reliability and compatibility with normal drilling operations, technology improvements had to be developed for seals, swivels, check valves, and nozzles. A commercial grade system has been undergoing testing for the past two years in Texas with Grace Drilling Company. Recent field tests have demonstrated greatly improved reliability and brought the system nearer to commercialization.

Organized and Sponsored by the Water Jet Technology Association.

1. INTRODUCTION

The potential advantages of applying high-pressure technology to increase penetration rates in drilling oil and gas wells were demonstrated in the early 1970s (Maurer, 1980). Early attempts at providing high-pressure (up to 103 MPa) mud for drilling required that the entire fluid stream be pressurized. This resulted in extremely high power requirements, reliability problems, and safety concerns.

FlowDril has developed a patented method of delivering ultrahigh-pressure drilling fluid to assist the mechanical action of the drill bit that is reliable and safe (Patent No. 4,624,327). The term "ultrahigh-pressure" is applied to this technology because it provides a pressure downhole significantly greater (up to 235 MPa) than high pressures previously used in oil and gas well drilling.

FlowDril began development of the high-pressure (ultrahigh-pressure), jet-assisted drilling system for oil and gas wells in 1985. Grace Drilling Company of Dallas, Texas, began working with FlowDril in July of 1988 to further development of the system. Grace/FlowDril of Tyler, Texas, a joint venture between Grace Drilling Company and FlowDril, was formed in April of 1990 to develop a commercial drilling system for the U.S.A. This system, referred to as the FlowDril™ system, holds the promise of increasing the speed of drilling several fold.

The FlowDril™ system was described in part by Butler, et al. (1990), Cure and Fontana (1991), and by O'Connor and Scott (1991). Early laboratory and field test results were discussed by Kolle' et al. (1991). The method consists of splitting the conventional mud stream at the surface into a low volume, high-pressure component and a conventional, low-pressure component. High-pressure drilling mud is centrifuged and pumped downhole to a modified drill bit through a concentric dual conduit drill string at flow rates up to 150 L/m. and pressures up to 235 MPa. The low-pressure mud is pumped conventionally through the internal annulus of the drill string to the bit where it is re-combined with the high-pressure mud and returned up the outer annulus to maintain borehole stability and accomplish transport of cuttings up the borehole.

2. THE FLOWDRIL™ SYSTEM

Figure 1 illustrates the major components of the FlowDril™ system. For convenience, the description is divided into surface equipment (above the rig floor) and downhole equipment (below the rig floor).

2.1 Surface Equipment

The high-pressure pumping unit consists of three skid-mounted, high-pressure water pumps set on a trailer. These are crank shaft driven triplex pumps, each powered by a Caterpillar diesel engine. The pumps are manufactured by Flow International, Inc. Each pump is capable of 235 MPa and 51 L/m. at 500 rpm. Through a closed loop water circuit, these pumps drive a water/mud central isolator on a separate skid that pressurizes the mud stream and pumps it downhole. The central isolator is a dual cylinder, one-to-one ratio floating piston pump. Rated output is 235 MPa and 136 L/m.

Drilling mud is drawn from the rig mud tanks, centrifuged, and fed to the isolator. High-pressure mud from the isolator is transported to the base of the rig through 28 mm internal diameter shielded high strength surface piping. Included in the surface piping is a safety check valve with bleed through poppets. From the base of the rig, flexible multiple wire braid kelly hoses conduct the mud up into the rig derrick and down to the high-pressure swivel manifold in parallel with the rig conventional kelly hydraulic hose. Three high-pressure kelly hoses are used to minimize pressure loss. Each hose is 12.7 mm internal diameter and 42 meters in length. The hoses are rated at 360 MPa burst pressure. Each hose is shielded and restrained at each end for safety.

The dual passage swivel is a modified Gardner Denver SW400 oil field swivel. A high-pressure swivel cartridge and inner conduit are added to accommodate the high-pressure mud flow. Immediately below the swivel is the dual conduit kelly, dual passage lower kelly valve (when required) and dual conduit kelly saver-sub. The lower end of the kelly, lower kelly valve, and saver-sub are below the turn table drive bushing during drilling.

2.2 Downhole Tubulars

A major consideration in development of tubular components was acceptance by the oil and gas well drilling industry. All components were designed to be compatible with conventional rig procedures and operations. For example, all of the drill string components, drill pipe, drill collars, and subs are handled on site and made up on the rig floor the same as conventional equipment. Standard API tool joints are used on all the tubular equipment.

Standard 114 mm diameter API drill pipe is used. Drill collars used vary in diameter from 159 mm to 171 mm depending on whether hole diameter is 200 mm or 222 mm. Each drill pipe, drill collar, and sub has a concentric beryllium-copper high-pressure inner conduit for the high-pressure mud flow. Drill pipe with inner conduit and high-pressure pins are shown in Figure 2.

Beryllium-copper is used because of its high fatigue life and resistance to corrosion. The internal diameter of the inner conduit is 28 mm. Inner conduits are joined together during make up of the standard API connection with a stab type pin and box arrangement as shown in Figure 3, that employs a proprietary high-pressure seal. Centralizers are used to maintain concentricity of the inner conduit with the outer conventional tubular equipment throughout the drill string. The length of each drill pipe and collar is 9.6 meters. A complete drill string consists of about 30 drill collars and about 350 joints of drill pipe.

Accessories developed for the drill string include various stabilizer assemblies, a shock sub, a drilling jar, a measurement-while-drilling (MWD) collar, and a dual conduit downhole mud motor. All of these components, except the mud motor, have been successfully tested downhole. A free point indicator makes possible free point determination for either the drill pipe or drill collars. String shot, back-off capabilities, and fishing capabilities have been successfully tested. A special slim hole inclinometer tool is used to measure borehole deviation and downhole temperature.

2.3 Bits

Standard off-the-shelf drill bits are used. A high-pressure nozzle tower is installed in the bit through the shank and throat to replace one of the three standard mud ports as shown in Figure 4. The proprietary high-pressure nozzles used are 2.0-2.4 mm in diameter. The bent nozzle tower assembly is designed to fit any 200 mm or 222 mm diameter bit with minimal machining of the shank and throat. Bits can be ordered, machined, dressed on site, and ready to go downhole in less than four hours.

The bit sub includes a high-pressure one-way check valve. The valve closes when high-pressure pumps are not operating, preventing the heavier drilling mud and cuttings from entering through the high-pressure nozzle(s). The check valve is also required for well control.

3. FIELD TESTING

To date, the commercial prototype FlowDril™ system has drilled 1,413 meters in the Dollarhide Field of West Texas during portions of three Grace-drilled wells, DH-9 through DH-11. Recent testing has been concentrated in East Texas where 19,708 meters have been drilled in portions of eleven Grace-drilled wells. To date there have been 1,997 total hours of testing. In 1992, 12,268 meters and 1,167 hours of drilling were conducted during accelerated testing in East Texas. The distance drilled, hours, and depth ranges for these test wells are summarized in Table 1.

3.1 System Reliability

Initial testing of the system involved pumping water only as the high-pressure fluid. For the system to have general applicability, it was necessary to develop high-pressure mud pumping capability. Formidable problems were overcome to reliably develop and deliver drilling mud under high pressure to the bottom of the hole.

3.1.1 Pumping System

The diesel driven high-pressure pumps are currently used only to pump clean, filtered water. To pump drilling mud, a central isolator was developed. High-pressure water is the fluid on one side of the floating piston, with high-pressure mud on the opposite side. Fluid enters and exits each end of the isolator through inlet and outlet check valves. Two isolator cylinders are used in concert. The cycling of the isolator piston is controlled by opening and closing of the inlet and outlet check valves on the water end. An air-logic control circuit is used to control operation of the valves.

When first introduced in 1991, the isolator required frequent maintenance and was difficult to service. As might be imagined, the mud check valves, operating at 235 MPa were the highest maintenance items. Through design changes and better material selection, life of the mud check valves has been extended from less than 20 hours to over 120 hours. Included in the design change was a cartridge packaging that enables the operator to change four check valve assemblies in less time than it takes to make a drill pipe connection.

3.1.2 Swivel and Nozzles

Swivels and nozzles were another area that needed improvement when mud became the fluid being pumped under high pressure. Nozzle life was improved through extensive laboratory testing. Laboratory nozzle life was extended from less than 20 hours to over 100 hours, enough for a complete bit run. The longest nozzle life achieved in the field was on a 106-hour, high-pressure bit run in East Texas. This nozzle had grown only 0.2 mm. in diameter.

Through design changes and laboratory testing, the high-pressure swivel seal life was improved. Life in the field when pumping water was 150 hours. On drilling mud, it was approximately 10 hours. During a recent field test, swivel seal life on high-pressure drilling mud achieved 160 hours.

3.1.3 Drill String Stab Seals

The most significant achievement in system reliability improvement has been the recent development of a reliable drill string high-pressure stab seal. The old design had not achieved better than five (5) failures per 300 joints drilled, approximately 250 hours of rotating time. Searching for drill string high-pressure leaks had been a major source of downtime. Causes of stab seal failures included 1) dirt and contamination, 2) pin and box misalignment, 3) deteriorated or damaged pin surfaces. These effects are further compounded by relative motion of the sealed joints, high downhole temperature, and the mud-particle environment.

An intensive engineering effort was mounted to solve the stab seal problem. An exhaustive analytical and laboratory testing program was developed to handle all of the options. To assess sensitivity to dirt and contamination, the surfaces to be sealed were both dipped in motor oil, then in 80 mesh garnet abrasive. The assembled pin and box were then heated to 160 Celsius and subjected to repeated pressure cycling between zero and 235 MPa. To verify misalignment tolerance, the pin and the box were misaligned at such extreme angles that the pin was permanently deformed. The assembly was again subjected to the high temperature pressure cycling test. To simulate a damaged sealing surface, a pin was threaded with a shallow fine-pitch thread along the sealing surface. This provided a continuous groove along which leakage could occur. Again the assembly was subjected to the high temperature pressure cycling test.

3.1.4 Field Test Results

The technical improvements described above were introduced into the field system for the East Texas well, ET-9. As can be seen in the downtime record in Figure 5, these improvements had a significant effect. Downtime for the last three wells, ET-9 through ET-11, was 12, 15 and 13 percent, respectively.

The effect of the new stab seal on downhole problems was dramatic. The new stab seal was implemented in a complete drill string before ET-9. The effect was to significantly reduce the number of downhole seal problems and thereby increase average time between failures. The effect on average time between downhole failures is shown in Figure 6. Although one (1) downhole static seal failure occurred on each of the three wells, none of the failed seals were the newly developed stab seals. In fact, the same actual physical stab seals installed for ET-9 have been successfully used in the drill string in the last three wells in East Texas without a single failure, 696 hours of high-pressure drilling.

3.2 Drilling Performance

Two factors affect drilling performance: reliability of the system and rate of penetration (ROP). ET-9 was set up as a test well to evaluate the overall performance of the FlowDril™ system. The target was to reduce the drilling time on the well by 20 percent for the portion of the well on which the FlowDril™ system was used. The FlowDril™ system started at a depth of 1,300 meters and drilled to a total well depth of 3,050 meters. The actual drilling curve for this portion of ET-9 is shown in Figure 7. The average Grace offset well drilling curve in Figure 7 is an average of the three fastest Grace wells drilled in the same vicinity, within the previous six months, by the same crew and drill rig. As shown, the FlowDril™ system drilled the well in four days less than the average offset, reducing the time on the well by almost 21 percent, meeting the target objective.

Shown in Figure 8 is the ratio of the average joint-by-joint ROP, with depth achieved by the FlowDril™ system, to the average joint-by-joint ROP of the three offset Grace wells drilled conventionally. Overall the FlowDril™ system was able to drill the portion of the well shown at an ROP 1.5 times faster, including connection time, than the conventional system.

4. FUTURE DEVELOPMENTS

Now that the FlowDril™ system has demonstrated that ultrahigh-pressure drilling mud can be developed and delivered downhole, the focus is on reduction of costs and faster ROP.

4.1 Cost Reduction

FlowDril is developing a new triplex mud pump that will use one-third fewer components than the current pumping system and operate at 15 percent higher efficiency. The direct mud pumping unit will be rated at a pressure of 345 MPa, 110 MPa higher than the current system. All of the current system components are rated for 275 MPa, except for the kelly hoses. The new pumping system will replace the current high-pressure water pumping units and the isolator. This will result in reduced system cost and less maintenance costs.

Several components of the drill string will be redesigned to reduce costs and extend operating life. More durable stab pin surfaces are required to accommodate higher pressures, temperatures, abrasives, and corrosives. Current pin surfacing is hard chrome plate. This surface has been adequate in field testing thus far, but has shown wear in dynamic sealing conditions, and does not have adequate corrosion resistance. New coatings that use ultra-hard surface treatments of corrosion-resistant alloys have been successfully field tested.

Centralizers for the inner conduit will be improved to reduce wear on drill pipe and collar components. Inner conduit movement of even 0.1 mm causes wear in a mud environment in all dual conduit components. The current collar centralizers require extensive maintenance every 250 hours due to relative motion between the collars and inner conduit. A new concept that eliminates the need for centralizers in the collars is waiting to be tested in the next available test well.

4.2 ROP Enhancement

Through ET-3, ROP of the FlowDril™ system was between two and three times that of conventionally drilled offset wells. Since ET-3 was drilled in the Fall of 1990, conventional bit technology has improved through improved bearing technology and better cutting structure design. As a result of this improvement and a very competitive drilling market, Grace drillers are running the bits harder and longer. This has resulted in increased ROP over the last two years for conventional drilling. The ROP ratio of 1.5 times conventional rate achieved during ET-9 is not cost effective for the FlowDril™ system. Consequently, an improved jet-assisted ROP of 2-3 times current conventional ROP is a primary focus of development.

To facilitate bit development, FlowDril has upgraded its drill bit testing facility to accommodate full size bits up to 311 mm diameter with full high-pressure flow capacity. The facility was originally constructed , Kolle' (1991), to test half-scale bits up to 121 mm diameter.

Jet-assisted PDC and jet-assisted roller cone bits are currently under development. Laboratory tests verify that jet assisting an advanced design PDC bit not only allows the bit to negotiate harder rock, but yields a higher ROP with less bit weight and less torque. These PDC bits achieve ROP ratios of 3 to 4 with high-pressure jet assist. Optimization of jet assisting roller cone bits has led to an ROP enhancement from the current 1.5 times to between 2 and 3 times conventional ROPs. Testing of these enhanced ROP bits is currently waiting for a test well opportunity with Grace Drilling Company.

5. CONCLUSION

Through accelerated field testing over the last year, design changes to the FlowDril™ ultrahigh-pressure drilling system have been identified and implemented. This has significantly improved the reliability of the system to develop and deliver ultrahigh-pressure drilling mud to the hole bottom. If the ROP enhancements that have been realized in the laboratory can be demonstrated in the field, commercialization of the FlowDril ultrahigh-pressure jet-assisted drilling technology will be well underway.

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Table 1
FlowDril Test Wells

Well	Start Date	Total Well Depth, m	Start Depth, m	Stop Depth, m	Distance Drilled, m	Drilling Hours
DH-9	6/4/91	2347	929	1118	189	14.7
DH-10	6/22/91	2438	931	1517	586	40.5
DH-11	7/10/91	2408	930	1567	638	49.5
ET-1	2/15/90	2957	1046	2204	1158	75.5
ET-2	6/21/90	3048	770	2490	1720	154
ET-3	9/22/90	3036	999	3036	2037	265
ET-4	8/24/91	3231	548	2049	1501	120
ET-5	10/31/91	3055	2340	3055	716	112
ET-6	2/19/92	3066	587	3066	2479	177
ET-7	3/25/92	3084	20	3084	3064	157
ET-8	6/15/92	3065	2241	3065	825	135
ET-9	8/1/92	3051	1299	3051	1752	206
ET-10	8/29/92	3071	765	3071	2306	253
ET-11	11/23/92	3265	1258	3265	2007	237

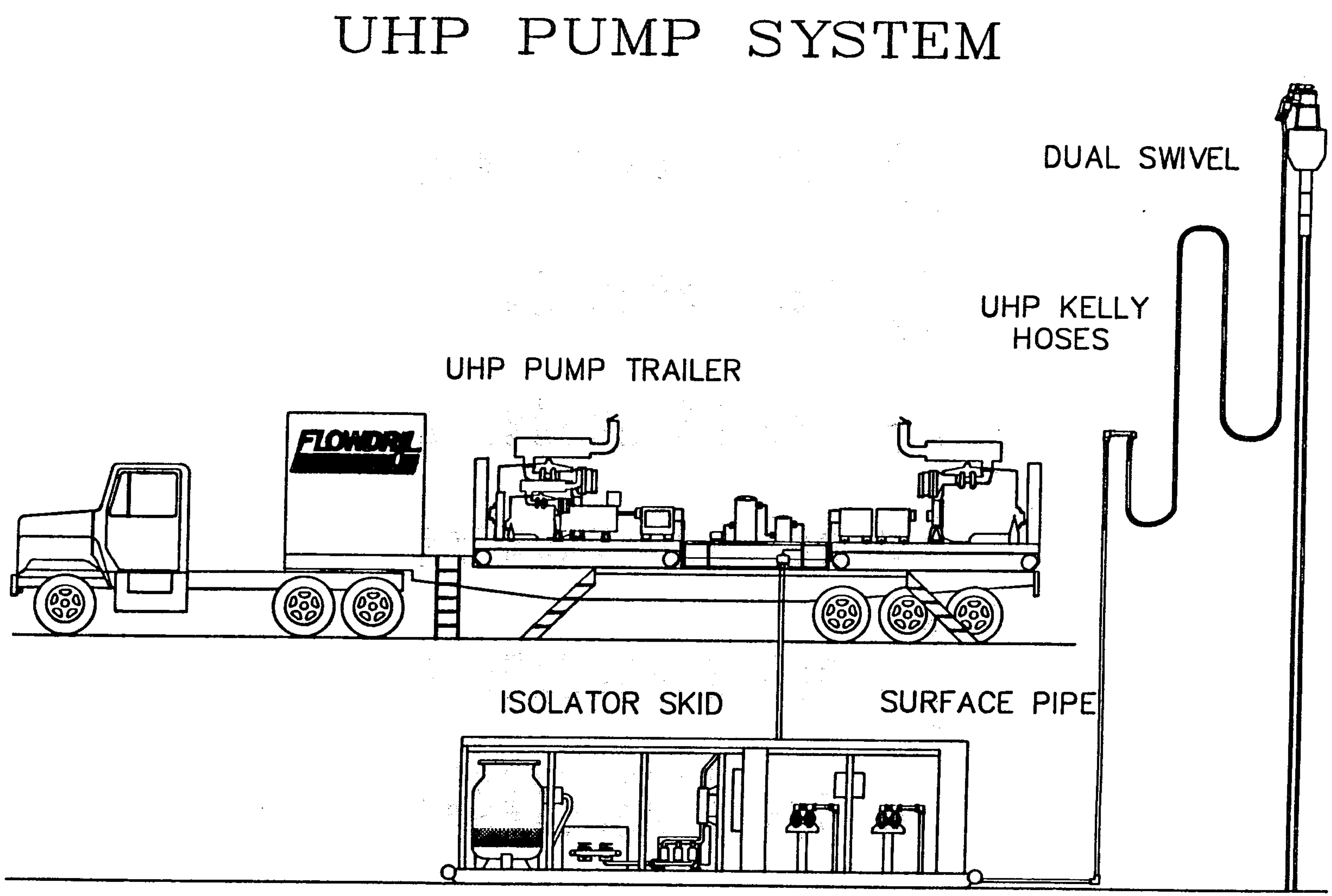

Figure 1. FlowDril™ System for Oil and Gas Well Drilling

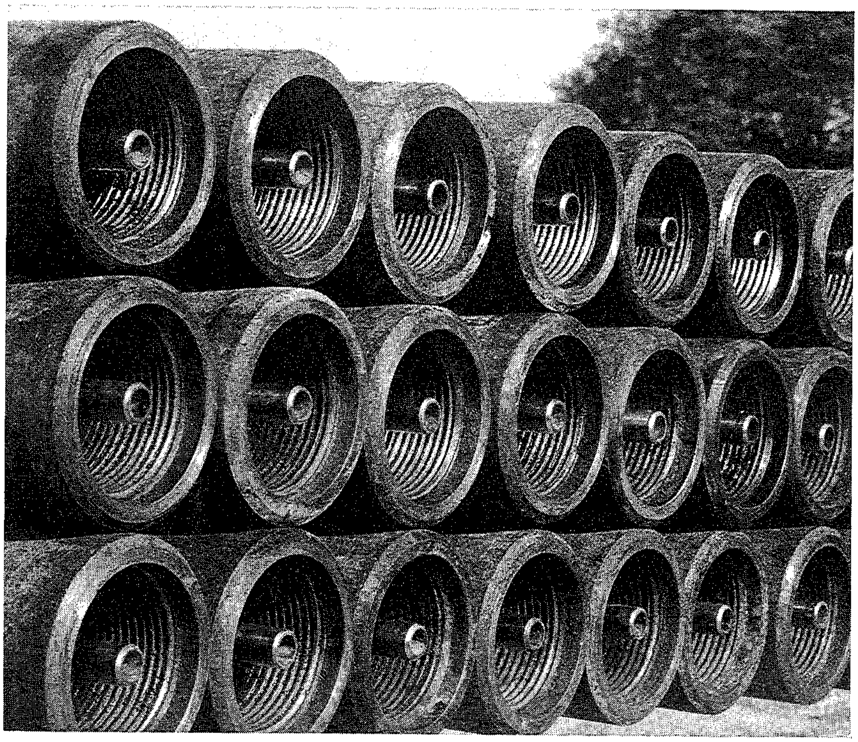

Figure 2. Dual Conduit Drill Pipe, Pin End

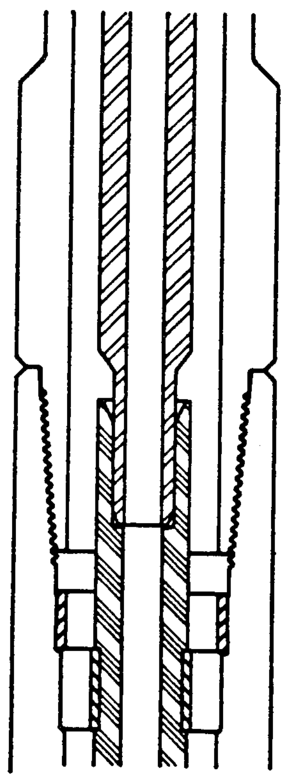

Figure 3. Stab Seal Joint

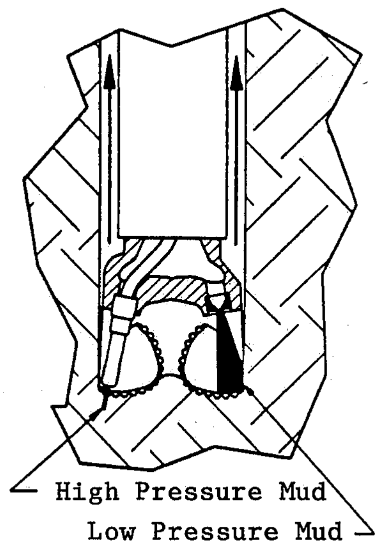

Figure 4. Ultrahigh-Pressure Drill Bit

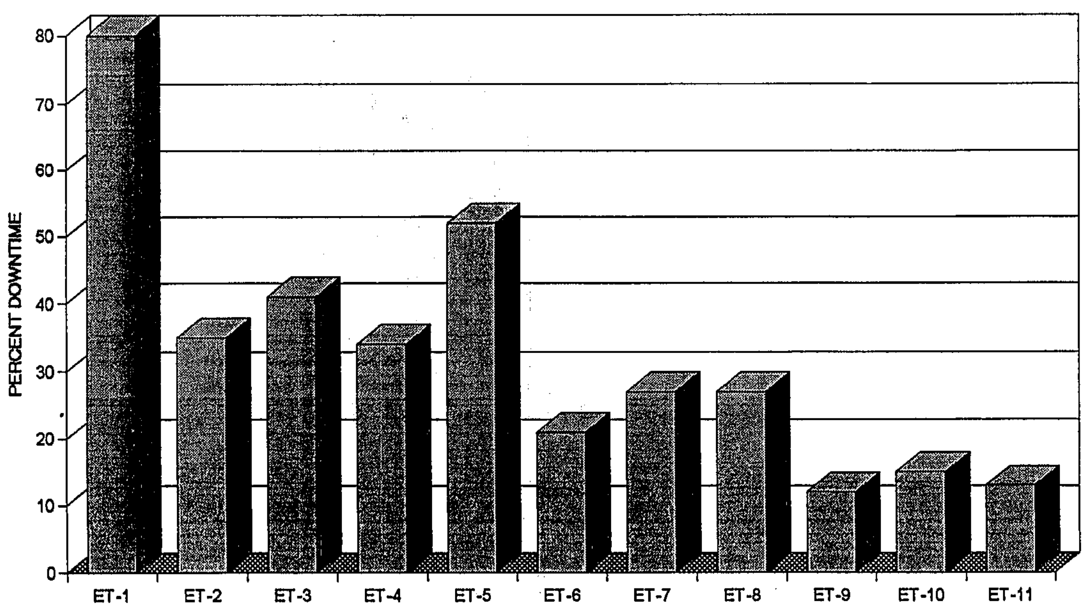

Figure 5. FlowDril Downtime Experience, East Texas Wells

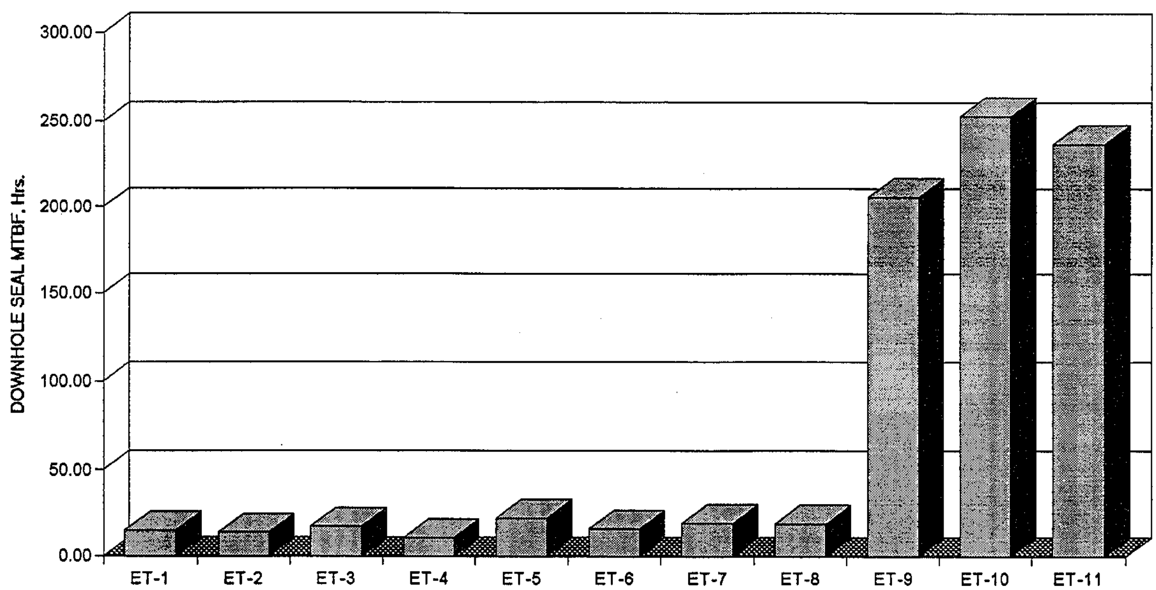

Figure 6. Downhole Seal Mean Time Between Failure (MTBF)

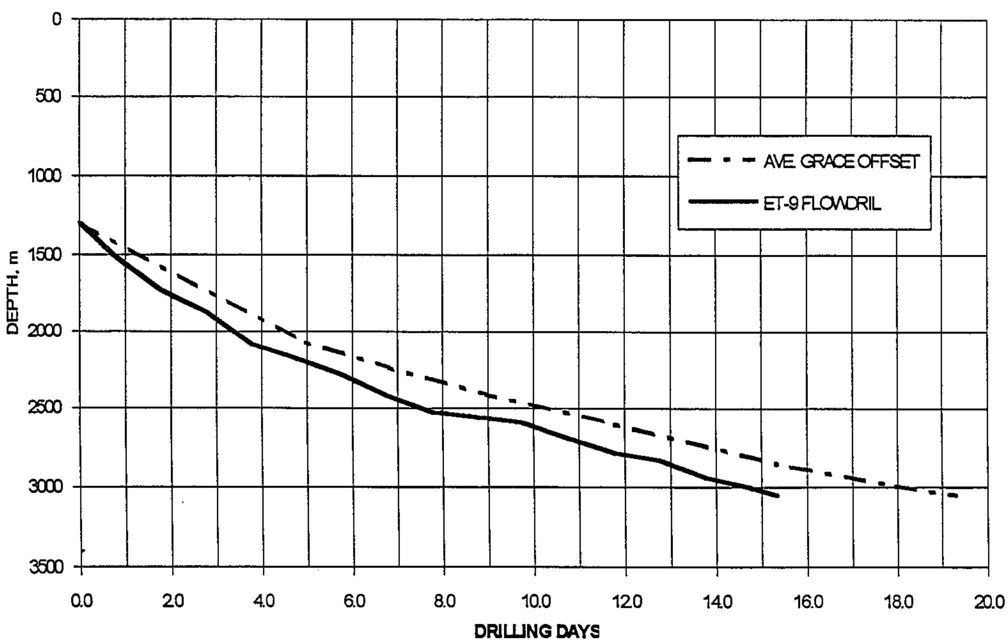

Figure 7. Actual Drilling Curve, ET-9 FlowDril

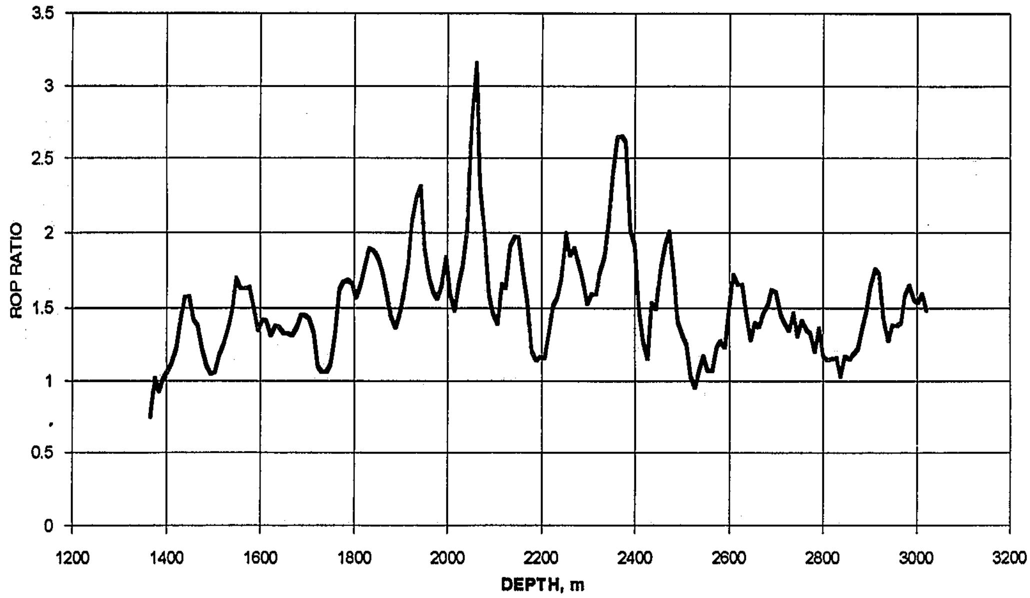

Figure 8. ROP Ratio, ET-9 to Average Grace Offset

7th American Water Jet Conference
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Paper **38**

PULSED JET NOZZLE FOR OILWELL JETTING DRILLING

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ABSTRACT

The submerged jet performance of the new type pulsed jet nozzle, the self excited oscillation pulsed jet nozzle (SEOPJN), and its erosion effect on impacting rock specimens under the submerged jet with vessel pressure have been researched experimentally in this paper. It is concluded that the oscillating pressure in the hole bottom is very large. It can form great wall pressure potential and widen the influence region of the cross flow. Using the SEOPJN for oilwell roller bits, the effects of the jet breaking rock and removing the chippings can be increased. The field test has shown that the rate of the penetration and the footage for the roller bits assembling the SEOPJN have increased by 11.1% to 100% and 9.1% to 56.4% respectively.

Key words: nozzle, footage, ROP(rate of penetration), jetting drilling, self-excited oscillation.

1.0 INTRODUCTION

Many investigators corroborate more and more that improving the hydraulic characteristics of the oilwell bits is one of the key factors to increase the rate of penetration of oil well drilling in recent years. But they have various opinions in optimizing the hydraulic parameters. Some investigators think that the impact force of the jet is very important; some investigators think that the maximum hydraulic horse power of the bits is the important factor in design but the maximum jet velocity is very important for other investigators. In other words, under the condition of presenting nozzle diameter the rate of penetration is increased by raising pump pressure. The practice of the jetting drilling in China can illustrate that the ROP of oil well drilling has been greatly increased by raising pump pressure[1]. But when the pump pressure is over 22Mpa, not only the expenses of the device greatly rise but also a series of questions are brought for the maintenance and the administer. However, how is the hydraulic characteristics further improved and can the ROP be increased? The authors have thought to use the self-excited oscillation jet nozzle and change the jet characteristics of ordinary nozzle in roller bits. This is that the continuous jet is changed into the self-excited oscillation pulsed jet and the instantaneous hydraulic horse power is increased, oscillating pressure is produced and the great wall pressure potential and its influence region in hole bottom are formed. So the self-excited oscillation pulsed jet can not only break rock but also remove effectively the rock chippings in the bits surface and hole bottom. The chippings held down in hole bottom below the jet center may be holden up and the "hold-down effect" can be restrained, and the ROP can be added. Therefore, a new type pulsed jet nozzle, the self-excited oscillation pulsed jet nozzle, fitted roller bits and PDC bits have been researched by authors and the nozzle to produce this jet is introduced as follows:

2.0 THE PRINCIPLE OF THE SELF-EXCITED OSCILLATION PULSED JET (SEOPJ).

The SEOPJ is that the initial disturbances of the hydraulic system transfer the steady energy into periodic energy and feedback part energy to self-sustain and develop the hydraulic system oscillation. It is made up of steady energy, initial disturbances and feedback system. The nozzle producing feedback effect has been designed and the requisite to produce the self-excited oscillation has been formed. The nozzle is shown in figure 1. Its oscillation principle is as follows:

When a steady high pressure water flowing from upstream nozzle enters the cavity, the stationary fluid around the jet in cavity is drawn into the jet. The movementum exchange can be produced between the jet and the fluid in cavity, and sheer layer formed.

The shear layer is of instability turbulent shear layer for high velocity of jet. The vortex is induced because the fluid around the shear layer is entrained and the vortex exists and moves as vortex ring. The disturbances with some frequency exist in the sheer layer. When these disturbances in company with the jet move to the downstream edge and impinge on the downstream edge. So the pressure disturbances waves with some frequency are induced in impinging region. These pressure disturbance waves reflex with high velocity into separation region. The separation region is very sensitive to the disturbances and the new disturbances are induced in separation region.

The instability shear layer has amplifying effect on the disturbances with some frequency when the disturbances in company with jet moving down-stream satisfy its amplifying condition, these disturbances are amplified in the sheer layer. The amplified disturbances impinge on the exit edge again. Above process repeats again. Thus, the shear layer in impinging region is resulted in very high transverse oscillating and the self-excited oscillation pulsed jet is produced. Obviously, the diameter of the upstream nozzle and downstream nozzle, the diameter of the cavity, the length of the cavity and the shape of the downstream edge and the density, pressure and discharge of the fluid have a great influence on the self-excited oscillation pulsed jet. The nozzle of the self-excited oscillation pulsed jet has been researched by authors [2,3,4,5]. The mathematics model and some geometrical parameters have been given by follows:

$$D2/D1=1.2\sim2.5$$

$$L/D1=1.5\sim8.8$$

The shape of the impinging edge is truncated cone and convex spherical, the geometry shape upstream and downstream nozzle is index curve. The experiment effect and field test results are introduced as follows:

The oscillating effect and the erosive effect on the rock impacted by the SEOPJ under the condition of the dismerged and the dismerged with vessel pressure.

According to the oscillating principle and its structure parameter, authors have designed the new type nozzle fitted the presenting roller bits. Its dynamic pressure and impacting rock effect have been conducted in laboratory and have been compared with the traditional nozzle used by presenting rollers bits in the similar condition.

2.1 The oscillation effect of the self-excited oscillation pulsed jet under the condition of the dismerged.

The oscillating pressure for the SEOPJ has been measured in various cavity length, and its results are shown in figure 2.

$$Prms=\sqrt{\frac{1}{T}\int_0^T p^2(t)\,dt} \qquad (1)$$

$$\delta p=(P_{max}-P_{min})/\frac{1}{2}\rho u_0^2 \qquad (2)$$

The root of the mean square pressure and the pressure oscillating rate are larger in L/D1=1.8-4.0 than in the other values for L/D1 from figure 2. It is to use the SEOPJN on the roller bits.

2.2

The jet center dynamic pressure and impact force versus the target distance and pump pressure have been conducted. The measuring curve for the impacting force is shown in figure 3, and the experimental result for dynamic pressure is given by figure 4. The impact force and dynamic pressure for SEOPJ are larger than those for presenting nozzle in the same condition from figure 3 and figure 4. The maximum instantaneous pressure is 2.5 times that of the presenting nozzle. The effect target distance of the SEOPJN is (8-12.5) times nozzle diameter and is rather larger than that of the presenting nozzle. These properties of the SEOPJN are very important for the jetting drilling. Because the attenuation of the SEOPJ is rather slower than the presenting jet, it still has large dynamic pressure when it spreads to the hole bottom. The SEOPJ spreading to the hole bottom breaks rock as it removes the chippings for the

SEOPJ is wider than the presenting jet. The more important thing is that the oscillating pressure of the SEOPJ oscillates greatly. It is possible to remove the chippings held down in bottom.

2.3

The erosion effect on impacting rock specimen of the SEOPJ under the condition of the dismerged with vessel pressure. The experiment to impact rock specimen has been conducted under the condition of the dismerged and the dismerged with vessel pressure. The rock specimen is the white block. The time to impact rock specimen is 15 seconds. The experiment results are shown in figure 4 and figure 5.

$$\hat{V}t=\bar{V}t/\tau \qquad (3)$$

The velocity of the erosive volume of the SEOPJ is larger than that of the presenting jet on the similar condition from figure 4. The maximum value for the velocity of the erosive volume of the SEOPJ is 3.5 times as large as that of the presenting jet. The velocity of the erosive volume for both the SEOPJ and the presenting jet decreases with the increase of the vessel pressure on the similar condition. But the sensitivity of the SEOPJ to the fluid returning from the hole bottom and the vessel pressure is rather less that of the presenting jet because the instantaneous velocity of the SEOPJ is greatly than that of the presenting jet. So the velocity of the erosive volume of the SEOPJ is obviously larger than that of the presenting jet with the increase of the vessel pressure. Its maximum value is 2.75 times as large as that of the presenting jet. Of course, increasing the pump pressure, the velocity of the erosive volume of the SEOPJ can be greatly larger than that of the presenting jet under the condition of high vessel pressure.

2.4 The effect of the erosion wear of the impinging edge on the SEOPJ

It can be seen that the impinging edge has an important role in the feedback mechanism from the principle of the self-excited oscillation. But the erosion wear of the impinging edge is unavoidable.

It is essential to research the effect of the erosion wear of the impinging edge on the SEOPJ.

It is supposed that wear radius of the impinging edge is WR.

$$\text{So} \qquad WR = K(D-D2) \qquad (4)$$

In order to study the effect of the erosion wear of impinging edge on the SEOPJN, the SEOPJN have been weared intentionally and six weared nozzle have been tested, whose wear coefficient K is 0.033, 0.066, 0.1, 0.14, 0.17, and 0.5 respectively. The test results are given by fig. 8 and fig. 9. It can see that the oscillating rate of the pressure decreases gradually as the wear coefficient increases; when the wear coefficient is equal to O.12, the oscillating rate of the pressure decreases dramatically from fig 8. On the other hand, the erosion effection on impacting the specimen is more and more worse as the impinging edge is weared; when the wear coefficient is 0.5, there exists the very small shallow crater on the specimen (see fig. 9) so,

if $k <= Ko$

The station self-excited oscillation pulsed jet can form using the SEOPJN.

if $k > ko$

The performance of the SEOPJ deteriorates and the SEOPJN loses efficiency. Fortunately, the SEOPJN used in the bits in the field test have been measured, whose maximum wear coefficient is smaller than kc. Therefore, it can be concluded that the SEOPJN can be used in the bits as though the impinging edge has some erosion wear.

2.5 Put the SEOPJN together the roller bits

The advantages of the SEOPJN is introduced from its instantaneous pressure, the effective target distance and erosion effect. The superiority between the SEOPJN and the presenting jet nozzle has been demonstrated by field test. So, a series of the SEOPJN whose diameters are 8-14mm have been designed according to the parameter of the SEOPJN and the flow pipe of the roller bits. Hundreds of the roller bits assembling the SEOPJN have been conducted in Zhongyuan, Shengli, Daqing, Kelamwyi and Chuandong oil fields in China. The ROP and the footage increases rates of the roller bits assembling the SEOPJN in those oil fields are shown in figure 10. Comparing with those of the roller bits assembling the presenting nozzle, the ROP of the roller bits assembling the SEOPJN increases by 100% and 11.8% respectively, the maximum and minimum footages of the roller bits assembling the SEOPJ increase 56.4% and 9.1% respectively. The sketch of the SEOPJN and assembly drawing of the SEOPJN in roller bit are given in Fig.11 and Fig.12.

3.0 CONCLUSION

3.1

The instantaneous dynamic pressure, impact force, the effective target distance and the velocity of the erosive volume of the SEOPJ are greatly larger than those of the presenting jet.

3.2

The SEOPJN can produce greatly oscillating pulsed jet. The hydraulic characteristics of the roller bits is highly improved. The chipping in hole bottom can be removed effectively and the SEOPJ can break the rock.

3.3

The structure parameters of the SEOPJN is suitable for presenting roller bits and PDC bits.

3.4

Some erosion wear of the impinging edge for the SEOPJN has a little effect on the SEOPJ. In other words, if the wear coefficient $k < ko$, the function of the SEOPJN can not deteriorate.

3.5

The field tests have shown that the mean ROP of the roller bits fitting the SEOPJN can increase by 55% and the mean footage of the roller bits fitting the SEOPJN can increase by 11.8%. The better profit has been obtained in the course of field test.

4.0 NOMENCLATURE

D_2 :diameter of the downstream nozzle, mm
D_1 :diameter of the upstream nozzle, mm
L :length of the cavity, mm
P_{rms} :the root of the mean square pressure, MPa
P(t):recording pressure ,MPa
T :period, s
ξ_p :pressure oscillating rate
Pmax:maximum pressure ,MPa
Uo :jet velocity, m/s
ρ :denisity of water ,Kg/m^3
V_t :the velocity of the erosive volume ,m/s
$\bar{V}_t$:the erosive volume ,m
τ :impacting time ,s
WR :wear radius of the impinging edge ,mm
K :wear coefficient
D :the diameter of the cavity ,mm

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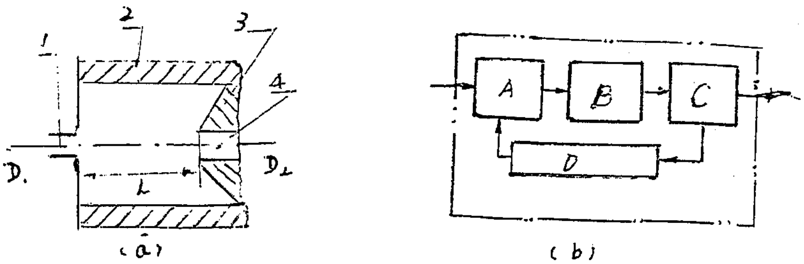

1—upstream nozzle
2—cavity
3—impinging edge
4—downstream nozzle

A—jet
B—instable shear lager
C—impinging edge
D—feedback

Fig.1 Typical Configurations and the Selfexcited Oscillation Block Diagram for the Self-excited Oscillation Nozzle.

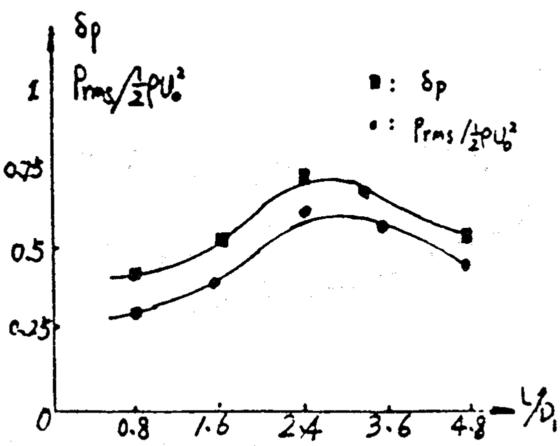

Fig.2 Variation of the P_{rms} Value and Oscillating Rate of the Dynamic Pressure with Cavity Length

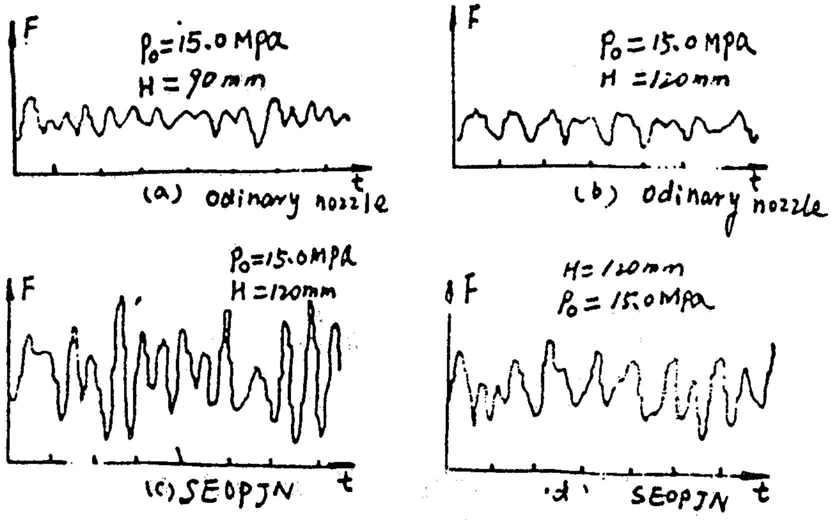

Fig.3 The Recording Curve with the Oscillograph for the Impacting Force F

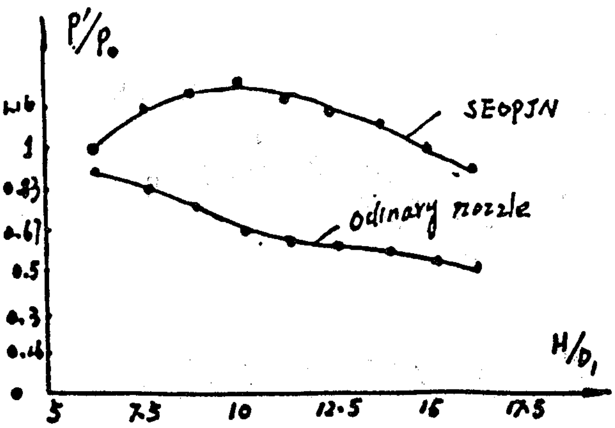

Fig.4 Variation of the Instantaneous Pressure

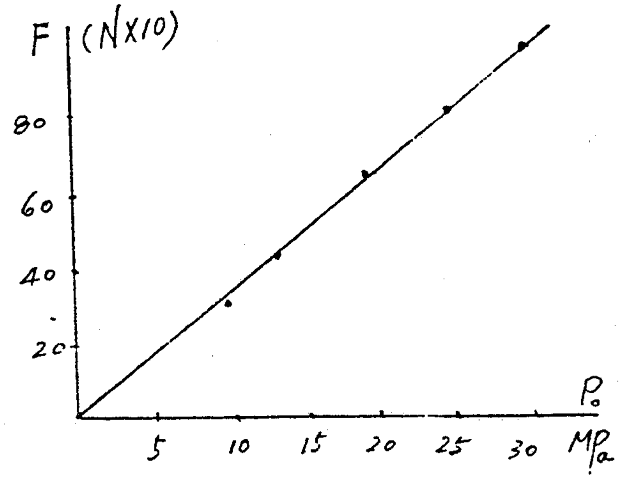

Fig.5 Variation of the Impacting Force with the Pump Pressure

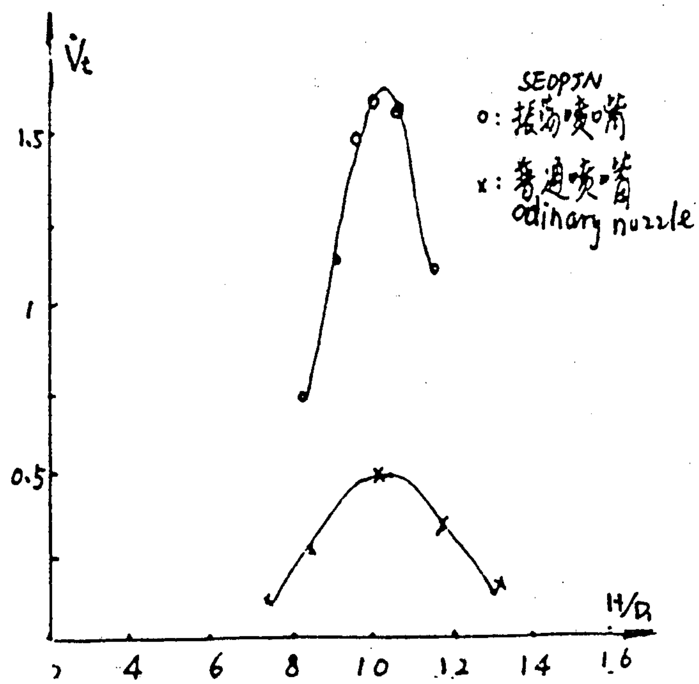

Fig.6 Variation of the Removed Erosive with Target Distance

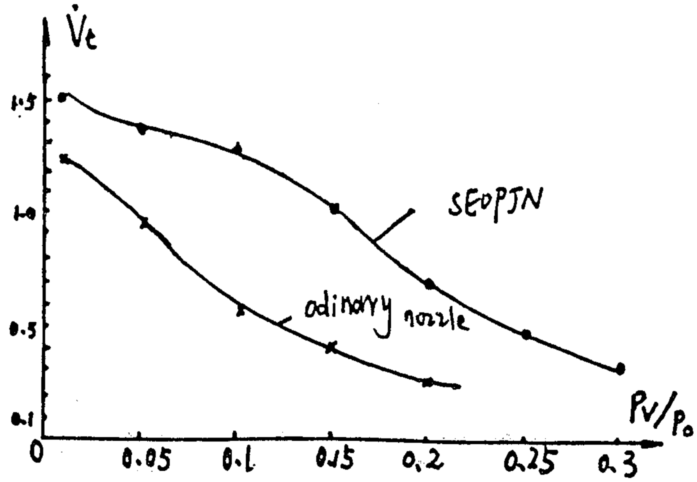

Fig.7 Variation of the Velocity of the Removed Erosive Volume with Vessel Pressure

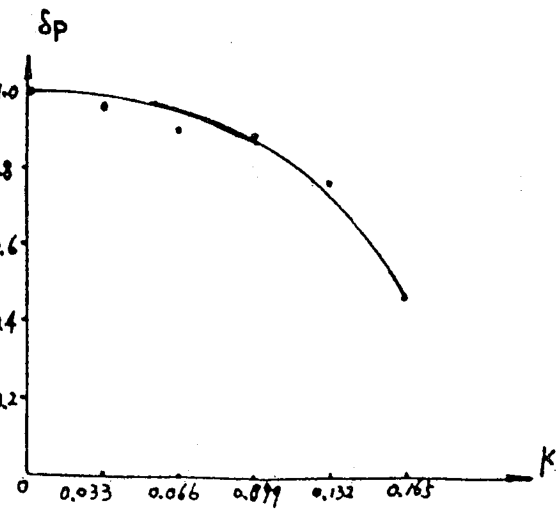

Fig.8 Variation of the Oscillating Rate of the Dynamic Pressure with the Wear of Impinging Edge

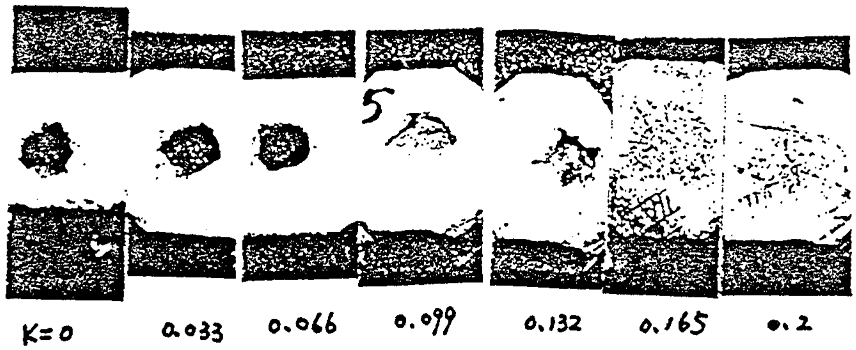

Fig.9 The Erossive Craters Impinging by the SEOPJ for Different Erosion Wear of the Impinging Edge

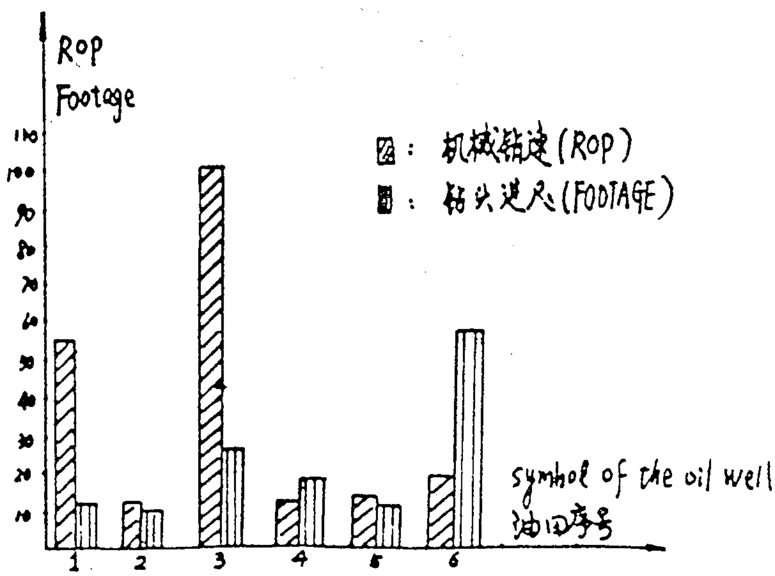

Fig.10 The Increase Value(in percentage) of the ROP in Same Oilwell

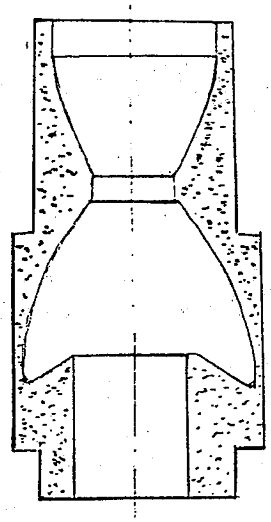

Fig.11 Sketch of SEOPJN

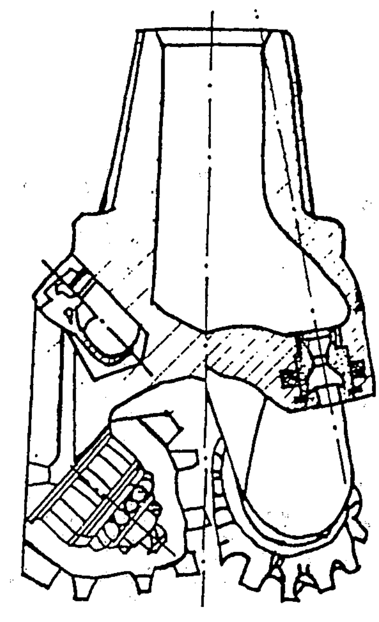

Fig.12 Assembly Drawing of SEOPJN
in Roller Bit

7th American Water Jet Conference
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Paper 39

PERFORMANCE ENHANCEMENT OF DIADRILL OPERATIONS

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ABSTRACT

The use of abrasive waterjets has grown significantly over the last ten years. In the normal operation of this equipment, however, the abrasive is largely destroyed on its first passage through the equipment and upon target impact. Replacement abrasive costs have, therefore, come to play a very significant financial role and a not inconsequential logistics cost in the operation of such abrasive jet systems.

Performance of an abrasive waterjet drill has been enhanced by changing from garnet to steel shot as the cutting abrasive. Not only does this change provide an abrasive which will survive multiple passages through the equipment and on to the target, but it also is an abrasive which can easily be separated from the cuttings issuing from the hole.

The design of a drill using the steel shot and the recirculation equipment attached for recovery of the abrasive is described. In addition, both laboratory and field experiments demonstrating drill performance in dolomite and other rocks are reported. The ability to use smaller shot effectively has meant that more orifices may be inset into the cutting head. This, in turn, has increased the speed of drilling and reduced the irregularity of the holes drilled.

Organized and Sponsored by the Water Jet Technology Association.

1.0 INTRODUCTION

Conventional drilling of rock, in most mining applications, uses the mechanical impact of a metal tool to create the advancing hole. This technique, which has gradually increased in power and thus penetration rate has, however, certain inherent disadvantages. These range from the overall weight of the equipment which must be located at the free face of the hole to the maintenance of alignment over long distances, particularly with smaller diameter holes, where the limitations of thrust delivery through the small diameter rod can limit performance.

Because of these disadvantages alternative methods for drilling such holes have been sought over the years, and of the many methods tried, waterjet application appears to show considerable promise. Continued experimentation has shown that use of water power alone has not yet reached the comprehensive ability to drill all rock at acceptable power levels and penetration rates. Although over the long term cavitation in high pressure jets may give such performance levels, at the present stage of development the introduction of abrasive to the waterjets has the greatest potential.

In earlier papers the alternate methods for introducing the abrasive into the water stream have been reviewed and the potential advantages of the method known as DIAjet (for Direct Injection of Abrasive jet) injection described (Summers, et al., 1990; Yao, et al., 1991). In earlier work penetration rates for this tool have been somewhat lower than hoped, although the advantages which have been identified, particularly in drilling through fractured and clay striated ground, have shown potential applications for this new tool.

2.0 OBJECTIVE

The development of a practical rock drill must consider many practical limitations which arise in equipment use which are not necessarily evident with laboratory testing. One particular problem for example, is that in many mining operations the drill must be manually carried to its point of use. The driller, particularly with manual equipment, must re-connect the drill into the supply system after it has been located and set up. Thus, there are constraints on the weight and the hoses and other connections which must be considered in developing a fieldable tool. In addition, when abrasive is injected into the cutting stream, the weight collection and disposal of the abrasive become an important consideration. Thus, in the development of this prototype equipment abrasive use became a particular concern.

When an earlier version of the drill was used under the Gateway Arch, sand was used as the cutting abrasive since its performance had earlier been shown equivalent to that of garnet. However, the difficulties in collecting the sand at the site meant that quite large quantities were used in the cutting operation and this had some economic impact on the overall system use. Research at Rolla has shown that particularly in cutting rock, steel has a significant advantage over the other abrasives (Figure 1). The reasons for this relate to the mechanism by which the abrasive-laden waterjets cut through this brittle material, a subject which has been discussed in more detail elsewhere (Summers, 1991).

Steel has additional advantages in cutting rock beyond the simple one of being a more effective cutting medium. In earlier drilling tests when garnet had been used, the abrasive could be recirculated through the drill more than 10 times while retaining good cutting ability. However, on each pass through the system, the particles were degraded and the abrasive picked up more of the fines from the cutting process.

Steel shot, on the other hand, was found to retain its shape to a greater level than the garnet or the sand during the cutting process, and can be easily separated from the slurry leaving the hole by a magnetic technique. To achieve this separation the hole location was surrounded by a collar which collected the spent drilling fluid and carried it down a dedicated line to a magnetic separation system which pulled out the steel from the flow, while allowing the crushed rock and spent water to escape the system (Figure 2,3).

The spent shot could then be returned to the intake hopper for the drill, which could continue to supply the drill from a much smaller overall stock of abrasive. This is of considerable importance both from a logistical point of view (since it lowers the total volume and weight of supplies which need to be carried to the site) and in the cost of the abrasive. As a result, a much smaller supply train will be required to field the drill, and since the drill itself only needs a feed line to carry the abrasive from the high pressure pump and injection system, the actual drilling tool can be made quite light (Figure 4).

The potential benefits of the new method of cutting are particularly directed to the ability to make the cutting tool smaller and lighter. The reaction force from the drill can be expressed (for a single forward pointing jet) in terms of the thrust by the equation

$$\text{Force} = 0.052\ Q \sqrt{P} \quad (1)$$

where Q is the flow rate in gpm
P is the jet pressure in psi.

With a jet flow of 20 gpm and a pressure of 5,000 psi this translates into a maximum thrust on the drill of 73 lbs. However, angling some of the jets from the drilling head will lower this force on the drill. The low level of this maximum force on the tool means that the system components can be made smaller and lighter, and the power for the drive motors can be supplied by a small compressed air system.

Drill performance with the abrasive jet system is more efficient at low rotation speeds and thus a drive was developed which integrated rotational and advance rate of the drill with a friction clutch to slow the advance where penetration fell below that set for the drill. The resulting drill was light enough that the drill and carriage could be carried by one individual.

3.0 DRILL PERFORMANCE

The steel shot provided the potentially greatest cutting ability for any of the likely abrasives while cutting in the brittle regime of most rock sites. However, as discussed earlier, penetration rates for the tool had not shown the full potential that had been anticipated at the start of this program. A continued study of the problem indicated, however, that there had been an underlying misdirection to the study of earlier work.

Studies of individual particle impacts elsewhere (Yao, et al., 1991 and Hashish M. 1991) had shown (Figure 5) that the penetration ability of abrasives increased with particle size. This could be easily tested by cutting a sheet of glass. As the abrasive size was increased the extent to which the cracks extended from the line of cut into the glass could be seen to increase (Figure 6). This also suggested that the best cutting performance for this system could be achieved with use of larger abrasive sizes.

The use of a larger abrasive required a larger nozzle size (the throat diameter should be around three times the particle size to ensure that there is no blockage during drilling). Larger nozzle diameters use a greater volume flow and thus restrict the number of nozzles which can be supplied from a fixed volume pump and injection system. The original design compromised on these restrictions by considering the use of three nozzle orifices in the drilling head as being optimum, allowing the use of the greatest size of abrasive particle while providing jets which would cover the full face of the rock ahead of the drill.

Despite considerable effort, however, the penetration rates achieved did not increase significantly over the earlier experimental series. A series of tests was therefore carried out using conventional abrasive injection, but looking at the effects of abrasive feed rate and particle size on cutting performance (Galecki, Summers, 1992).

These tests, which were particularly directed at examining the effects of some of the performance parameters in conventional abrasive injection also revealed that it was not the size of the abrasive which was the most effective parameter in its use, but rather the overall weight percentage which was added to the water flow. It is currently believed that part of this change in this reflected result comes about with steel shot because of its consistent size, and greater density which each particle has, even in the smaller size ranges, relative to the other conventional abrasives used (Figure 7).

This finding has a considerable bearing on the design of drilling nozzles, since the ability to use smaller grades of steel shot without any overall degradation in performance, provided the same mass flow rate is retained, means that a larger number of smaller nozzle orifices can be used in the drilling head. The ability to use a greater number of nozzles means that the face of the rock ahead of the drill can be more comprehensively attacked, and that the drill performance does not depend to as great an extent on the ability of each individual jet to cut a wide and deep swath ahead of the bit.

However, while this approach has proven to be successful in the development of the abrasive drill, and brought the performance of the tool up to the levels originally anticipated for this generation of the tool, the subsequent testing of the head has revealed the critical demands on the design of the drilling head in order to obtain these high levels of cutting penetration. This can be illustrated by the comparison between the performance of two relatively similar drilling heads. During the testing nozzle inserts with various diameters were used in the different locations across the drilling head.

Various rock types were used during the testing, but, for the particular tests described, the original testing was in basalt of the type commonly used for monument stone.

The two nozzle designs used (Figure 8) each contained five nozzles, relative sizes could be changed but the locations and angles of the inserts were fixed. By advancing the drill as fast as possible areas where the design was insufficient would become evident by the wear of the nozzle body where ribs of rock, not removed by the jets, would come into contact with the bit.

It was found that relatively small increments of angle and changes in axial offset (from 0.32 to 0.37 inches for nozzle 4 for example) were required to give the even distribution of cutting power across the face and to provide the even removal of rock which would allow the most efficient drilling advance. Where this was not the case then a relatively rough hole, typical of much abrasive waterjet drilling, was achieved (Figure 9). Where such a distribution was achieved, however, the drill would cut a smooth walled hole through the rock at a steady advance rate (Figure 10).

Once the drill had been thus optimized in the drilling of the basalt, at an advance rate of 6 inches/minute it was tested in drilling the local dolomite, where test performance to date had varied between 2.5 and 3.5 ft/minute depending on the rock condition.

4.0 CONCLUSIONS

The optimum nozzle configuration and abrasive choice having now been established continuing tests with the drill are scheduled at the UMR Experimental mine where the problems to be encountered in drilling longer holes will be determined for a range of drilling angles.

5.0 ACKNOWLEDGMENTS

This work is being carried out, in part, under funding from the Generic Minerals Technology Center program of the United States Bureau of Mines, through the Mine Systems Design and Ground Control Center at Virginia Polytechnic Institute.

This interest and assistance is greatly appreciated.

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7.0 NOMENCLATURE

Q	=	the flow rate in gpm
P	=	the jet pressure in psi.
Force	=	$0.052\ Q\sqrt{P}$

8.0 FIGURES, TABLES, AND ILLUSTRATIONS

Table I. Configuration of the Two Nozzle Assemblies.

	Axial Offset 1	Axial Offset 2	Angle 1	Angle 2
Orifice 1	.630	.626	14	14
Orifice 2	.560	.536	10	10
Orifice 3	.430	.418	6	4
Orifice 4	.335	.290	0	4
Orifice 5	0	0	-7	-8

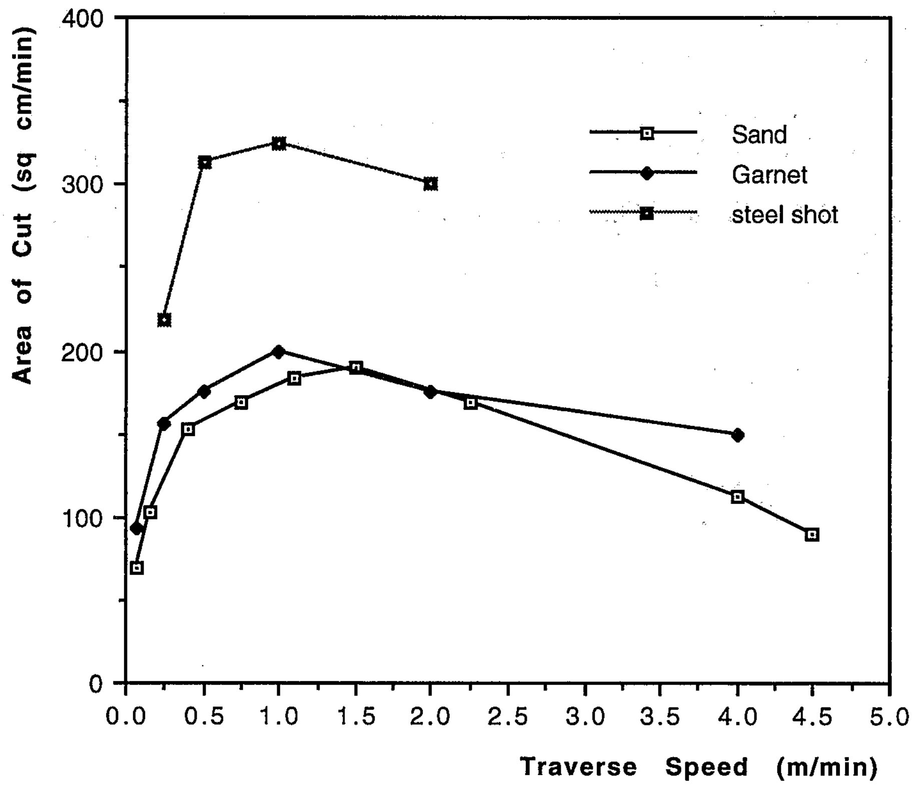

Figure 1. The Effect of Various Abrasives in Cutting Dolomite.

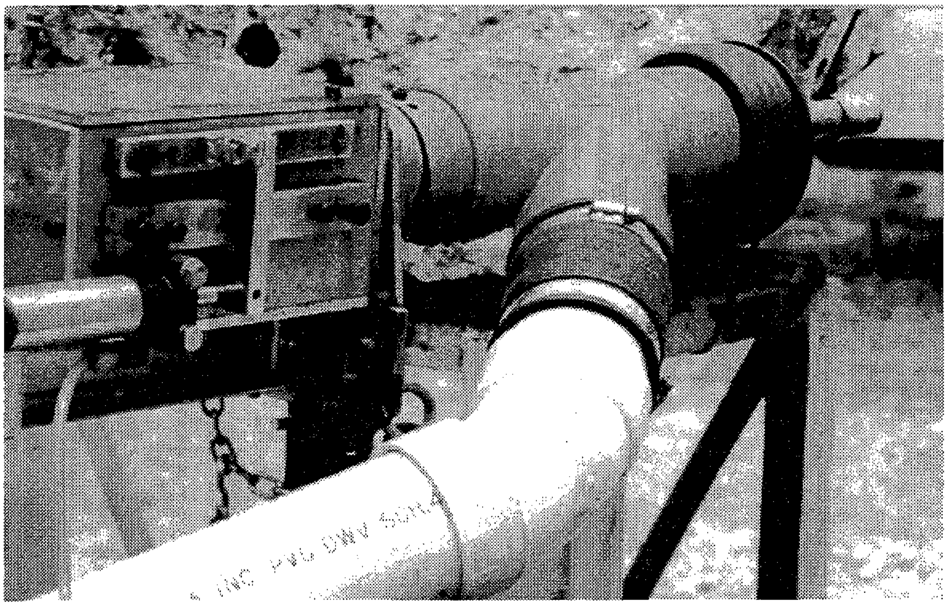

Figure 2. Suction Head to catch the drill cuttings.

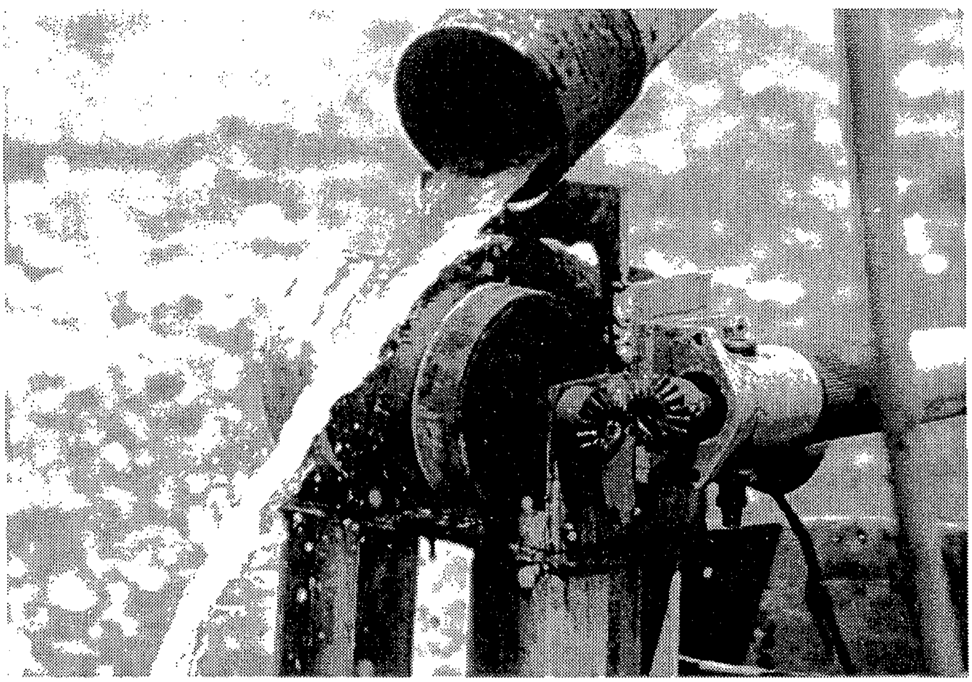

Figure 3. Magnetic Separation System.

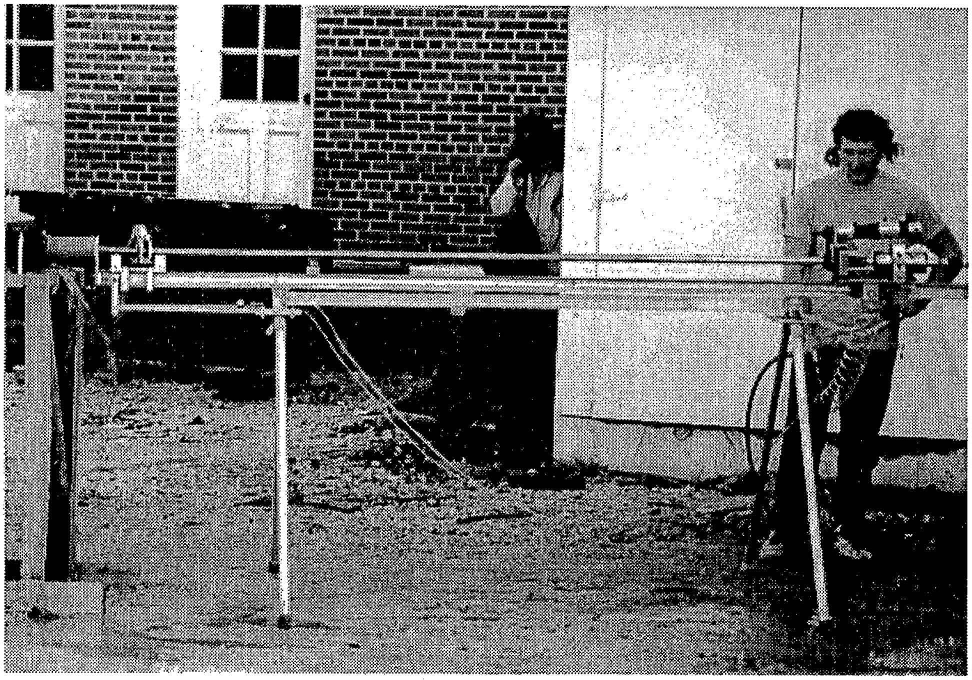

Figure 4. Light-Weight Drilling Tool.

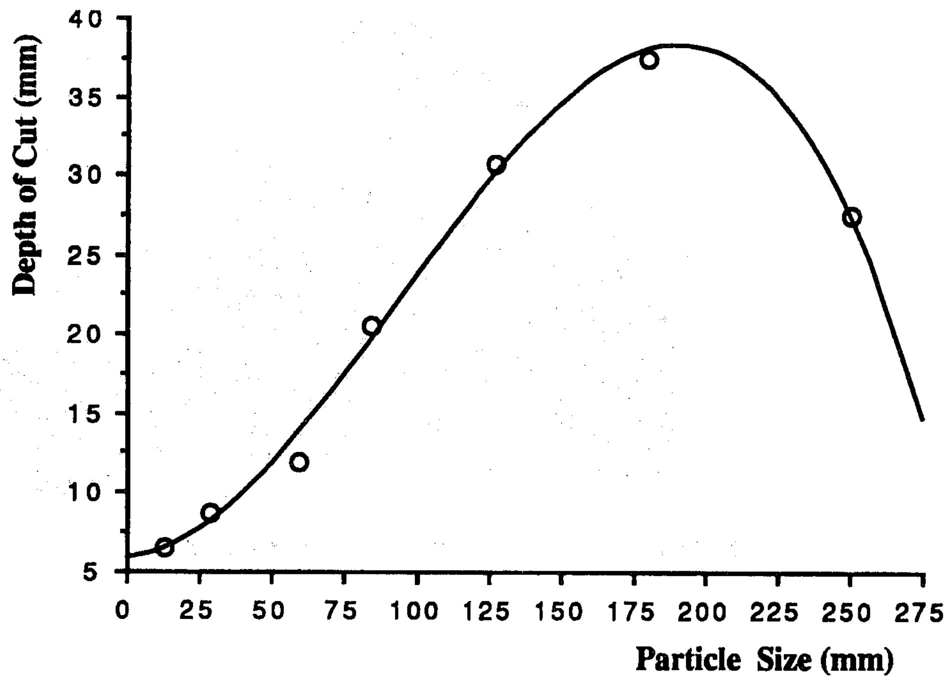

Figure 5. Depth of Cut versus Particle Size.

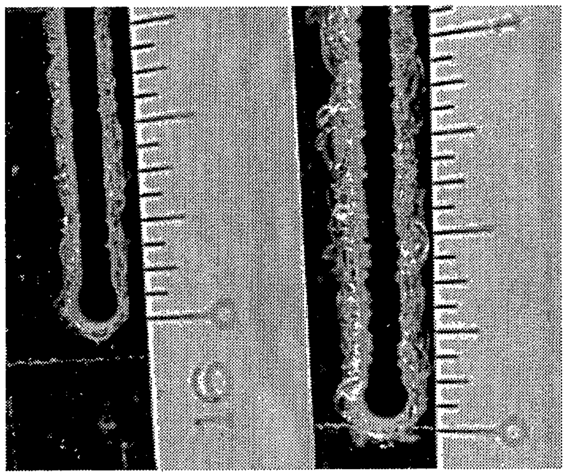

Figure 6. Glass Cuts using Different Sizes of Steel Shot.

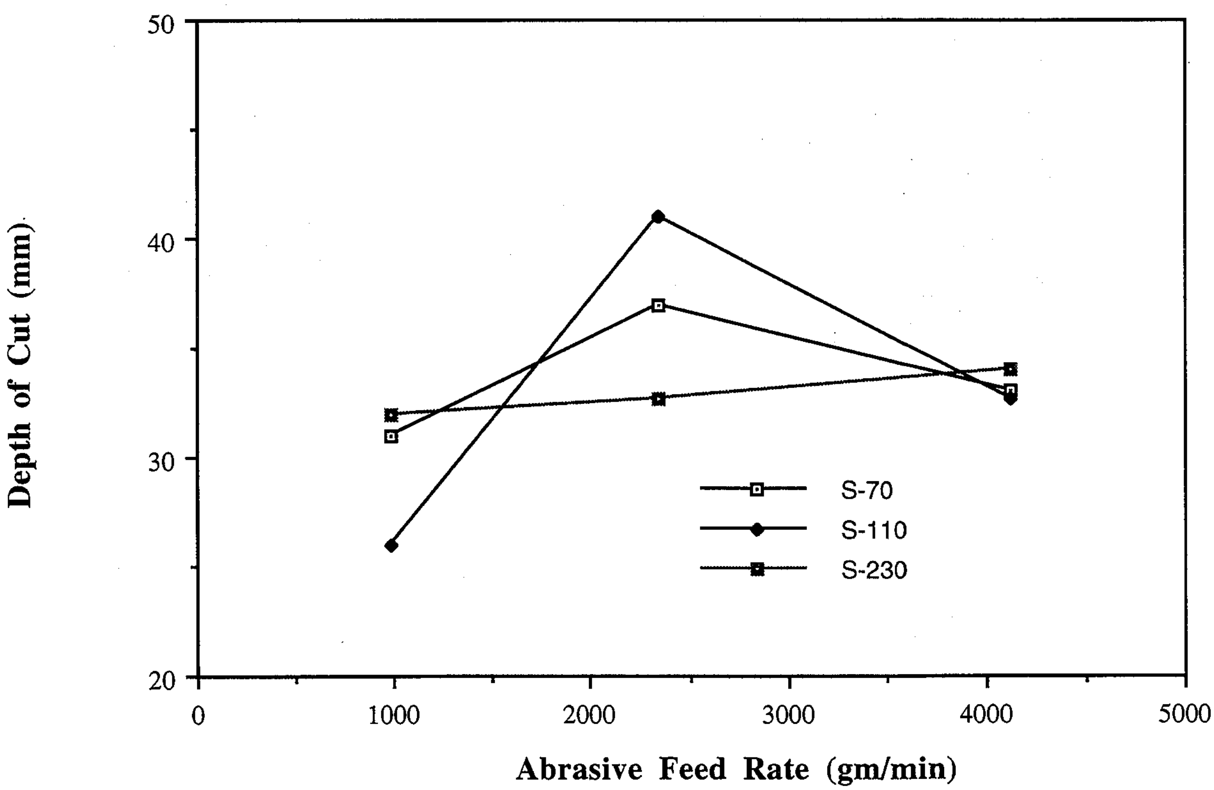

Figure 7. The Effect of Increase in Abrasive Feed Rate, with changing particle size, on the Depth of Cut in Dolomite.

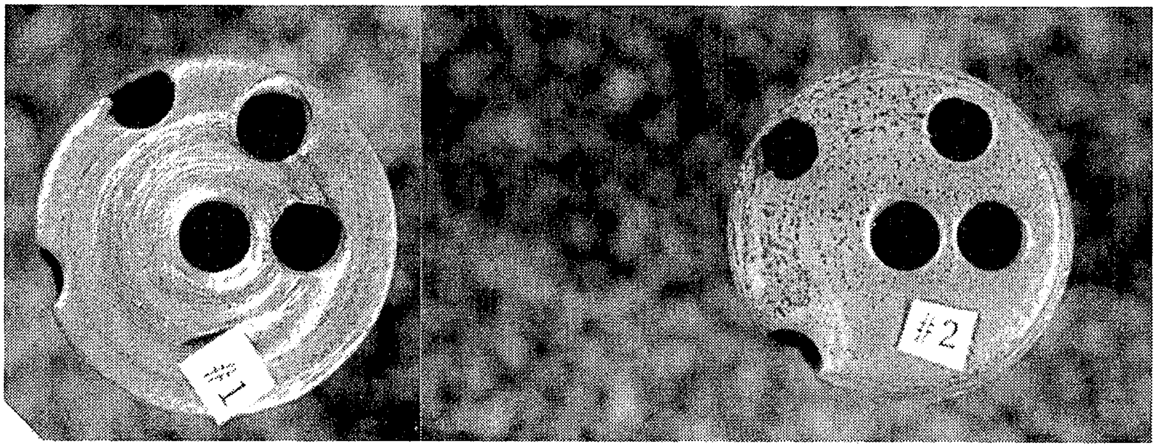

Figure 8. Nozzle Designs used for Rock Cuts.

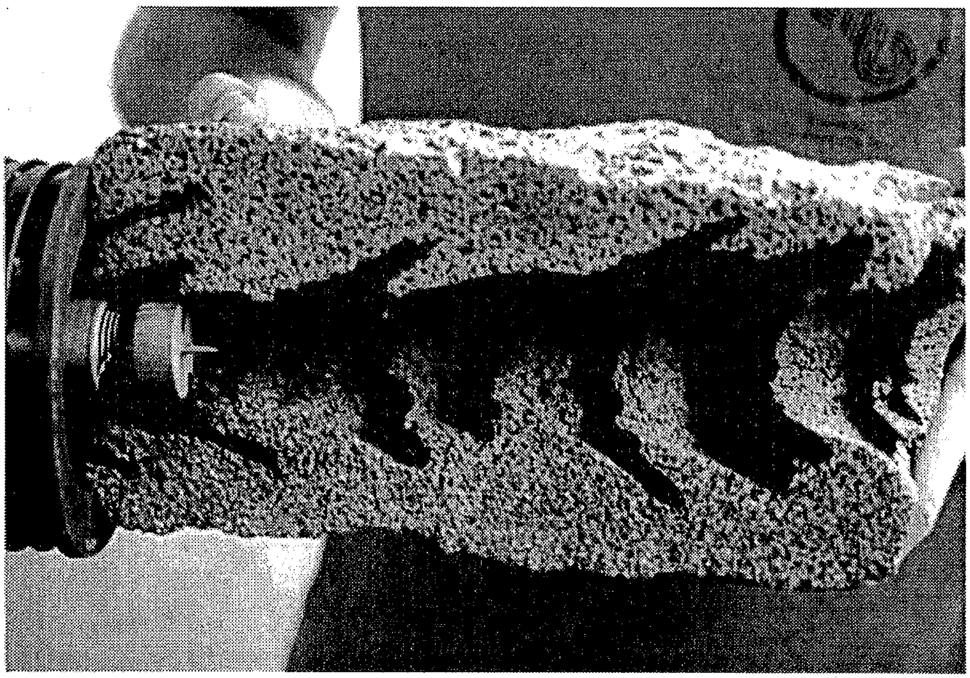

Figure 9. Sectioned Rough Drill Hole in Basalt.

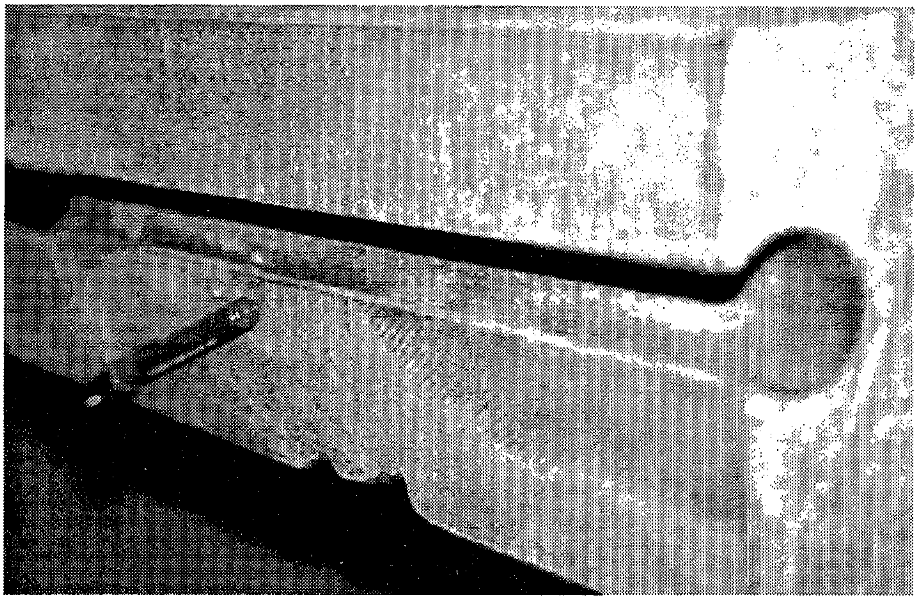

Figure 10. Sectioned Smooth Hole in Basalt.

7th American Water Jet Conference
August 28-31, 1993: Seattle Washington

RECENT DEVELOPMENTS IN WATER JET USAGE IN GROUND AND TRAFFIC AREA REBUILDING

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ABSTRACT

The paper describes the usage of plain high-speed water jets as tools for rebuilding. In detail, the paper contains a report on the development and application of a water jet based unit for asphalt re-roughening and removing, respectively. In a second chapter it is reported on the application of water jets for cleaning of contaminated grounds. A review is given on technical principle, performances and results of two general methods for water jet based ground decontamination.

Organized and Sponsored by the Water Jet Technology Association.

1.0 INTRODUCTION

The application of water jet based tools for building sanitation - for example paint removal, concrete breaking and cutting - has been well known for some years. But there is hardly any experience in processing of asphalt and contaminated ground. For the future, the importance of these cases of application will increase because of the high amount of damaged road layers and contaminated sites.

2.0 ASPHALT PROCESSING USING WATER JETS

2.1 Roughening of Traffic Asphalt Layers

Figure 1 shows the influence of roughness and moisture on car tire grip. It can be seen that small roughness and moisture lead to small tire grip. Small roughness is a result of polishing the minerals due to conventional traffic and milling up of mortar due to heavy traffic at high temperatures.

The traditional methods to roughen asphalt layers are the supplementary placing of small sharp edged minerals or the usage of road milling machines. As an alternative, WOMA has developed and tested a water jet based roughening device (fig. 2) which consists of a 17,000 I tank, a pump unit including working platform and a street cleaning machine. The working platform is equipped with three rotating nozzle heads. The tool movement is complex and is managed by a remote controlled system. Table 1 contains information about performance details and results. Figure 3 shows the structure of an asphalt surface before and after water jet treatment. Similar to concrete sanitation, only the mortar will be removed in a controlled manner, whereas the aggregates remain in place.

2.2 Removing of Asphalt Layers

Often, for example on bridges, asphalt layers are surfaced on steel panels. To prevent asphalt movements on these panels, they are equipped with zigzag iron bars. In case of removal of damaged asphalt layers from the construction it is not possible to use mechanical tools like mills or jack hammers to remove the material between the bars without destroying mounting parts. The only alternatives are water jet cutting or a combination of water jet technique and mechanical machines. In the case illustrated on fig. 4 and fig. 5 it was decided in favor of the second solution. While the top layer was milled off down to the tip of the zigzag irons, the asphalt between them was removed by means of high-pressure water jets. The bridge area was connected with a double filter system. The asphalt was completely removed (fig. 4). The zigzag iron bars of the sheet steel bars remained undamaged (fig. 5). Table 2 contains further technological and performance information.

3.0 CLEANING OF CONTAMINATED GROUND USING WATER JETS

3.1 General Problems

The number of decontaminated grounds and sites in Germany is estimated of about 80,000. For many of them - 26,000 - the situation is acute and their sanitation must be started without loss of time. Figure 6 shows the general methods of cleaning contaminated grounds. In general one can discern in-situ and on-site methods. Water jets are applicable for extraction and hardening methods, respectively. In Germany, first experience exists in both decontamination technologies.

3.2 Hardening Method

Decontamination using hardening method is based on the well known jet grouting principle and is described by Balthaus (1990) and Sondermann (1991). Both solutions are similar (figure 7). The process differs from jet grouting in only water being injected into the ground in the eroding stage. The eroded soil and the water are then air lifted to the surface where it enters a completely enclosed treatment system. The remainder of the material is then disposed of at a licensed site where additional decontamination, for example using biological treatment, can take place. The partial cleaning takes place in closed rooms, in jacket tubes. Inside this room the high-energy water jet shears the contaminants from the soil particles. In case of phenole contamination it is necessary to cover the ground by using a concrete slab (Sondermann, 1991). The cleaning of the ground goes step by step, by an interlace pattern of several jacket tubes. The application is possible also under buildings. A summation of some results is to be found on figure 8.

One must take into account the specific conditions on every side. In general it is found that highpressure water jet based hardening devices are excellent tools for cleaning contaminated grounds. The advantages of this technology are

- in situ performance,
- reusing of the cleaned soil,
- mobile devices,
- small space required,
- applicable on built-up places,
- high cleaning depth,
- applicable for high degree of contamination,
- applicable for organic and inorganic, soluble and antisoluble agents,
- combination of decontamination and stabilization is possible.

3.3 Extraction Method

An example for using extraction method is described by Heimhard (1987). He reports on a special jet tube (fig. 9). The contaminated soil and air will be drawn off through the focus point and cleaned by the water jet. The whole complex consists of distribution device, water jet cleaning tube and high-pressure pump, drainage works, waste water treatment, waste air treatment, and a device to treat and discharge the contaminants. All parts are placed in containers. The technique is applicable for removing of

- chlorinated hydrocarbon,
- aromatic hydrocarbon,
- polycyclic hydrocarbon,
- alipathic hydrocarbon,
- heavy metal,
- alipathic hydrocarbon,
- heavy metal,
- cyanide.

The disadvantages of this method are (Stein und Niederehe, 1992):

- discontinuous impurity removing,
- fragmentation of soil particles,
- air entrainment into the soil-water suspension during pressure pumps.

Figure 10 shows some cleaning results for contaminated soils using the water jet extraction method. Table 3 contains some general information on all methods. Sondermann (1991) and Balthaus (1990) have discussed a combination of water jet usage and microbiological decontamination as an interesting alternative for further developments.

4.0 ACKNOWLEDGEMENTS

The author is grateful to WOMA Apparatebau GmbH for preparing the paper and to Philipp Holzmann AG, Dusseldorf, and Keller Grundbau GmbH, Offenbach, for their information about decontamination technique.

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Table 1

Performance details of asphalt roughening device

Pressure	700 - 900 bar
Flow rate	240 l/min
Nozzle number	12
Tools	rotating heads
Feed motion	5 - 15 m/min
Efficiency	700 m2/h
Roughness (sound test)	1.5

Table 2

Performance details of asphalt removing device

Pressure	900 bar	
Flow rate	185 l/min	
Removal depth	40 mm	160 mm
Efficiency	40 - 60 m2/h	18 m2/h

Table 3

Technological details of high-pressure water based decontamination methods

Parameter	Site		
	Bremen (Balthaus, 1990)	Hamburg (Sondermann, 1991)	Berlin (Heimhard, 1987)
Pressure	500 bar	400 bar	350 bar
Contaminated area	15000 m^2	1200 m^2	—
Soil volume	—	10500 m^3	7000 t
Contamination depth	10 m	12 m	—
Efficiency	12 t/h	—	15 - 40 t/h
Costs	—	DM 1000/m^3	DM 130 - 200/t
Occupied place	200 - 250 m^2	—	55 containers

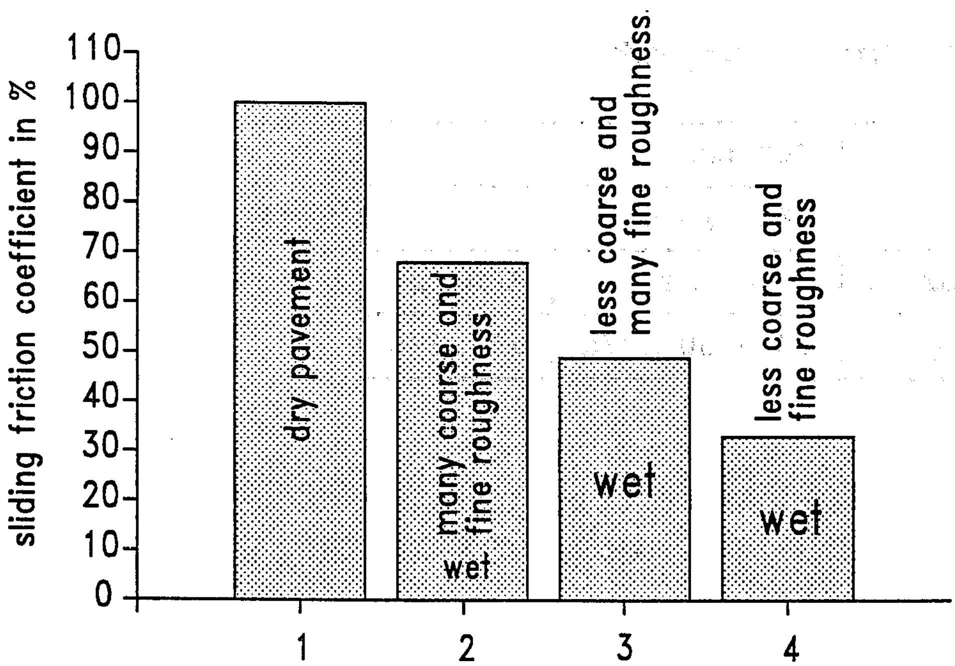

Figure 1

Influence of roughness and moisture on car tire grip (Dübner, 1988)

Figure 2

Water jet based asphalt roughening device

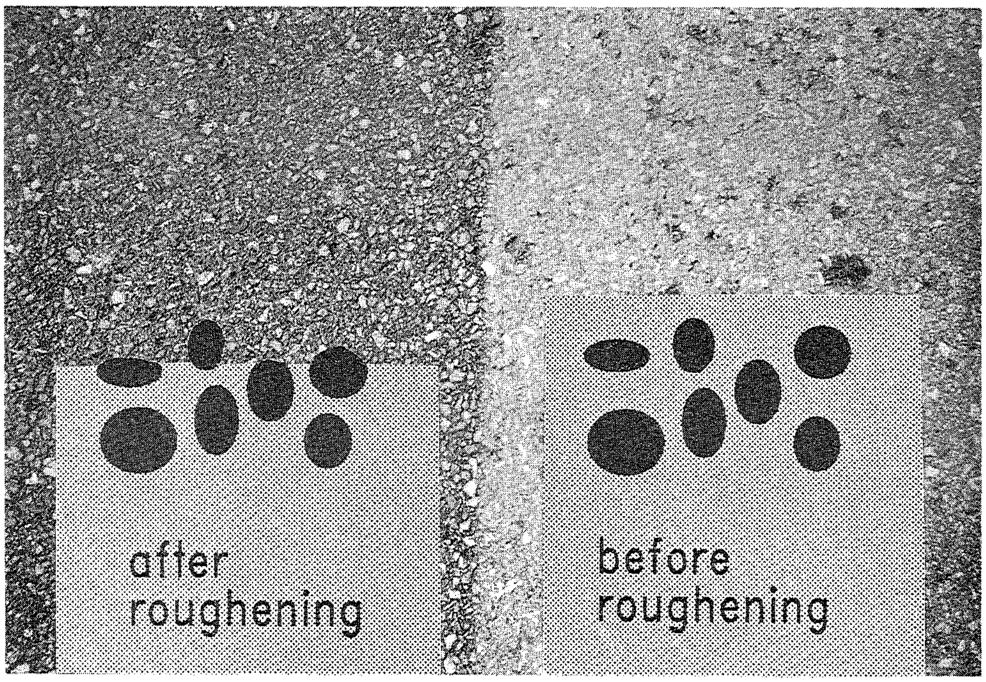

Figure 3

Texture of an asphalt surface before (right) and after (left) water jet treatment

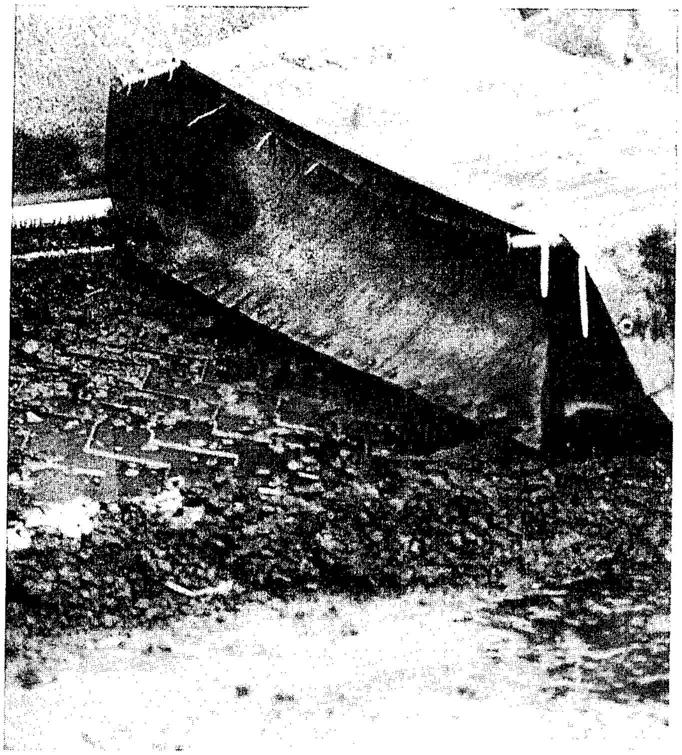

Figure 4

Asphalt coating removal from steel using water jet technique

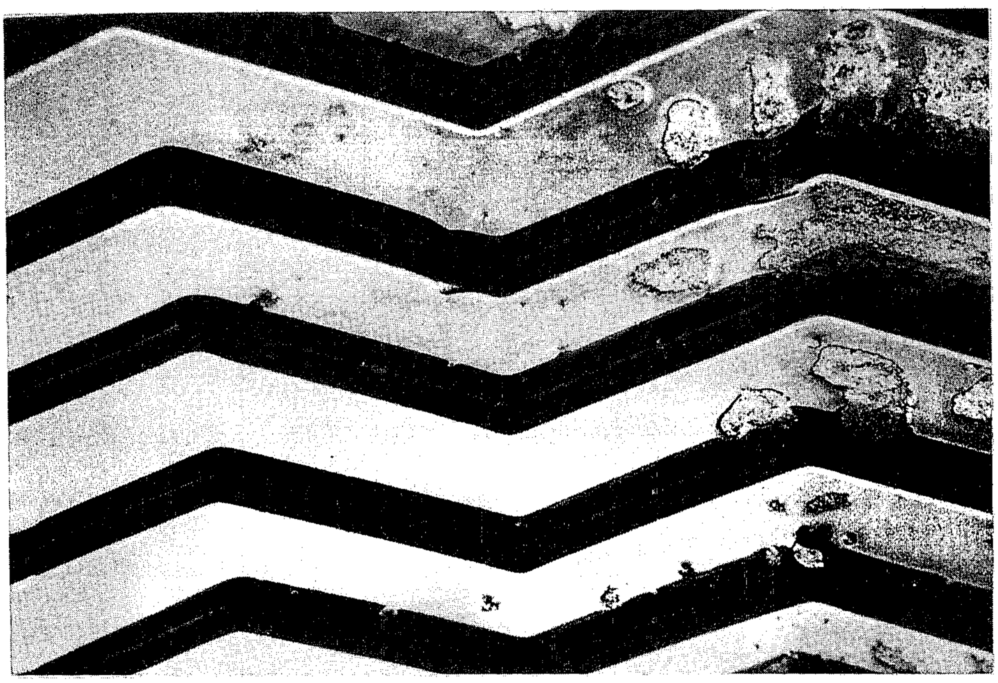

Figure 5

Situation on the steel panel surface after asphalt removal between the zigzag bars

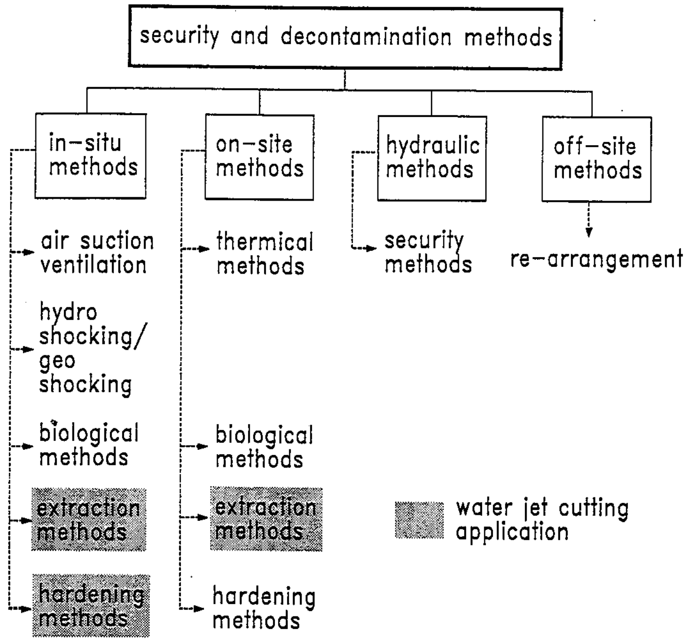

Figure 6

General methods of ground decontamination according to Jessberger (1991) and Stein und Niederehe (1992)

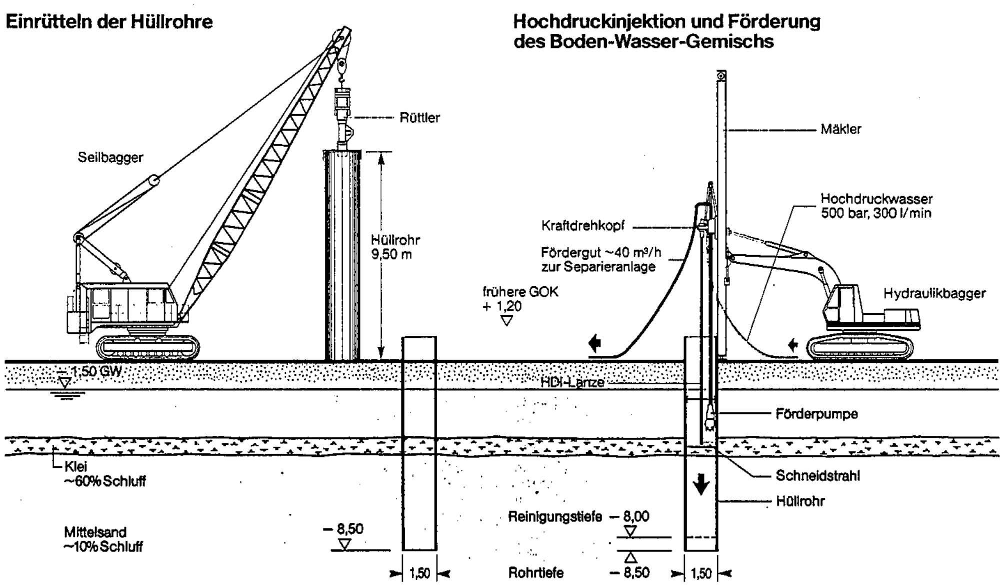

Figure 7a

General structure of ground decontamination using modified jet grouting method (Philipp Holzmann AG, Düsseldorf)

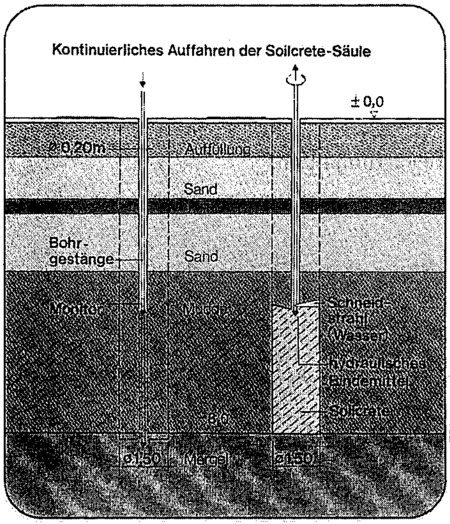

Figure 7b

General performance of ground decontamination using modified jet grouting method (Keller Grundbau GmbH, Offenbach)

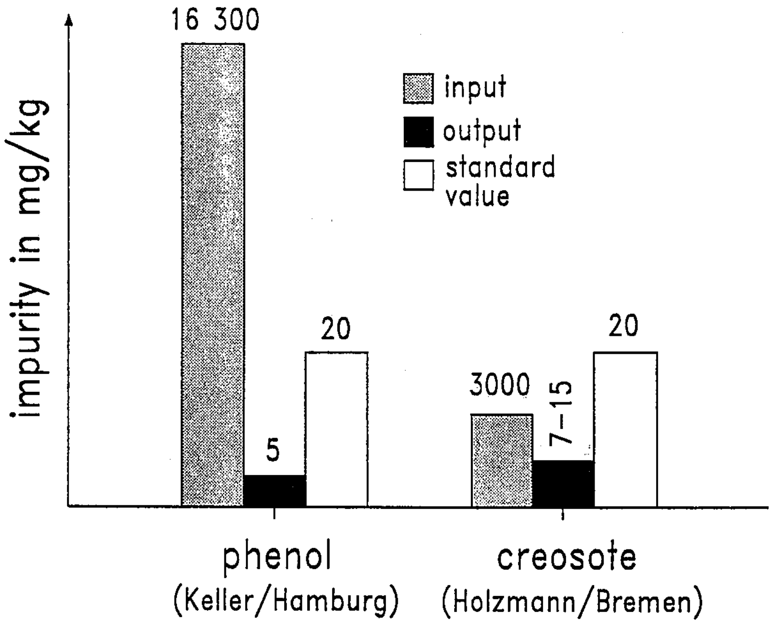

Figure 8

Results of decontamination works using water jet based hardening methods

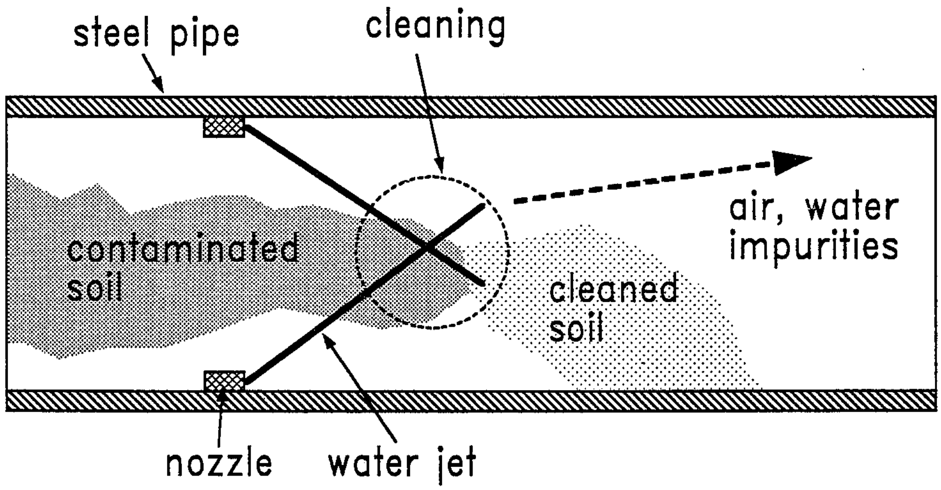

Figure 9

Soil cleaning principle using a special jet tube (Klöckner Oecotec GmbH, Duisburg)

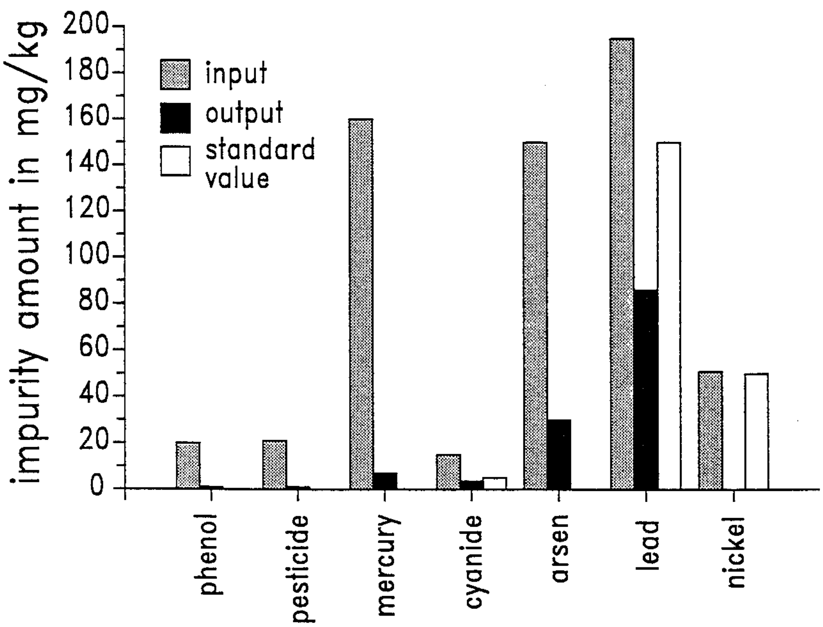

Figure 10

Results of decontamination works using water jet extraction method (Heimhard, 1987).
For further experience see BAM, 1987.

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HYDRODEMOLITION: WHY 'YES' AND WHY 'NO'

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ABSTRACT

Water jet technology has been known for well over 20 years. One of its best known and developed applications is hydrodemolition of concrete structures provided for rehabilitation. Using hydrodemolition in place of conventional jackhammers provides a number of advantages, such as excellent surface preparation, far superior to the traditional method; the concrete is well saturated, free of chlorides, rough, with perfectly cleaned rebars; and when new toping is placed, slowly migrating moisture enhances its curing. Hydrodemolition eliminates harmful structural vibrations, dust and high noise level associated with jackhammering operations. By avoiding structural vibrations and secondary damages caused by jackhammers to the sound concrete longer between-repairs time can be achieved.

Despite of all benefits provided by hydrodemolition, and its long history, commercial use of this technology is still rather marginal.

In this study effort was made to identify all parties involved in a typical concrete restoration project, their approach to the problem, and resulting effect on the selection of the technology finally employed.

It is not only contractor's decision to use or not to use hydrodemolition. The problem is more complex and to efficiently promote the technology it is not enough to improve its technical parameters. Efforts are needed to convince both the public (the repaired structure owners) and consultants that quality of the job done by water jets and its long-term repercussions should dominate over the short-term cost savings.

1. INTRODUCTION

Advantages of water jet technology in various applications have been well known for over 20 years. One of the domains where the technology and the equipment for its application is well commercially developed is construction industry, and particularly, demolition of concrete structures before their rehabilitation.

By using high-energy water jets one can affect concrete selectively, removing already weakened fragments while avoiding damages to the sound material. Such damages, due to transmission of vibrations are typical to commonly used jackhammers, and moreover, they can spread far away from the actually repaired area reducing considerably life-time of the whole structure. The perfect bonding between the old and the newly poured concrete in case of hydrodemolition-prepared surfaces is well documented. Despite of this predominant and other benefits such as high productivity, more quiet and comfortable operation, reduced risk of vibration-induced injuries to the personnel, the hydrodemolition is still rather of marginal use.

There are several reasons why contractors, even those aware of the benefits of hydrodemolition, in their jobs employ jackhammers. In the paper presented an effort was made to point out those reasons, and to validate them. It is hoped that the knowledge where the real barriers are can help to break them out.

It should be understood that in such a paper weaknesses of the technology are emphasized while its benefits are not discussed here.

2. STATE OF THE ART

Currently several manufacturers over the world offer hydrodemolition equipment. These are for example: Atlas Copco, Aqua-Dyne, Jet Edge, Hammelmann, Water Blast, Cristanini, FIP Industriale, NLB, Indescor and others. The commercially available equipment operates typically at a pressure range about 103 to 207 MPa (15,000 to 30,000 psi) and water consumption about 56 to 230 l/min (15 to 60 gpm). Most of the units are designed for floor operation, with computer controlled parameters. There are few models adapted for vertical and overhead work including hand held lances for hard to reach areas. The production unit consists of: high pressure pump unit powered by a diesel or electric motor (several hundred HP), and a robot which can operate up to a few hundred meters away from the pump.

When traditional jackhammers are used, they are 7 kg (15 lbs) units for concrete partial removals, and heavier ones allowed only in the case of complete demolition of the structure. The 7 kg of mass limit was established because of excessive crack propagation outside of the repair area.

2.1 Hydrodemolition versus other methods

Any technique of restoration of concrete involves the removal of the degraded, poor-quality concrete. During this operation it is essential to:
- remove all traces of spalled, delaminated, and poor concrete;
- avoid damage to reinforcement;
- avoid damage to still good-quality concrete;
- ensure good bonding to concrete repair material.

From this standpoint there are some benefits of hydrodemolition (HD) versus draw-backs of other methods (Ref. 1, 2, 3) as shown in Table 1.

3. PARTIES INVOLVED IN A TYPICAL CONCRETE REHABILITATION PROJECT

Generally any concrete rehabilitation project involves the following parties:
- owner
- consultant
- contractor
- public
- legal authorities, represented by by-laws, regulations etc.

Each of the parties has its own specific approach and motivations, and the consensus reached is often far away of what could be seen as optimum by researchers developing the hydro-demolition technology.

The owner: usually it is a government (roads, bridges) or private real-estate corporations (garages, parking). In both cases the ownership of the object is likely to be with the same owner for a long time. This would imply long-term financial policy and sensitivity to methods providing the longest possible life-time of their properties. From this point of view hydrodemolition is a better option than jackhammers since it imposes no secondary destructive effects onto the sound structure and the reinforcing grid, and removes effectively contaminants (chlorides) from the concrete and reinforcing steel. That kind of surface preparation provides for a longer period before the next repair is required.

However, the dominating practice of today is to call the tenders for the job, and to select the lowest bid. The owner need not have a technical knowledge relating to variety of methods available for contractors. His concern is to have the job done at the price which is acceptable for him. And even if he knows that something more is available except jackhammers the total time and range of commercial use of the hydrodemolition technology is not long enough to practically prove its superiority in terms of between-repairs time.

The owner, therefore, tends to prefer - although indirectly and unknowingly - jackhammers as the less expensive alternative.

Consultant is the owner's representative hired for professional preparation and management of the project. His position requires balancing between financial restrictions imposed by the owner and technical capabilities of contractors. It is, however, his decision of which method of performing each given task shall be employed. Contractors usually shall comply with terms of the project specification set up by the consultant. Consultant's (engineer's) awareness of all aspects of the hydrodemolition, its benefits as well as limitations, is therefore essential for promoting the technology.

Contractor is the next to the consultant in his position to choose the technology and, in practice, his voice can even dominate. A number of contracting businesses operate on contract-to-contract basis. They rent the equipment and hire the people depending on the project they already have won. From their point of view each project has to pay for itself. Capital cost of the hydrodemolition equipment is high and it capitalizes after approximately ten thousand square metres (one hundred thousand square feet) of the surface demolished. If one wants to reach that point within, say, three years, he would have to operate the machine 8 hrs a day for about 200 days a year. For a small- or even medium-size contractor such an equipment utilization is rather a dream, especially in present economic conditions. In contrary conventional jackhammers with all what is necessary to run them, are inexpensive.

Another point here is qualification of the operator for hydrodemolition. Since the equipment is expensive it would be unwise to hire casual workers to operate it. The owner of such an equipment should rather keep the operator on a permanent position. This means he has to pay him high salary even if there is no contract pending. On the other hand people for operating jackhammers need to have simple training only and can be hired for each contract solely.

This is obvious that the contractor will opt for a less expensive equipment, unless he specializes in demolition and anticipates full load for the machine over the next few years.

In some cases the equipment is offered for a rent. However, as contractors indicate this, the renting rate is set at such a level, that it can hardly compete with jackhammers.

Public: In the case of apartment buildings, which are occupied at all times, tenants would exercise some pressure on the contractor to reduce noise, vibration and dust propagation throughout their building. It was reported that the tenants even on the 15th floor were still complaining about unbearable effects of jackhammering in the adjoining parking garage structure.

Would the public be fully aware that hydrodemolition is much less noisy and nuisance than jackhammers, there is no doubt it would insist that contractors use it.

By-laws: Many, if not all, of the cities have their own by-laws regulating noise levels during and after business hours. Since most of the potential projects such as underground parking garages are located in the downtown core and business areas, this poses limitations on the hours of work and equipment used. In the office towers this could be controlled by working after business hours, at night. In some cases, such as hotels, even during night operation the noise level have to be reduced, since disruptions to the business activities cannot be tolerated. Those noise level regulations would prefer hydrodemolition over jackhammers.

In an otherwise attractive area of restoration of bridges severe restrictions as to waste water disposal might reduce interest in hydrodemolition. Environmental regulations that water disposed into the natural streams or municipal sewer systems must not contain chloride, solid particles (and so on) charge contractors with an additional burden and cost of compliance with those requirements. In order to do so one has to collect all the water, at least separate the solids, and dispose both components separately. Since at the time being no standard commercially available equipment exist for this purpose, contractors considering using of hydrodemolition have to solve the problem individually. However, time restrictions - common in bidding process - as well as lack of experience and, therefore, uncertainty as to the results, would direct them toward well known jackhammers rather than towards hydrodemolition.

4. EXAMPLES OF HYDRODEMOLITION IN OTTAWA

In the Ottawa-Carleton area two concrete rehabilitation projects can be looked at as typical examples of consultants, contractors and public attitude.

Bank Street Canal Bridge

In the summer of 1991 the Regional Municipality of Ottawa Carleton called a contract for the rehabilitation of the Bank Street Canal bridge, crossing over the Rideau Canal (Ref. 4). The bridge is the major link across the Rideau Canal and is designated as a heritage structure. The bridge itself is a six-span, closed spandrel, concrete arch structure, and has been in continuous service since it was built in 1911-1912 (see Fig.1 and 2). The bridge was a typical example of where the hydrodemolition should be employed and, indeed, it was recommended by the consultant that concrete removals to the arches be done using this technology. However, many local contractors did not like the idea, claiming lack of experience, difficult equipment adaptation for overhead and vertical works, and most of all, environmental restrictions related to waste water disposal. The specifications had to be revised to allow for jack-hammers as well. And the contractor who specified this traditional method won.

One interesting aspect of this project may be highlighted. The bridge crosses areas which are under three different jurisdictions. Two of them are responsible for roads over and under the bridge, and one for the section crossing the canal. The agencies commented that it would be allowable to work on the bridge deck over road but not over the water course, unless the water be collected and filtered. The Ministry of Natural Resources and Parks Canada will not permit construction activities which will cause chlorine, ammonia, debris or other contamination enter water and which may be detrimental to marine life or quality of water.

Underground garages in high-rise buildings

On another occasion, one of the authors was retained as a technical advisor for the rehabilitation of the underground parking garage. After a few weeks of struggling with noise, dust and poor workmanship, especially on soffit repairs, he convinced the owner to retain a subcontractor for all concrete removals with water-jets. The owner listened and never looked back. The noise from the pump unit now was reaching only the third floor, versus vibrations felt before throughout the whole building. Since the high pressure pump unit was located outside of the building and in front of its balconies some additional noise-shielding was used. It was very simple to construct, by placing plywood sheets around and on top of the high pressure pump unit to deflect sound. By experimenting for a while with this not so sophisticated arrangement, the contractor was able to satisfy everyone. The owner did not have any major reservations as to the water intake (from a fire hydrant standpipe) and disposal (Ref. 5).

In this project the subcontractor retained was the one specializing in hydrodemolition for several years. As such and having his own equipment he was able to commence the work in time required, with minimum risk to general contractor.

5. RESEARCH BY QUESTIONNAIRES

In order to investigate what the actual state of awareness and knowledge about the hydrodemolition is among main parties dealing with concrete rehabilitation, a questionnaire research was performed.

Over 60 questionnaires were sent out to three groups: clients, consultants and manufacturers of the equipment, and contractors. At time of this publication 15 responders replied (three clients, four consultants, one manufacturer, and seven contractors), (Ref.6). Summary of the responses is shown in Table 2 as a comparison between the hydrodemolition and jackhammers.

The most trustworthy answers are those given by four contractors using the technology. In their opinion the noise level is definitely lower and the surface preparation is better with no opposing answers. However, the points for water and water/debris problems are distributed equally, what indicates the weak points of the technology. The weight of the water/debris disposal is even more clearly seen from the answers given by consultants, who indicate it unanimously. Some of them accent this point stating that extensive provisions of ponds and drainage control have been discouraging them from specifying the hydrodemolition.

6. SUMMARY

The aim of the performed survey was to identify the weak points and the areas which need improvement. It was found that those who had any experience with HD were willing to use it again in the future. However, they would like to see a better solution for waste water disposal, and a more affordable equipment. Also, the price of the equipment makes it available only to those contractors who are willing to specialize in HD, what in turn keeps the demand low.

Analysis of factors affecting the range of application of hydrodemolition technology indicates the following:

1. It is not the contractor alone who makes the decision to use either the hydrodemolition or jackhammers. Two parties most responsible for such a decision are consultant and contractor, but their move is biased - directly or indirectly - by the owner's position and by relating by-laws and regulations, such as noise and water control.
2. In order to break the barriers imposed by water-relating regulations development of portable water/debris collecting and clarifying systems is necessary.
3. Since at the present time one of the factors guiding the owners is the total cost of the restoration, it is critical to convince them of the long-term savings due to better quality of the job done by use of hydrodemolition instead of by jackhammers (prolonged life-time of the structure).
4. It is important, therefore, to emphasize in all marketing materials the long-term effects of using the hydrodemolition in place of jackhammers, namely avoidance of secondary damages to a sound structure by vibrations, and therefore, prolongation of between-repairs periods (relating research are strongly recommended).
5. Unless the hydrodemolition systems are available at lower price or on rental basis a few specializing subcontractors only could afford to buy it rather than a number of general contractors dealing with concrete rehabilitation.

ACKNOWLEDGMENTS

The authors wish to thank all the respondents for their contribution.
Special thanks go to Mr.S.T.Johnson of Jet Edge for his letter with valuable remarks on economical aspects of the application of HD technology.

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Table 1. Brief comparison of concrete demolition by use of water jets and conventional methods

Hydrodemolition	Conventional methods
- removes concrete selectively with minimum damage to good concrete in adjacent areas; - the water descales and polishes reinforcing bars without damage to the reinforcing grid, thus eliminating a need for costly steel repair and sand blasting; - water jet directly exerts pressure on concrete's microcracks, eliminating them and flushing away the chloride deposits they contain;	- jackhammers and milling machines (even when used in conjunction with sandblasting) are ineffective in the removal of chloride concentrations lying within the cracks around the steel reinforcement; - corrosive contaminants remain in many of the rebuilt road and garage structures of today reducing considerably their future life-time;
- eliminates harmful structural vibrations, dust and high noise level; - does not create additional microcracks propagating through a sound part of the structure;	- vibration and impact created by jackhammers can cause rebars damage and need for their repair;
- does not damage the aggregates, and therefore provides three to four times stronger bond strength than that by jackhammers; - leaves a vertical, slightly undercut edge, thus making for a strong mechanical bond with the replacement material; - blasts away the faulty material while leaving the sound concrete with a rough texture which is perfect for bonding the newly poured concrete;	- abrasive rotating discs are sometimes used, but they are generally ineffective and leave a surface which is too smooth to allow good bonding to restoring materials;
- incorporates features that enable the operator to easily remove concrete from underneath the reinforcing steel;	- result of using jackhammers are linked to the ability and sensitivity of the operator;
- eliminates diamond saw cutting; - eliminates sandblasting; - saves the labour: two operators of HD can replace ten to twelve labourers with jackhammers;	- jackhammer operators suffer considerable occupational stress and have an average absenteeism of 33%;
- reduces cost per square foot by one third to one half compared to the conventional method; - is quiet so the contractors can use night shifts; - offers high cutting efficiency for precise cuts;	- vibration and noise associated with use of jackhammers limits considerably time available for the contractors to perform the job;
- the prepared concrete is well saturated, rough, with proper undercuts along the edges and when new topping or shotcrete is placed, slowly migrating moisture enhances its curing; - without major problems, the concrete can be removed to approx. 2 inches all around the rebars which remain rust free;	

Table 2. Summary of the questionnaire research on hydrodemolition vs. jackhammers

Question	Number of answers given by:					
	All respondents		All contractors		Contractors using the HD	
have you ever used / seen in use HD	Yes 11	No 3	Yes 6	No 1	Yes 4	No --
noise level	Lower 11	Higher 1	Lower 6	Higher 0	Lower 4	Higher 0
cost per unit area	Lower 4	Higher 6	Lower 3	Higher 3	Lower 3	Higher 1
water supply	A problem 5	Not a problem 7	A problem 3	Not a problem 3	A problem 2	Not a problem 2
water and debris disposal	A problem 11	Not a problem 2	A problem 5	Not a problem 2	A problem 2	Not a problem 2
surface preparation	Better 10	Worse 0	Better 6	Worse 0	Better 4	Worse 0

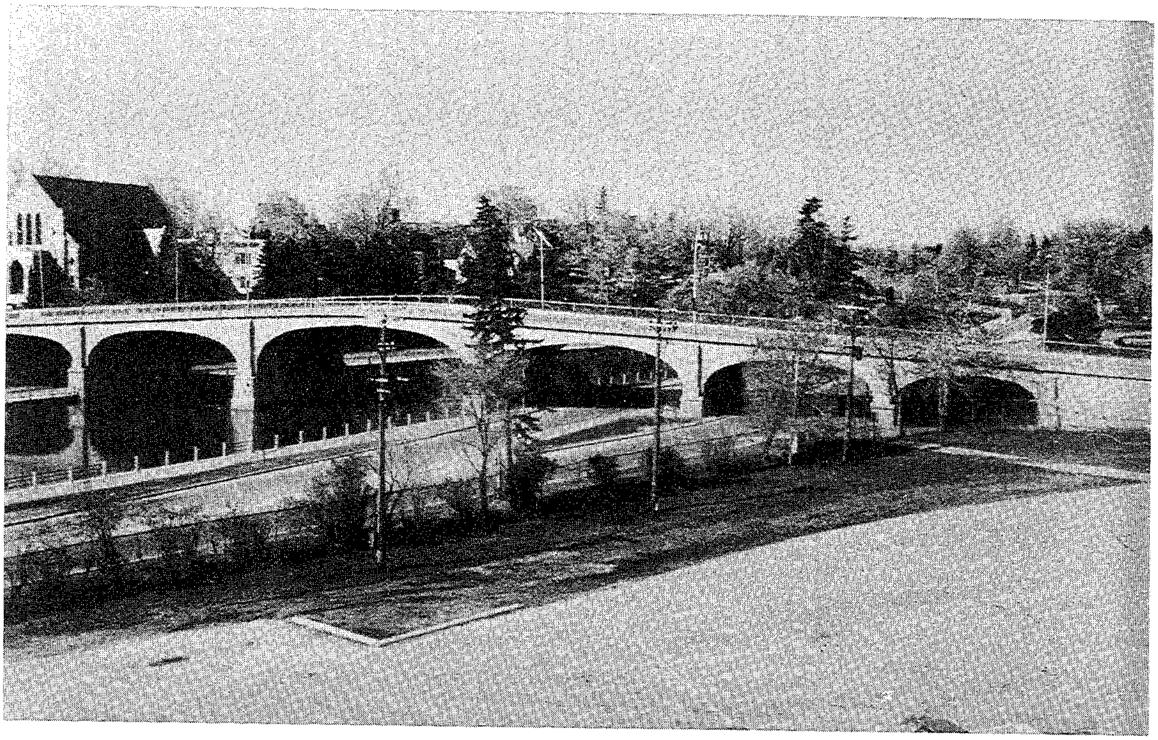

Fig. 1 Bank Street Canal Bridge in Ottawa, designated as a heritage structure, is a typical example of where the hydrodemolition should be employed. It was not used because of environmental restriction related to waste water disposal.

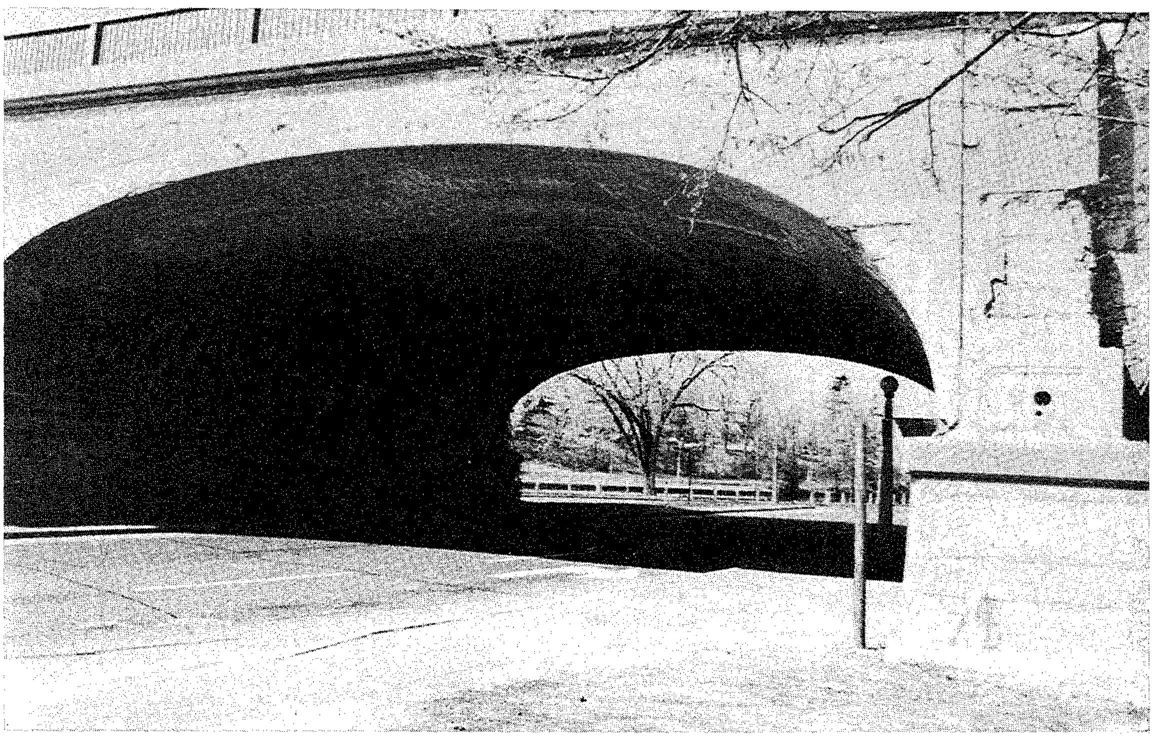

Fig. 2 A detail of the bridge shown in Fig. 1. All the concrete on arches as well as on the front faces of the spans was to be removed to the depth of up to 100 mm.

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Paper 42

THERMAL SPRAY REMOVAL

WITH

ULTRAHIGH-VELOCITY WATERJETS

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ABSTRACT

This presentation discusses the original development, acceptance and current use of clean, ultrahigh-velocity waterjets to remove thermal spray coatings as widely encountered in the aerospace and land based gas turbine industries. Within this paper, successful removal of various coatings and related base materials are presented. Several coating removal systems that will remove a wide range of thermal spray coatings from complex and varied jet engine parts are presented. The environmental advantages of using this process instead of existing and outdated methods will also be discussed.

Organized and Sponsored by the Water Jet Technology Association.

1. BACKGROUND

Technology dating back to 1983 has shown that rotary, ultrahigh-velocity (UHV) small diameter multiple orifice waterjets, at supersonic speeds of 695 meters per second (2,281 feet per second) and pressures up to 2,381 bar (35,000 psi), are effective in removing coatings such as paint from automotive car carriers, lead paint from various structures, rubber from runways, deposits/process materials from heat exchangers, and solid propellant from rocket engines. There is no detrimental effect on the underlying surface, provided the orifice(s) traverse speed and power are precisely controlled. Much of the previous work was done with hand held devices and control of parameters was dependent upon an individual's physical capabilities and limitations. Water pressure and orifice size determine velocity, flow rates and thrust. Low thrust, due to low flow rates through small orifices, made many manual jobs easier and much safer for the operator. Moreover, concentration of horsepower into a very small area provides an efficient and sharp cleaning process. Small diameter waterjet cohesion degrades over a relatively short distance. This enhances the safety for other workers in the same area. Some very basic motion equipment was first used in conjunction with ultrahigh-velocity waterjet cleaning for heat exchangers and rocket propellant removal between 1983 and 1985. Efficiency is further increased when motion control is incorporated with ultrahigh-velocity waterjets.
Reference Illustration Figure 1.0

2. THERMAL SPRAY COATINGS

2.1 General Description

Thermal sprays include any coating that is applied above room temperature. Many types of materials such as metallics and ceramics are applied by heating the material to a molten state and propelling it onto a carefully prepared surface. There are three main methods for heating the material. They are Electric Arc, Flame Spray, and Plasma Arc Spray. Prior to heating, the materials are in either powder, rod or wire form. The acceleration is achieved by atomizing jets or process gasses. Molten droplets impact the surface, attach, cool, and build up as more are applied.

2.2 Common Uses

These coatings are most typically used for clearance control (abradable or knife edge seals), heat protection (thermal barrier), corrosion control, wear reduction, and dimensional restoration on jet engine and land based gas turbine components. These coatings are routinely removed and replaced during scheduled engine overhaul.

2.3 Coating Variations

The density and bond strength of the material varies to a great degree due to application methodology, materials, surface preparation and engine operating conditions. If the droplets are accelerated to higher speeds and the overall process is better controlled, denser and more tenacious coatings are achieved. Additionally, engine operating temperatures and flame shape can create a localized effect on nearby coatings. The removability with waterjets also varies proportionally.

3. THE INITIAL STEPS

Northwest Airlines engine maintenance personnel and a waterjet technician, were watching a patented waterjet runway cleaning system in operation and pondered the ability of the process to remove rubber without damaging the tarmac. Research and subsequent parametric lab testing on scrap jet engine parts proved the feasibility of removing jet engine coatings. Initial contacts with an engine manufacturer indicated stringent requirements to insure no detrimental effects to the engine component base metal. Due to the newness of the process, scrutiny was very high. Northwest Airlines in Atlanta, GA purchased an ultrahigh-velocity waterjet system and the world's first approval process was jointly undertaken.

4. REMOVAL METHODS PRIOR TO WATERJETS

Conventional thermal spray removal (TSR) has its own set of difficulties.

4.1 Chemical

Parts are soaked in chemical filled vats to remove coatings. The chemicals are designed to selectively attack the coating. Chemical removal is hazardous and creates environmentally detrimental waste products. This process also exposes personnel to potential safety and health hazards. In some cases the chemical does effect the base material as well.

4.2 Mechanical

Mechanical removal is done with conventional machining equipment such as mills and vertical lathes or with grit blast. Set-up for machining off the old coatings is time consuming as parts are often slightly out of round. Base material removal reduces the part life, yet is virtually unavoidable even when machinists take great care in centering the part. Additionally, there is no easy way to distinguish between the coating and the base materials.

TSR with grit blasting induces high residual surface stresses, creates process induced waste, complicates crack detection and removes base material. This process is also non-selective. Use of a light grit blasting process after component repair, and just prior to application of new coating, is still required by engine manufacturers.

5. PURPOSE OF INITIAL TESTS

Initial tests were conducted to determine the feasibility of TSR and effect on base materials. The final desired result was extensive engine manufacturer and FAA approvals.

6. PROCESS EVALUATION

6.1 Comparisons

With this new process came the question "how do we evaluate the effects?". The engine manufacturer's test requirements and related comparisons were based on known conditions as existed with other accepted methodology. Primarily, comparisons were made with grit blast, as it was deemed to be the most commonly used and aggressive method.

6.2 Preliminary Sequence of Tests

Initially scrap components were tested. Later, uncoated test coupons of the base materials were subjected to extreme exposure to the waterjet process wherein damage was intentionally created to determine process limits. In this case, the parameters used were beyond what one would normally need for removing the coating. In the case of one particular component, non-rotary waterjets were used. Stringent evaluation and subsequent judgments were made by the engine manufacturers as to:

- Erosive effect on base materials
- Induced residual surface stress
- Effectivity of coating removal process
- Thin material distortion evaluation
- Maximum parameter limits

Coating conditions as effected by engine operation were used. "As sprayed" materials were not considered critical. It was discovered and demonstrated that this condition is easier to remove than engine run coatings. Testing was focused on the most representative real world samples. Basic energy level requirements for removal were established.

7. THE INHERENT PHYSICAL PROPERTIES OF WATERJETS AND THEIR EFFECT ON THERMAL SPRAY COATINGS.

Several physical properties of the waterjet effect coating removal. The most noticeable properties can be directly related to the interaction with the characteristics of the coating to be removed. The main forces fall into the following categories with varying degrees of overlap. The energy density required to remove the coating will vary depending upon the coating density and adhesion.

7.1 Cutting Force

There are some relatively low strength coatings and materials that are actually cut by the stream. These materials can be removed at very high production rates. An example would be acoustical composites and adhesives on fan cases.

7.2 Hydraulic Force

In the case of porous coatings, with low bond strength between the formed droplets, the waterjet acts upon the grain boundaries, voids and imperfections. The static pressure of a jet stream creates a very low level of hydraulic pressure within the coating cracks and voids that creates a thrust of sufficient strength to separate the weak boundaries.

7.3 Compression/Tension

In this case, the coating is weakly bonded to the base material. There is a rapid change of condition as the highly concentrated waterjet moves across the material. The coating and base material starts out in the normal state. As the waterjet contacts the target material, it is put into a compressive state and, as the waterjet quickly moves off the area, it achieves a slightly tensile state. Small droplets, which peel off the jet stream due to friction with the atmosphere, also impact the surface. This rapid conditional change can be compared to the interaction between an extremely narrow, weighted tire rolling across a layered asphalt road surface. In both cases, the strength of the material, thickness, bond strength, and condition are related to the removal rate of the "coating". In the case of the asphalt, the first noticeable effect is chuck holes. With thermal sprays the coating comes loose at the mechanically bonded interface with the base material.

7.4 Erosion

In cases where the coating is dense, strongly bonded and without voids or other imperfections, the physical property of the waterjet that effects the coating is erosion. In many instances the coating actually achieves a metallurgical bond, at molecular level, with the underlying material. Waterjet erosion occurs due to extremely fine particulate matter carried within the high velocity jet stream. This results in a micro machining process which is generally of a slower removal rate than with other coatings. Waterjets operate most reliably with very clean water and, in most cases, the level of particulate matter is quite low. Exacting parameters are required to prevent erosion of the base material, though the process is far less aggressive than grit blasting.

8. EVOLUTION OF THE TECHNOLOGY

8.1 Original Equipment

Components for general coating removal have existed for nearly fifteen years. Intensifier based pumping systems provide a source of reliable ultrahigh-velocity water. Velocities required for efficient removal of tougher jet engine coatings normally requires speeds of 871 mps and 3,742 bar (2,859 fps and 55,000 psi), and flow rates of up to 7.57 liters per minute (2 gpm). Coating removal tips with an acceptable configuration for initial feasibility tests were of an old and somewhat inefficient design as used for hand held applications; single radius tips were used. Coating removal tip technology had been previously enlarged and improved to meet the high production rates and uniform cleaning required for mechanized and patented runway rubber removal systems. Computer models were used for rotary tip design. Strategic positioning or orifices provided a more even energy distribution across the linear path than the smaller tips used for hand held cleaning.

8.2 Application Specific Design Requirements

Design improvements were required to increase capacity and efficiency at the delivery end of the waterjet system. One example is the increase on high RPM swivels from 2,380 bar to 3,742 bar (35,000 psi to 55,000 psi) rating at 1,200 - 1,500 RPM. The design knowledge and computer model, as developed for runway cleaning tip design, was utilized for thermal spray removal tips. The resultant design provided the most uniform energy distribution possible across the cleaning path with rotary or non-rotary orifices. Efficiencies were increased and effect on base material was further minimized.

See Illustration Figure 2.0

8.3 Systems Integration

Systems were developed to contain and control the process. Precision closed loop motion control, noise abatement and water treatment, among many other things, were developed. Approval by the Engine Manufacturer and FAA dictates accurate monitoring and a preference for process parameters recording. The CNC controls incorporate tracking software and flight recorder-type data logging with hard copy capability.

9. PHASE TWO TEST PROCEDURES

9.1 The Purpose

The first feasibility tests were done with rotary and some non-rotary orifices on actual used components. After some very challenging coatings and coating conditions were encountered, more basic tests were required in order to better understand the physical causes and effects as compared to previous cleaning knowledge. These tests were to identify major process parameters and these were used to optimize designs.

9.2 Required Samples

Varying temperatures within a typical jet engine have noticeable effects on the coatings. Some components are exposed to temperatures which vary across a small distance and this often results in differences from one area to the next. Due to minimal accessibility to non-scrapped and representative components, prepared samples were required. In order to approximate the real world, the focus had to be on worst case conditions. Preparation of accurate and uniform samples was crucial.

9.3 Coupon Preparation

A bond coat for thermal barrier applications and related base materials were selected. Equal sized sample coupons of the appropriate base materials were uniformly prepared to an engine manufacturer's specifications. Hastelloy X was grit blasted using METCO #60 grit aluminum oxide at 2.72 bar (40 psi) air pressure and subsequently coated with METCO 382-NS-2. Coating thickness ranged between 0.127 mm and 0.2032 mm (0.005 inches and 0.008 inches). The bond coat samples were then subjected to 1000° C (1800° F) for a period of 50 hours to closely approximate engine run conditions. This proved to be very accurate when tests were repeated on the most heat effected zones of actual combustion chambers.

9.4 Orifice Selection

Initial test involved extremely high quality factory waterjet orifice assemblies that provide a very long and coherent jet stream. Various diameters were selected.

9.5 Fixtures

Fixtures were designed to provide repeatable parameter testing and accurate orifice positioning.

9.6 Designed Parametric Test

Parameters were selected by utilizing a commercially available software which produced a full quadratic mathematical model and showed trends and relationships between various factors.

10. SUMMARY OF TEST RESULTS

The results of these tests to determine major parameters are summarized as follows:

10.1 Velocity/Pressure

Increase waterjet velocity as a result of increased water pressure substantially increases TSR rates. Substantial increases were clearly identified when increasing from 788 mps and 3,061 bar (2,586 fps and 45,000 psi) to 871 mps and 3,742 bar (2,859 fps and 55,000 psi).

10.2 Standoff

Standoff distance is an important factor at least up to 50 mm (2 inches) when combined with a small diameter orifice. The process, however, is not extremely sensitive to normal standoff changes, particularly when comparing to mechanical removal methods on eccentric parts.

10.3 Sizing Orifices

A given orifice power can be divided into smaller multiple orifices or used through fewer, larger orifices. Small orifices are more effective than larger ones. The most efficient use of orifice power is with multiple small jets versus one large jet. Expected increases in removal rates for a sequentially larger, and larger single orifice as compared to increased orifice kW (horsepower), do not occur.

An example would be a comparison between a 0.2286 mm (0.009 inch) diameter orifice which provides a path width slightly wider than the orifice diameter, and two 0.1524 mm (0.006 inch) diameter orifices that provide a path width slightly wider than the sum of the two widths. In each example, an equal velocity/pressure of 871 mps and 3,742 bar (2,859 fps and 55,000 psi) is used.

Example 1 — A path width of approximately 0.254 to 0.3048 mm (0.010 - 0.012 inches) is achieved with 9.48 kW (12.71 horsepower)

Example 2 — A path width of 0.3556 to 0.4064 mm (0.014 - 0.016 inches) can be achieved with 4.21 kW (5.65 horsepower)

Reference Illustration 1.0

Note: All kW (horsepower) calculations are for the orifice power and do not include the actual prime over requirements to offset normal hydraulic and intensifier inefficiencies prior to the orifice. Inefficiencies in the use of orifice power are multiplied by this factor and result in even higher electrical power consumption. On average, orifice power represents approximately 60% of the prime mover power output.

10.4 Coverage Methods

Total time on the part is a major factor. A greater number of passes at higher surface speeds produces virtually the same results as a lower number of passes at a slower speed, provided extremes are avoided. Extremely slow surface speeds are more likely to over-clean as some components and coatings are more readily cleaned than others. If aggressive single passes are used in such cases, the operator will not have the opportunity to view the progress and change parameters to match actual conditions. High speed multiple passes on the other hand, allow visual checks and parameter modification, throughout the process. Excessively high surface speeds with a rotary tip can exceed coverage capability and result in coil shaped tracks and uncleaned areas. This is directly related to maximum rotary speed capabilities.

10.5 Optimum Angle of Impingement

Optimized rake angle is 90°. It is initially believed that an increased angle might augment the coating removal rate. For the tested coatings the best results were achieved with direct impingement, though slight angles will not adversely affect production rates.

10.6 Comparison to Field Data

Optimized parameters were performed on heavily used combustion chambers as supplied from an engine overhaul facility. Production rates and overall results were directly comparable when testing coupons from a real world component using the test orifice and fixtures. This qualified the accuracy of the prepared samples as well as the optimum methods as deduced from the designed test. This was not, however, the case when using multiple orifice rotary tips. It was discovered that multiple orifice rotary tips have inherent inefficiencies due to the physical nature of the motion, no matter how finely balanced, and waterjet interactions that affect the coating removal process. Waterjet interactions can also affect non-rotary multiple orifice tips. Some lesser results over simple multiplication of the previous tests with single orifice rates to match the number of orifices in a coating removal tip, must be expected.

10.7 Test Conclusions

The culmination of the initial tests was the world's first approvals for this unique application and a viable new process. Moreover, the physical characteristics of coatings and waterjets were better understood. These secondary tests provided a greater understanding of the best parameters for tougher coatings. Additionally, rotary tip design limitations and new design criteria were clarified. As knowledge of this new process is expanded, new advantages become clear.

11. ADVANTAGES OF WATERJET COATING REMOVAL

Many advantages became apparent as the process and production equipment design evolved. Some advantages are as follows:

- Selective removal of the coating with virtually no effect on the base material.
- Faster turn-around times due to more rapid set-up and removal speeds; up to 100 times faster.
- Reduction or elimination of hazardous chemical use and related increase in worker safety and cost savings.
- Reduction of waste such as spent grit blast media and mixed metals which are considered hazardous.
- Enhanced quality control inspections through improved visibility of surface imperfections.
- Low flow rates and related thrust induce six times less residual surface stress than grit blasting.
- Relatively low water flow rates are conducive to containment, treatment and recycling of the spent coating and water.
- Time consuming masking for over-spray control is reduced. The waterjet can precisely remove excess spray while leaving the desired areas intact.
- No distortion of thin materials such as combustion chamber louvers.
- The process is not overly sensitive to standoff, thereby eliminating process difficulties with eccentric parts and related base material removal.

12. TSR SYSTEM CONFIGURATIONS

Increased knowledge of the advantages, processes, and experience in system requirements results in better equipment designs. The following is a general description of a typical system.

12.1 Cell

The cell is the environmental chamber in which the thermal spray removal takes place. All the noise, mist, water, and removed coatings must be contained within the cell structure. Noise abatement must reduce the noise level to 80 - 85 dbA, depending on the end user's exact requirements. Normally, the cell is lined with stainless steel. A swing door mounted rotary table provides easy part loading. Slides of actual installations are included in the presentation.
Reference Illustration 3.0

12.2 Motion Control

Four axis gantry robots are used to control the standoff, waterjet impingement angle and traverse speed. Normally, the robot is located on top of the cell. This configuration offers similar functions as a vertical lathe. Access to the inside diameters of tall parts is simplified. All critical components, such as servo motors, ball screws and sensors, must be located outside the coating removal cell. The more robust mechanical devices which are located within the cell, must be completely covered by a rubber boot. An indexing rotary table serves as the fifth axes and may be mounted on a swing door for ease of use.

12.3 Mist Collection

Mist must be removed from the air prior to venting into the shop or outside the building.

12.4 CNC Controls

Controls are key to the system operation. Monitoring of all critical system functions, i.e., system pressure and rotary tip speed, are achieved through the CNC and related software. This includes maximum parameters allowed on the part. Should the parameters fall outside the engine manufacturers' limits, the system must shut down to protect the part from potential damage. The software must record all critical parameters. Additionally, parts programming must be simple for the end user.

12.5 Closed Loop Filtration

Spent coatings often contain heavy metals such as nickel and chrome. Disposal of a mixture of these metals and water is tightly restricted by local authorities. Sanitary drain requirements prevent disposal of process water. Closed loop filtration offers a solution. All water, except the small amount that evaporates, is used over and over. Intensifier pumps require a high quality of water supply, therefore filtration is crucial. The metals are separated and deposited in a barrel. In some cases the metal is recycled. Water consumption is reduced to replacement of the small amount which evaporates.

12.6 Ultrahigh-Velocity Waterjet Pump

The requirements for such a system do not exceed 7.57 liters per minute at 871 mps and 3,742 bar (2 gpm at 2,859 fps and 55,000 psi). Per the test findings, efficient use of orifices results in high production rates and low power consumption.

13. CONCLUSION

The process and related equipment is now highly accepted. The initial tests with Northwest Airlines in Atlanta, GA resulted in the first approvals in the world as well as Pratt & Whitney SPOP 322. It has now become a written procedure within the documentation of all three major engine manufacturers. Reference: Pratt & Whitney SPOP 322, G.E.A.E. Standard Practice Manual and Rolls Royce Manuals. Numerous systems are in operation. In some locations a second system has been installed, thus indicating the end user's acceptance as well. The world's first acceptance for use on highly sensitive rotating parts for commercial engines has been achieved on the CF-6 engine. Financial and environmental advantages have been proven. This process has revolutionized the thermal spray removal industry and has resulted in rapid return on investment (ROI). Closed loop filtration is now both a necessity and a reality.

Related Papers Reference:

SAE 910933 Author: Jeffrey Watson and Steve Sisson
Removal of Coatings from Jet Engine Components with Ultrahigh-Pressure Waterjets
27th Annual Aerospace / Airline Plating & Metals Finishing Forum & Exposition. Published March 26 through March 28, 1991. Contact the SAE Customer Service Department for copies. Copyright, SAE.

Velocity (fps) $= 12.19 \sqrt{\text{Pressure(psi)}}$

OR $= \dfrac{0.4085 \text{ Volume Flow Rate (gpm)}}{C_D \text{ (Diameter (in))}^2}$

Example V: $= 12.19 \sqrt{55{,}000 \text{ psi}}$

$= 12.19 \sqrt{234.5}$

$=$ 2,859 fps

Reynolds No. $=$ 7700 Velocity (fps) Dimension (in)

Volume Flow Rate (gpm) $= 29.84\, C_D \{\text{Diamter (in)}\}^2 \sqrt{\text{Pressure(psi)}}$

$C_D \approx .65$ for HP orifices

Orifice Horsepower (hp) $= \dfrac{\text{Pressure (psi) Volume Flow Rate (gpm)}}{\text{1714 Pump Efficiency}}$

Example: $= \dfrac{55{,}000 \text{ (psi) } 2 \text{ (gpm)}}{1714}$

$= \dfrac{110{,}000}{1714}$

$=$ 64 hp

In this example, the 64 hp is focused through a 0.020" diameter orifice or can be divided into multiple smaller orifices. Horsepower is a finely focused stream with a small cross secetion which provides a sharp cleaning tool.

Pressure (psi) $= .00673 \text{ (S.G.) } \{\text{Velocity (fps)}\}^2$

Figure 1.0

Force (lb)	=	$1.571\ C_D$ (Pressure (psi)) (Diameter (in))^2
OR	=	$.053\ Q \sqrt{P}$
Where CD	=	Coefficient of Discharge
P	=	Pressure (psi)
Q	=	Flow (gpm)

Example: = $.053\ \ 2\sqrt{55{,}000\ \text{psi}}$

24.86 lbs

In this example, 2 gpm at 55,000 psi is delivered through a single orifice. The force can be divided between multiple orifices.

Head Loss in Pipe (psi/ft) = $\dfrac{\text{Volume Flow Rate (gpm)}}{1758\ \text{(Diameter (in))}\ 4.75}$

Figure 1.0

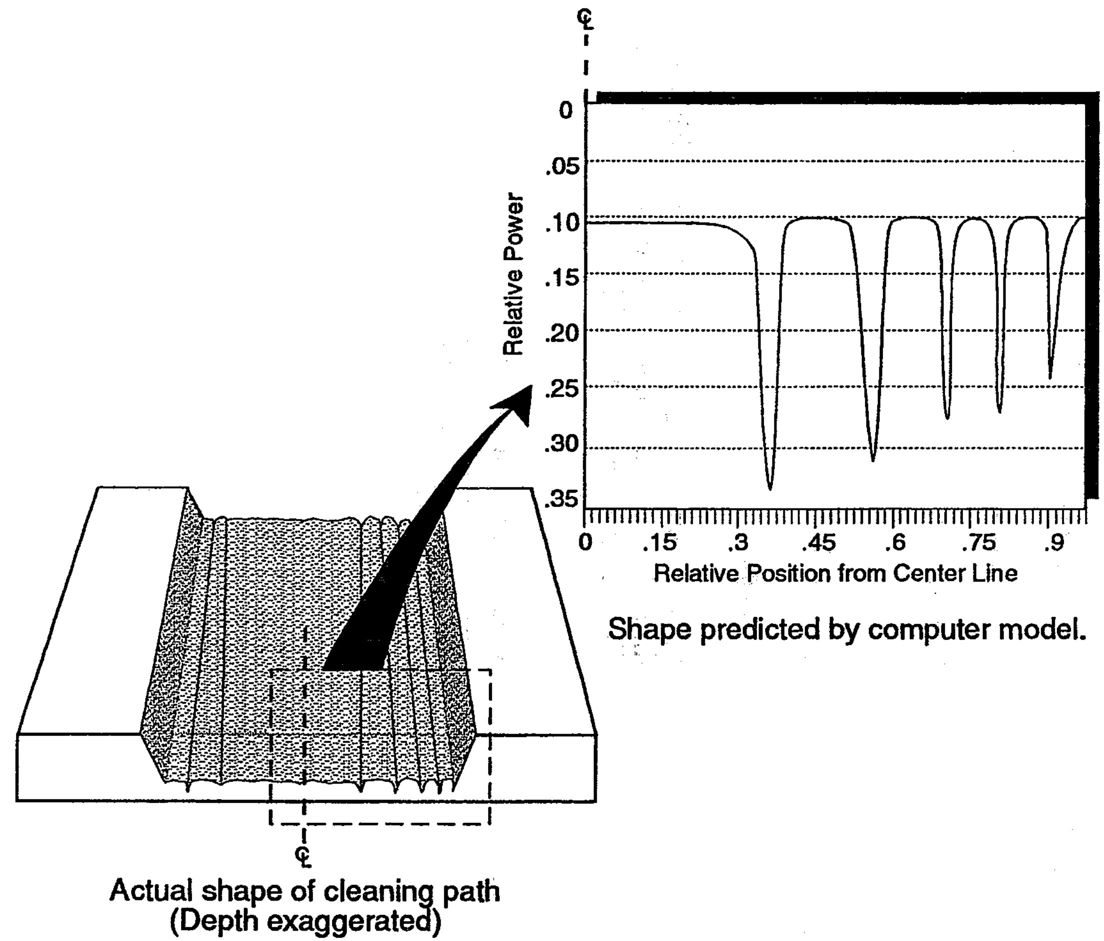
Relative Power
0
.05
.10
.15
.20
.25
.30
.35
0
.15
.3
.45
.6
.75
.9
Relative Position from Center Line
Shape predicted by computer model.
Actual shape of cleaning path
(Depth exaggerated)

Figure 2.0

TYPICAL SYSTEM CONFIGURATION

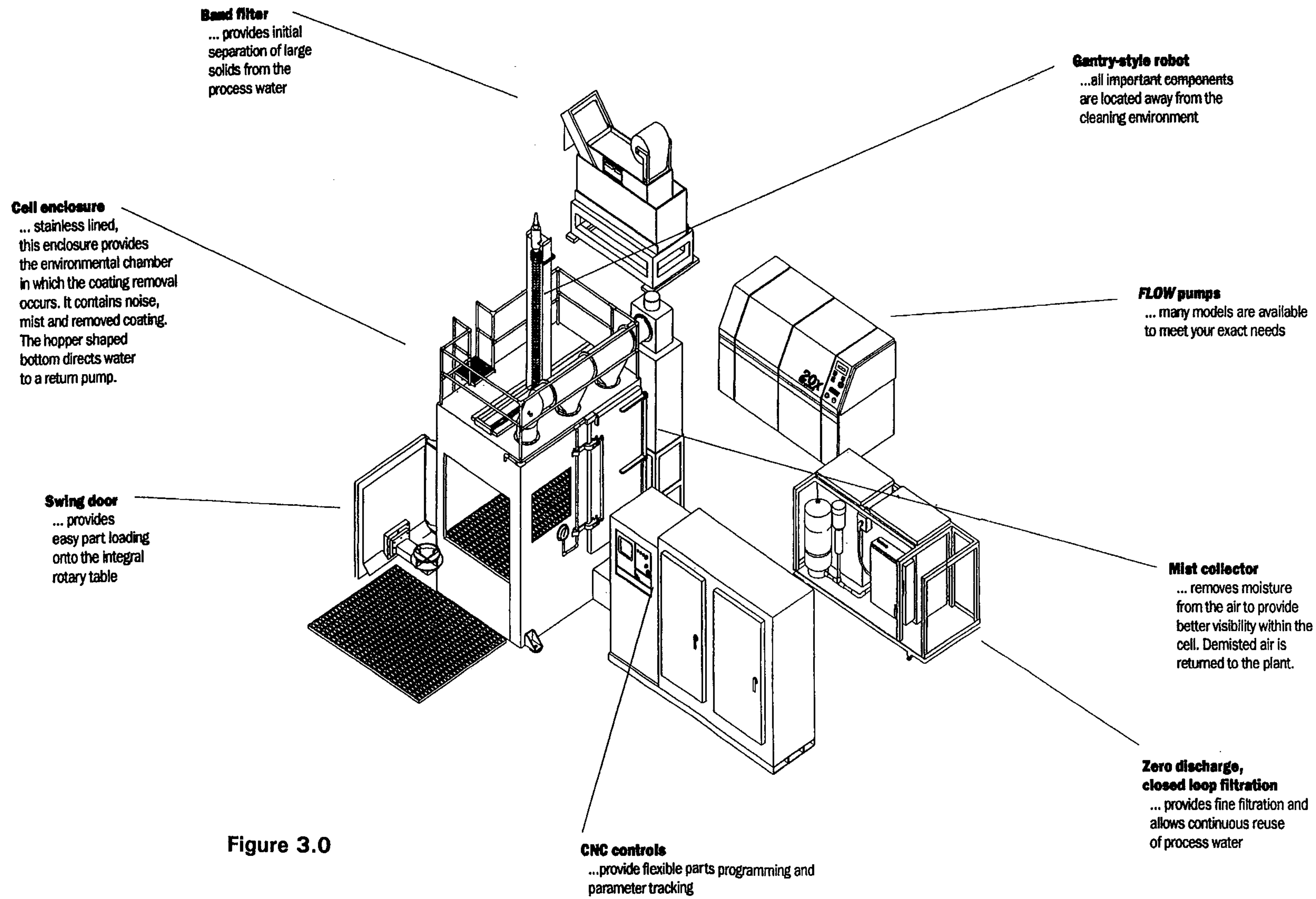

Figure 3.0

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Paper 43

WATERJET NOZZLE DESIGN FOR COMPLEX SURFACES

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ABSTRACT

Pratt and Whitney Waterjet Systems is developing high pressure water as an alternative technology to replace the current chemical stripping processes for coating removal from aircraft and aircraft components. Many of these components consist of surface areas of complex geometries. Consequently, waterjet coatings removal using traditional nozzles and methods can not be used on these geometries. New shape specific nozzles need to be designed for coating removal. Pratt and Whitney Waterjet Systems has developed a variety of nozzles designed specifically for coating removal from complex shapes and geometries. The modeling, design, and use of these nozzles will be discussed in this paper.

Introduction

Pratt and Whitney Waterjet Systems is currently using high pressure water to remove coatings from various components and substrates. Coating and substrates being processed include paint from aircraft and aircraft skins, plasma sprayed metal and ceramic coatings from aircraft engine componenets, paint from helicopters and helicopter components, and other miscellaneious components. The variety of coatings and part configurations often requires a specific nozzle configuration be used for a specific application, particulary if a part configuration is geometrically complex.

Pratt and Whitney Waterjet Systems has developed waterjet nozzle modelling software from which nozzles have been designed and which accurately predicts the coating removal pattern of the nozzle. This paper will discuss this modelling effort, and further methods Waterjet Systems has used to develop new and unique nozzles for processing of complex surfaces.

Initial Work with Flat Rotating Nozzles

The initial waterjet work that Pratt and Whitney Waterjet Systems became involved with was developing a waterjet system which would remove paint from aircraft skins. Aircraft skins generally consist of alclad or bare aluminum, 0.032 inch thick, and are very succeptable to overprocessing. The aluminum alclad material in particular will show overworking much earlier than most substrate materials.

When P&W Waterjet Systems began working with waterjet to remove coatings, a commercially available nozzle was used for stripping paint from the aluminum. Pressures between 20,000 and 35,000 psi were used with flows between 2 and 4 gpm. Although the commercial nozzle was capable of removing paint within these parameters, removal rates were limited and two particular areas of the stripping width showed excessive damage. Other areas across the width showed no damage, or in some cases, no paint removal.

To alleviate the problem of uneven stripping across the width of the nozzle, Waterjet Systems developed computer software to model the energy distribution generated by an orifice of a specific size and location in the nozzle. This was accomplished by first modeling the impact energy of the orifice size, and then incoporating this impact energy distribution into a nozzle at a specific location. Rotational and translational movements of the nozzle were then added to the model and an overall impact energy distribution for the nozzle was developed.

Initial modelling was carried out using the commercial nozzle, which contained 4 orifices at particular locations. The energy impact distribution for this nozzle is shown in Figure 1, and shows two areas of increased impact energy. When compared to panels processed with this nozzle, these two peaks coincided exactly with the two areas being overprocessed on the aluminum. In an effort to decrease these peaks and even out the energy distribution of the nozzle, a new nozzle was designed and fabricated which contained four orifices of different sizes at locations derived from the model. The energy distribution for this nozzle, Xn1, is shown in Figure 2. The redesigned nozzle provided a much more even profile than the commercial nozzle, and processing with this nozzle showed a much more even stripping intensity.

Development of Flat Rotating Nozzles

As the model was very successful in predicting the locations for the 4 orifice nozzle, further modelling was carried out to optimize the number of orifices in the nozzle. A final nozzle, Xn14, with a 2 inch diameter and 8 orifices at optimized locations was designed and tested. Although the stripping rate achieved with this nozzle was slightly better than with the four orifice nozzle; however, substrate damage was significantly lower.

Figure 4 shows a graph of a calculated kinetic energy term, p, vs average roughness for both the commercial and Xn14 nozzles. More energy could be used with the Xn14 nozzle without causing as much surface damage as the original commercial nozzle.

After the success of modelling and testing a 2 inch nozzle, the model was further used to design 4 inch and 6 inch nozzles in an effort to increase stripping rates on aircraft paints. The four inch nozzle, Ln5, was successfully used and has been tested under the Air Force LARPS (Large Aircraft Robotic Paint Stripping) Program. The six inch nozzle is currently being evaluated for the LARPS program and for use on naval vessels. Both nozzles have to date shown a significant increase in stripping rate combined with a decrease in substrate damage.

The nozzle model has been successfully used to design nozzles having smaller diameters for use in stripping coatings, particularly plasma or flame sprayed metals and ceramics, from other structures and components. These materials are generally removed at significantly higher pressures than aircraft paints and require nozzles with limited flow but with significant impact energy. A variety of nozzles have been developed with stripping widths from 0.5 inch to 2 inch, containing from 2 to 8 orifices. The nozzle model has been successful to date in making nozzle design simple and accurate, allowing a quick redesign of nozzles for specific applications, and reducing hardware development costs through computer simulation.

Development of Nozzles for Complex Shapes

Flat rotating nozzles perform well on flat or slightly curved surfaces. However, if processing parameters are not very robust, changes in contour can significantly affect the stripping capability of this type of nozzle. In addition, the flat nozzles perform best at a particular standoff, and if this standoff can not be achieved perpendicular to the surface, the stripping efficiency of the nozzle declines. For example, vertical surfaces or channels, as shown in Figure 4, can not be efficiently stripped with a flat rotating nozzle. Contoured surfaces can also be difficult to strip of the radius of curvature is small, as shown in Figure 4. Also, an inherent limitation with flat rotating nozzles is that rotation must be supplied to a nozzle, and this can not be done in non-line of sight areas or blind corners.

New nozzles were designed for stripping vertical surfaces or channels by using the original nozzle model but not including rotational motion. By designing a non-rotating nozzle, a vertical surface could be stripped by manipulating the nozzle into place from the parallel, as opposed to the perpendicular, see Figure 5. The original model took a particular orifice at a specific location, rotated it, and translated it in the direction of motion. An entire nozzle was modeled simply by locating several orifices and incorporating both types of motion. Designing a non-rotating nozzle was easily done by not including the rotational motion in the nozzle model. Two nozzles were designed using this method. Both have 16 orifices and can strip with a 2 inch stripping width. The impact energy distribution for both nozzles is shown in Figure 6.

One of the nozzles was fabricated so that all orifices are on one face and aim directly at the surface to be stripped. The other nozzle is in the shape of a cylinder, with the orifices located in 4 columns around the cylinder. This nozzle is designed to be rotated about the center; however, this rotation is not included in the model because in relationship to a point on the surface, the orifices are not moving in rotation, but in translation. The nozzles are both designed with the same size orifices; however, the location of the orifices is very important to achieve the best overall impact energy distribution

Initial work with these nozzles has been done; however, no in-depth evalations have yet been carried out. Although the nozzles perform as predicted by the model, they show a higher energy intensity than modeled, and are not quite as evenly distributed as predicted. The explanation for this may be that machining differences and orifice wear can give a slightly different orientation to an orifice, and this will affect the overall energy distribution. This type of phenomena is less noticeable with a flat rotating nozzle because every area being stripped with a rotating nozzle is being processed by many orifices. With the non-rotating types of nozzles, a particular area is only being stripped by one orifice, and if this orifice is not exactly on target, the area will not be processed at all.

Both of the non-rotating nozzles can be used to process vertical surfaces. The non-rotating nozzle with all orifices on the same face also allows processing of blind corners. Water can be supplied to this nozzle through any type of tubing configuration. The only process requirement is that the nozzle must be parallel to the final surface. Nozzles where rotation must be supplied require a straight shaft for rotation, and are significantly limited for non-line of sight work. Work continues to evaluate the non-rotating nozzles and defining exact fabrication and processing techniques to use these nozzles to their best advantage.

One other nozzle has been modelled and fabricated for use in stripping vertical surfaces. This nozzle has 8 orifices placed on one face. It is designed to oscillate along its major axis. The oscillation gives an extra degree of movement that is perpendicular to the movement of the nozzle itself. The oscillating nozzle was computer modelled with a different program than the flat rotating nozzles. In this program, the nozzle motion was modelled by defining a cam length and sinusoidal motion amplitude. These variables define the speed and type of motion profile that the nozzle face will be undergoing during processing. Again, the size and location of the orifices was optimized to produce the best energy profile for this oscillating nozzle. The profile for this nozzle is shown in Figure 8. No stripping work has been done with this nozzle. Since this nozzle oscillates, designs for a vibration mechanism is required and are currently being developed.

Curved areas of a substrate, as in Figure 8, provide a different problem for flat rotating nozzles. Standoff can vary significantly over the width of the nozzle, and this can significantly affect stripping capability. A nozzle was designed which would process such a curved area in a more even pattern, while achieving similar rates. This spherical shaped nozzle was not based on the rotating model as before. Mathematical calculations were used to determine the best location of each orifice in relation to the other orifices, the angle of incidence of each orifice, and the size of the orifice.

Work with this nozzle has been very successful. Corners with definite curvature have been evenly stripped of paint, and work continues in using this nozzle for curved configurations of engine parts. One item to note with this nozzle is that the orifice sizes will vary depending on the curvature of the part being processed. Parts with larger curvature require less variation in orifice size in the nozzle layout, while parts with smaller curvature required a greater variety of sizes be used. At this time, this change in layout has not been computer modelled, and trial and error work has been conducted to optimize the orifice sizes in the nozzle. Waterjet Systems is continuing to model this nozzle and define its configuration based on the surface it is being used to strip.

Applications

Pratt and Whitney Waterjet Systems used many of these nozzles for coating removal in both its Engine ARMS™ and Aircraft ARMS™ systems. Both systems are automated systems. Robotic control is used to position the nozzles for stripping, and to control all process parameters. For applications such as paint removal from aircraft and coating removal from aircraft engine components, this type of automation is required to yield the best coating removal performance.

These systems are also used to remove personnel from a dangerous high pressure water environment.

The nozzle technology discussed in this paper is also applicable to alternate methods of waterjet processing. Watejet Systems is currently involved in evaluating a semi-automated process for the US Navy, in which a high lift will be used with an X-Y positioner to strip the sides of Navy ships. For this application, a manual high lift will be used to place the X-Y positioner, which is in control of motion for the nozzle and stripping end effector.

Manual and semi-automated processed can also benefit from the nozzle design technology. Processes which can use more robust parameters (i.e. standoff distance is not critical) will also benefit from a more even stripping distirbution in a nozzle. Operations for processing vertical surfaces or blind corners could also benefit from nozzles designed specifically for such tasks. Positioning of such nozzles manually should be much simpler than positioning a normal rotating nozzle. Nozzles could also be designed quickly for specific applications.

Conclusion

Pratt and Whitney Waterjet Systems continues to evaluate a variety of nozzle designs for use on complex shapes parts. Nozzles for stripping vertical surfaces efficiently and quickly have already been designed, and work is ongoing to improve their energy profile. A spherical nozzle has been designed for used on curved surfaces, and this nozzle allows orifice changes to be made depending on the actual surface being stripped.

Improvements are also being made in the rotating nozzles to improve jet coherency and energy. The combination of improvements in nozzle design and jet impact energy will increase stripping capabilities for many applications.

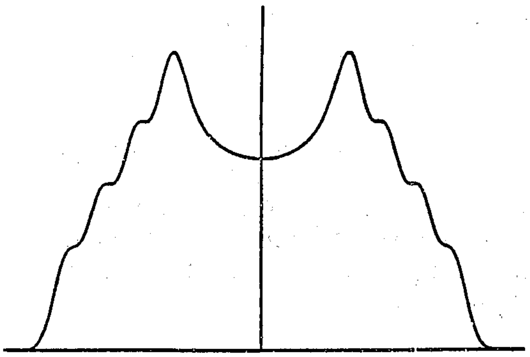


Figure 1. Energy Distribution for Commercial Nozzle

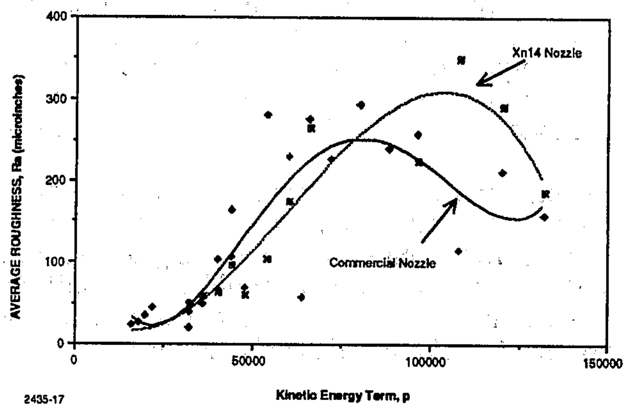


Figure 3: Nozzle comparison for Kinetic energy term vs roughness Commercial and and Xn14 nozzles

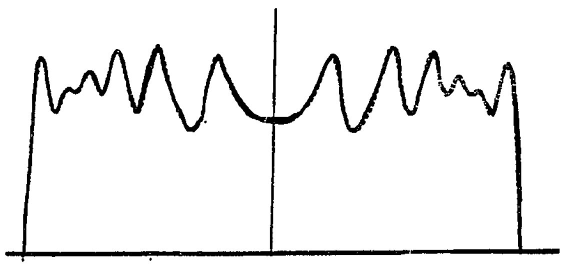


Figure 2. Energy Distribution for Xn Nozzle

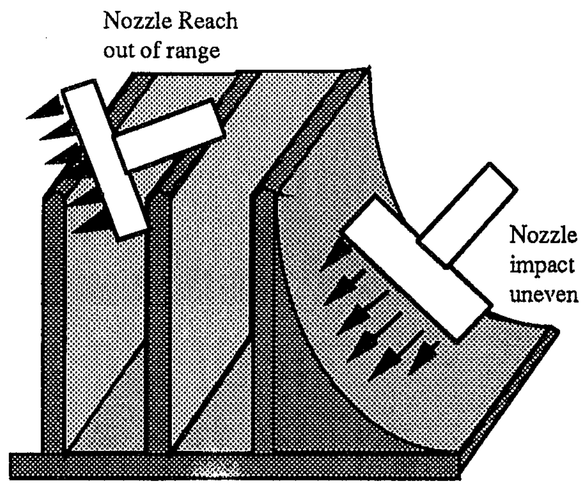
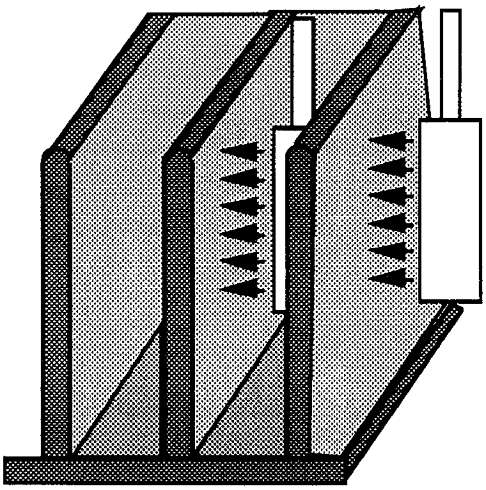
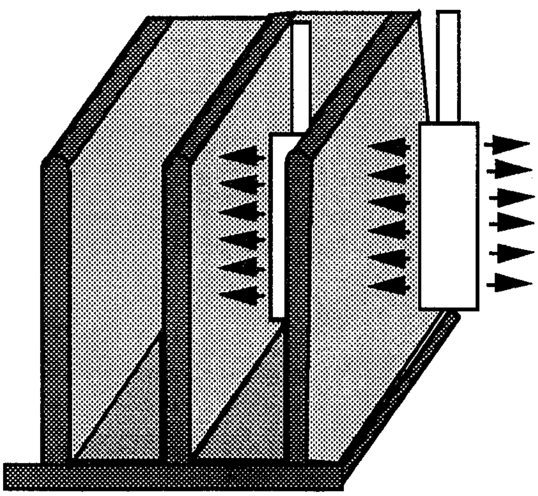


Figure 4. Complex geometry limitations for flat rotating nozzles



Non-Rotating Nozzle
Processes One Direction Only



Cylindrical Nozzle can
process two vertical
surfaces/channels

Figure 5. Vertical surfaces for Non-rotating nozzles

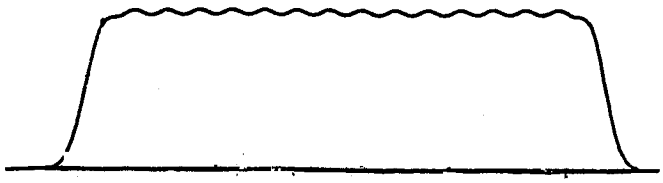


Figure 6. Impact energy distribution for non-rotating nozzles.

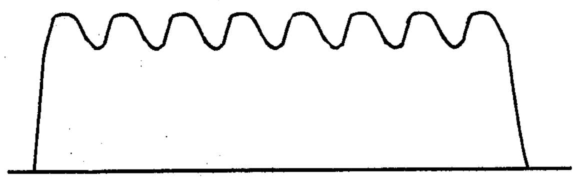


Figure 7. Oscillating nozzle energy distribution

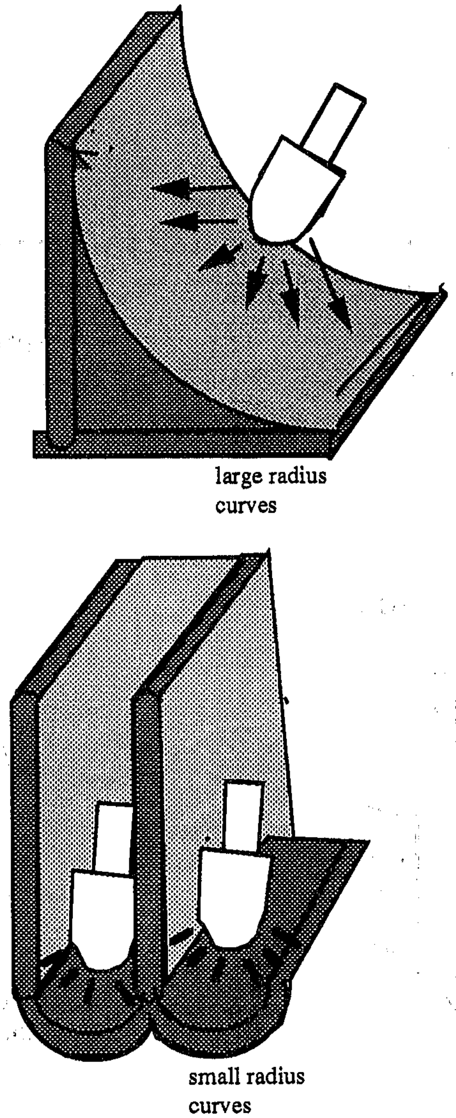


Figure 8. Processing curved surfaces with spherical nozzle

7th American Water Jet Conference
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Paper **44**

ADVANCES IN CLEANING AND COATING REMOVAL USING ULTRA-HIGH PRESSURE WATER JET TECHNOLOGY

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ABSTRACT

This report offers a comprehensive review of current and future projects utilizing waterjets operating at pressures of 36,000 to 60,000 psi for cleaning and coating removal. Applications discussed range from the removal of thermally sprayed coatings from jet engine components including titanium and aluminum substrates, to the paint removal of aircraft external surfaces. Other areas presented include the beneficial impact that higher pressures have on the automotive industry in terms of product quality, and complete recirculation of the low volumes of water.

An overview of the current generation of pumping equipment, nozzle designs, associated hardware and motion control systems will be presented for automated ultra-pressure waterjet systems.

Organized and Sponsored by the Water Jet Technology Association.

1.0 INTRODUCTION

In the last decade we have seen the wide spread development of pumping systems capable of generating increasingly higher water pressures. Several manufacturers market pumps that are able to reliably produce water pressures over 36,000 psi and as high as 60,000 psi. With the intensifier pump technology well established, we are seeing the focus shift to waterjet cleaning being integrated into production settings. This paper will examine several of these waterjet applications and the parameters to be considered in selecting a waterjet system.

One major market for waterjet cleaning and coating removal is in the automotive industry for the periodic cleaning of painting fixtures. In many cases, contractors using hand held waterjet tools performed this work on an "as needed" basis. These independent contractors typically come into an automotive painting facility on a regular schedule to remove accumulated material build-up. This usually involves moving multiple portable pumps to the job site prior to a complete plant shut-down. The majority of contractors use either intensifier or plunger pump units powered by diesel engines when working in this environment. (Figure 1) While these units are extremely portable, the use of diesel or gas engines restricts their operation to areas accessible from outside. Another requirement is the rigging of temporary water supply and discharge lines. Additionally, the requirements to contain and process the water used in the cleaning operation are increasing.

While the contractor type of operation will continue to be widely used in certain industries, the trend is to take a more integrated approach to facility maintenance. Almost every manufacturing facility is being asked to operate with fewer and fewer major shut-downs and to stream-line their operations. We have also seen the increase in demand to improve quality and decrease waste in all industries.

2.0 APPLICATION REVIEW

Today, many plants are installing and operating their own waterjet cleaning facilities. They are typically automated facilities using robots to maneuver the waterjets and are equipped with all needed services, including water reclamation systems. These water systems provide water of sufficient quality to be returned through the pump unit, forming a closed-loop system. By selecting an automated in-line system, the process equipment can be cleaned on every cycle. This reduces the risk that accumulated material build-up will interfere with the manufacturing process. Instead of using periodic shut-downs to remove heavy material deposits, a routine cleaning on a continuous basis removes light over spray.

The first installation we will look at is a dedicated system used to remove paint build-up from the carriers used to transport truck body components through an automated painting facility. In the past, this manufacturer used outside waterjet contractors to perform the cleaning operation on a quarterly basis resulting in the total shut-down of the facility for several days. The decision to incorporate an on-line cleaning system was based on several factors. One being that the paint build-up became too great between cleaning intervals and resulted in poor part registration. (Figure 2) The heavy build-up was also found to be a contributor to finished part imperfections as a result of peeling and flaking of the paint over spray. By adopting a preventative stripping procedure, the opportunity for this type of failure was eliminated. In addition to these considerations, there was a need to reduce their wast water stream.

An electrically driven intensifier pump was installed in a central pump room to provide high pressure water to two rotary stripping heads, mounted on pedestal robots. (Figure 3) The pump selected delivers four gallons of water per minute at 36,000 psi. The pressurized water is delivered via stainless steel lines to each cleaning bay. Inside the work area, the hydraulically powered rotary nozzles are connected to the high pressure lines with flexible hoses. The rotary tool uses nozzles equipped with four jeweled orifices arranged symmetrically around the nozzle face centerline.

The key to achieving high carrier stripping output rates lies in the combination of high pressure, low water volume and most importantly the waterjet stream coherency resulting from advanced nozzle design practice. Since the carrier is constructed of heavy section steel weldments and resists the erosive effects of the waterjet, a very aggressive nozzle design was selected. The design selected stressed stream coherency above all other criteria. The cross-section clearly shows the straight path to the orifices free of turbulence which would create changes in water direction. (Figure 4) These features and the use of an integral small attenuator chamber, located above the orifice, improve stream quality and deliver maximum stripping energy at minimum flow rates.

The use of waterjets for coating removal has recently expanded beyond traditional applications such as automobile paint carrier cleaning to the refurbishment of jet aircraft components. In this new process, coatings designed to provide thermal or wear resistant properties are removed prior to repair using ultrapressure waterjets. This application involves integrating the waterjet pump technology that was developed for material cutting with robots.

The coatings used to protect expensive aircraft engine components from heat and wear have always presented removal challenges to the operators of jet aircraft fleets. In order to examine the progress made in this field, it is necessary to review the existing methods and significant challenges waterjets were faced with.

Past removal methods involved prolonged part immersion in chemical baths combined with extensive hand grit blasting. While the chemical baths were effective and needed little operator involvement, they required upwards of twenty four hours to produce a partially stripped part. To produce a part suitable for recoating, each part had to be hand inspected and manually grit blasted. One of the other drawbacks, was the risk of base material removal resulting in further repair or a scrap piece. Another problem faced by the operators of these facilities was the need to dedicate valuable floor space to a toxic and hazardous process. (Figure 5) With the increasing emphasis on the environment and employee health, it was becoming prohibitively expensive to maintain the operations. The combination of environmental regulations and the need to stream-line expensive overhaul procedures triggered the exploration of alternative coating removal methods.

As with most industries, the aircraft manufacturers and operators gained experience with the use of high pressure water as a maintenance and cleaning tool in many areas of their operations. The fabrication equipment associated with composite and super-alloy components in aircraft include ultra-pressure waterjets. The pump technology developed for part fabrication provided the increased water pressures required to remove these tough coatings. Early work done in component coating removal combined the low-flow rate intensifier pumps with simple fixtures. These first systems typically used water flow rates under one gallon per minute and output pressures of 45,000 to 50,000 psi. Even with these limitations the results were very encouraging. It is feasible to remove thermally sprayed coatings from numerous substrates without damaging the base material.

Today's systems have incorporated numerous process refinements while giving users greater flexibility in the variety of parts, materials and coatings that can be processed in the same work cell. One of the first requirements to be addressed in the design of these new systems was the use of articulated arm robots to manipulate the waterjet. By returning to the automotive industry, waterjet system manufacturers were able to select highly accurate robots that had proven themselves to be durable and flexible in waterjet paint carrier cleaning operations. (Figure 6)

By using a readily available pedestal robot, the need for limited production gantries was eliminated. The ability of a robotic arm to simultaneously move in 6 axes gives the system access to almost any part. Since most of the components found in a jet engine are cylindrical, many systems include a rotary table located adjacent to the robot. Depending on the type of the robot-control selected, it is typical to see the robot control both the robot arm and the rotary table functions as part of a coordinated part processing program.

In the system described, a host computer controls the movements of the piece part and the robot arm along with regulating the operation of the intensifier pump. As with the other components in this system, numerous advances have been made in the field of ultra-high pressure pump technology. Among the advances are the significant increase in output performance and control sophistication. The pump used today has output capacity of 3 gpm while maintaining 55,000 psi continuous output pressure. This increase in output pressure and volume translates into reduced part processing times along with the ability to remove even the toughest coating. Another significant advance has been made in the use of micro-processors for the control of the intensifier pump functions. In this instance, the pump uses a GE FANUC programmable logic control (PLC) to regulate and monitor critical pump parameters. By using compatible robot and pump computer controls, the individual components can be linked together to ensure closed loop process control. A typical system uses process data generated and approved by the engine manufacturer to control all aspects of the motion system plus the pressure and flow rate of the pump unit. Another benefit of the information exchange is the assurance that any fault experienced at either the robot or the pump will shutdown the system without part damage. Operator safety is also greatly enhanced through the interlocking of access doors with the host computer. Any unauthorized entry into the work cell or program fault results in the complete shutdown of the system and the evacuation of all high pressure fluids through an integrated bleed-down valve. (Figure 7)

The last and probably most critical area of advancement in the development of waterjet stripping systems is in the area of nozzle design. Now that higher pressures and flow rates from the pumps are possible, the attention has shifted to delivering the maximum stripping energy to the part without causing base material damage. A unique computer modeling program developed by the Waterjet Systems, Inc. Division of Pratt and Whitney, has led to the development of nozzles capable of removing thermally sprayed coatings from aluminum engine components without substrate damage. (Figure 8) In order to produce these results, it is mandatory that a variety of conditions are met. Among the factors critical to maximizing waterjet stripping energy, is the ability to deliver the pressurized water to the orifices as efficiently as possible. By minimizing the length and complexity of the plumbing, the majority of the pump's output can be utilized. In most cases, the nozzles themselves are rotated at a programmed speed requiring particular attention to be paid to the size and location of the swivel joint. (Figure 9)

Once proper delivery of the pressurized water to the nozzle is established, it is possible to apply the nozzle optimization software program. By defining the material to be removed, the width of the stripping path and the type of base material, the program selects and locates the appropriate orifices in the nozzle. Depending on the parameters to be met, the number and size of the individual orifices will be customized to generate either an aggressive or gentle stripping action.

The knowledge gained in the development and implantation of the system will ultimately expand the use of waterjet cleaning and coating removal beyond the automotive and aircraft industries.

3.0 REFERENCES

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7th American Water Jet Conference
August 28-31, 1993: Seattle, Washington

Paper 45

THE LARGE AIRCRAFT ROBOTIC PAINT STRIPPING (LARPS) SYSTEM

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ABSTRACT

The Large Aircraft Robotic Paint Stripping (LARPS) system effort, USAF contract F33615-91-C-5708, is well underway. This paper presents program progress to date, current program status, and where the program is headed. This system will replace current chemical paint stripping of aircraft with the automated, stand-alone, high pressure water process. Emphasis is placed on complete system automation, process control, and process/robotics integration.

This MANTECH program, which began Phase I in July 1991, is currently in the fabrication and integration task of Phase II. The LARPS system utilizes a 9 degree of freedom robot to remove paint from C-135 and B-1 aircraft, while providing the capability to strip almost all other aircraft in the DOD and commercial inventories. The mobile robot itself is over 30 feet (9.22 meters) tall, with a 28 foot (8.53 meter) horizontal reach and a work envelope as large as the aircraft hangar it will be installed in. The system is to be operational, and Phase III complete, by early 1995. The system is targeted for the Oklahoma City Air Logistics Center.

Goals of the LARPS program include reducing manhours, reducing cycle time and, most importantly, protecting our environment by reducing chemical paint remover usage and hazardous waste by 90 percent.

This program is managed by the USAF's Wright Laboratory Manufacturing Technology Directorate and the Aircraft Division of the Oklahoma City Air Logistics Center. United Technologies Corporation's WaterJet Systems, Inc. subsidiary of Pratt & Whitney is the prime contractor.

THE LARPS SYSTEM

Although methylene chloride based chemical strippers are the most widely used in the aircraft industry (including military depot maintenance activities), the strippers will soon be a thing of the past. At the Oklahoma City Air Logistics Center, environmental programs dictate that methylene chloride use be halved by 1995 and eliminated by the year 2000. In conjunction with the Wright Laboratory Manufacturing Technology Directorate (Wright-Patterson Air Force Base, Ohio) a MANTECH program was developed to demonstrate the automation of an alternative method of removing paint to aid in meeting these environmental goals.

PROGRAM REQUIREMENTS

Program requirements include:
— Reducing hazardous waste by 90%
— Achieving an availability of 85% while seeking to achieve 95%
— Maintaining aircraft surface quality

Program goals include:
— Reducing organic coating removal flow time by 50% over present flow times
— Reducing labor hours by 50%

OC-ALC currently performs paint removal operations as part of their programmed depot maintenance (PDM) activities on Boeing B-52, C-135 series, E-3 and the Rockwell B-1.

Where does the LARPS system stand against these requirements and goals? No hazardous waste will be generated by the LARPS system. The limited amount of water left after repeated recirculation is considered regulated waste water by state and federal agencies. Paint chips are disposed of without containing residual chemical strippers. Rather than 85%, the system is being designed for 95% availability.

Surface integrity is being maintained through months of testing and process parameter setting associated with the high pressure water process. The results of testing on metals have been thoroughly documented (Stone, 1993) with successful conclusions to each test. Composite testing is currently underway with similar results expected for selective stripping. A stripping quality sensor is also incorporated into the system for process control.

Current cycle times can be met using a four inch nozzle (Stone, 1992) with the one robot configuration currently in fabrication. Two robots with the existing nozzle will reduce the overall cycle time by approximately 40%. It is projected that a six inch nozzle will replace the four inch nozzle in either scenario, further reducing cycle time. The one robot system will reduce labor hours approximately 43% with most of the savings coming from masking and demasking manhours.

CURRENT OPERATIONS

Aircraft are currently stripped in Bays I and III of Building 2122 at the OC-ALC (the hangar targeted for LARPS is Tinker AFB's Building 3105). The steps associated with the current process have been fully documented previously (Hofacker, 1992). All direct costs associated with current chemical stripping operations at OC-ALC are approximately $3.0M annually.

Current cycle times for the B-52, C-135, E-3 and B-1 are 5, 5, 5, and 6 flow days respectively, including masking and demasking. Hazardous waste produced is grouped into three categories: solid hazardous waste, industrial rinse water and air emissions. Each of these must be reduced by 90% to meet program requirements.

The first component of the solid hazardous waste is sludge pulled from trench screens in Building 2122 (1500-3000 lbs per plane) and the second is a finer sludge pulled from settling basins (100,000 lbs per year). Neither of these make it to the waste treatment plant. The treatment facility handles waste from all of Tinker AFB.

Treatable water waste is the effluent sent from Building 2122 to the treatment plant. Fiscal year 1991 numbers were 6,170,000 gallons. VOCs emitted in Building 2122 during FY 1991 765,000 lbs. The VOC emissions are directly proportional to the amount of chemical stripper used on the aircraft.

PROGRAM ACCOMPLISHMENTS TO DATE

The LARPS program is divided into three phases. Each phase is subdivided into tasks as follows:

Phase I
— Task 1, Requirements Definition and Needs Analysis
— Task 2, Viability Test Plan
— Task 3, Process Optimization/Validation
— Task 4, Scoping Document
— Task 5, Preliminary Design
— Task 6, Detailed Design
— Task 7, Technical Order Review
— Task 8, Test and Training Planning
— Task 9, Benefits Analysis - Preliminary
— Task 10, Phase I Review

Phase II
— Task 1, Fabrication
— Task 2, OC-ALC Personnel Training Plan
— Task 3, Validation
— Task 4, Technical Orders Conference
— Task 5, Phase II Review

Phase III
— Task 1, Installation
— Task 2, Verification Test Planning
— Task 3, Performance of Verification Testing
— Task 4, OC-ALC Personnel Training
— Task 5, Operator and Maintenance Instructions
— Task 6, Operator Training Instructions
— Task 7, Technology Transfer
— Task 8, Benefits Tracking
— Task 9, Technical Achievements Documentation

Phase I activities are essentially complete. Tasks 1, 2 and 9 were completed soon after the program began, with addendums to the Contract Data Requirements (CDRLs) submitted when necessary. A Preliminary Design Review was held in April 1992 and a Detailed Design Review (DDR) in November 1992. The metals testing portion of Task 3 is complete with composite testing now underway. Smaller tasks such as 4, 7 and 8 are now nearing completion.

Phase II began with the end of the successful DDR. The system is currently in fabrication with a projected robot subsystem integration completion date of March 1994 with a USAF validation test date in late July 1994.

Phase III installation is currently scheduled to begin in late August 1994 with the activated system turned over to the USAF in spring of 1995. It should be noted that a contract modification has been proposed to move the activation date to winter 1994-95 by combining the Validation and Verification tests at OC-ALC. Site preparation is also included in this change.

Two additional contract changes are also in work. One is to demonstrate high pressure water coatings removal in a naval shipyard. This is a joint initiative with the US Navy. The other is to produce an Aircraft Component Subsystem (ACS) for OC-ALC. The ACS will provide automated high pressure water coatings removal on smaller components that are removed from the aircraft during stripping. Examples of these components are bomb bay doors, landing gear doors engine cowls, ailerons and flaps.

LARPS SYSTEM DESCRIPTION

The system consists of a robot subsystem, a computer subsystem, a sensor subsystem, a guidance subsystem, a paint removal subsystem and facility subsystem as shown in Figure 1.

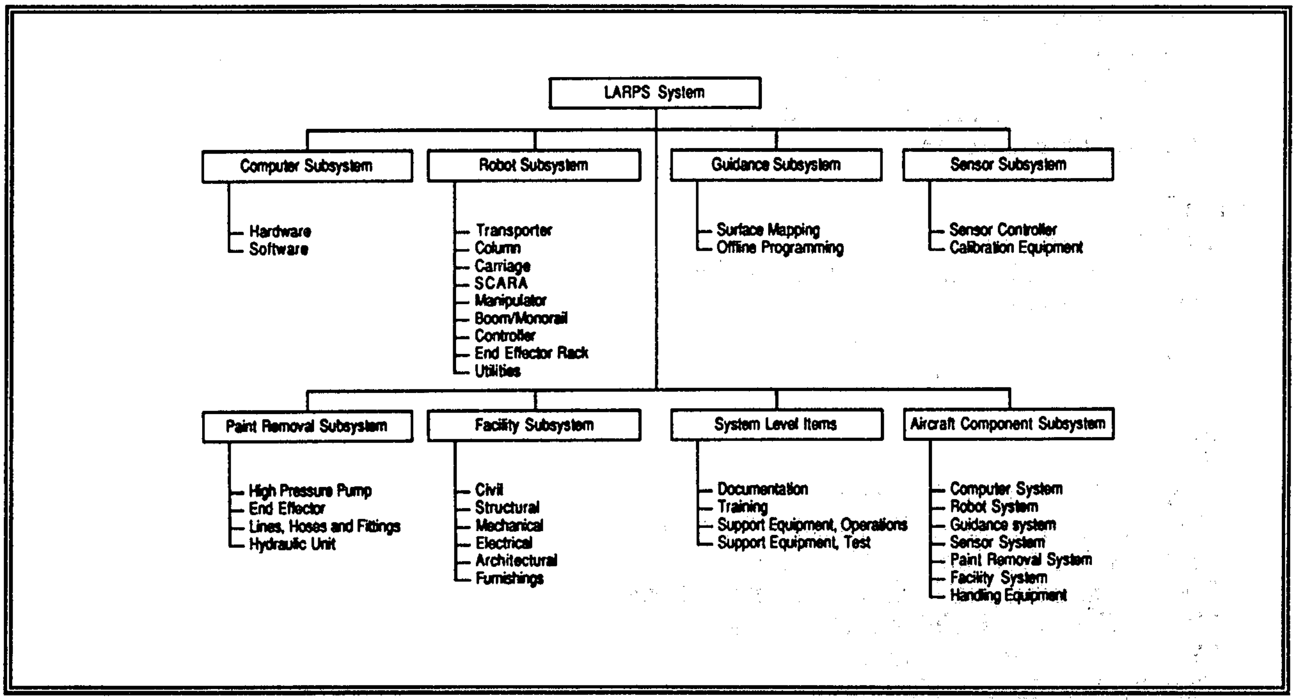

Figure 1 - System Elements

ROBOT SUBSYSTEM DESCRIPTION

The robot subsystem consists of a pedestal manipulator mounted to a SCARA (originally termed as a "selective compliant assembly robot arm"). The SCARA moves vertically on rails mounted to the column. The column rotates on a turntable mounted on the deck of the transporter. The transporter moves the robot subsystem from location to location following guidewires. Each aircraft requires multiple stop points around it to provide complete coverage. Utilities and communication lines are fed to the robot through an overhead boom, which travels along a suspended monorail. Selected specifications for the robot subsystem are shown in Table 1.

Table 1 - Selected Robot Subsystem Specifications

• Column Height	30-1/4 feet (9.22 meters)
• Transporter Width	10 feet (3.05 meters)
• Transporter Length	23-1/2 feet (7.16 meters)
• Total Weight	60,000 lbs (27,200 kg)
• Horizontal Reach* ** measured at the faceplate*	28 feet (8.53 meters)
• Vertical Reach* ** measured at the faceplate*	0 feet minimum, 29 feet maximum (8.84 meters)
• Payload	75 lbs mass (34 kg), 50 lbs backthrust (23 kg)
• Maximum TCP	24 inches/second (61 cm/sec)
• Repeatability	±0.25 inches (0.64 cm), 3 @ 2 inches/second (5 cm/sec)
• Degrees of Freedom **measured at the faceplate*	9 servo controlled

A right hand side view of the robot subsystem is shown in Figure 2. The end effector racks are visible on the rear side of the column. Up to four end effectors can be stored in these racks. Utilities are fed over the utility boom through a slip ring assembly and through a cable tray on the column. Access to the upper and lower chambers of the column are also provided on the right hand side. Racks and rails run the vertical length of the front of the column.

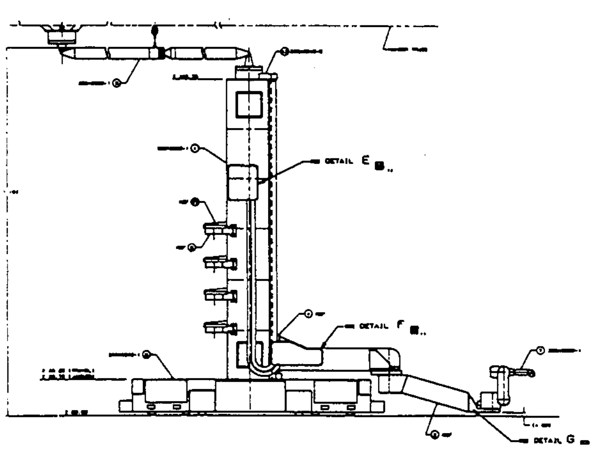

Figure 2 - Right Hand Side View

The left hand side of the robot subsystem (Figure 3) provides access to the upper chamber where electrical junction boxes and other connections are made, to the second chamber where the nozzle rotation hydraulic unit is located, to the third chamber where the process controller is located, and the fourth and the fifth chambers where the robot controller is housed. The sixth chamber, at the bottom of the column contains connections to the transporter and base rotation drive motors.

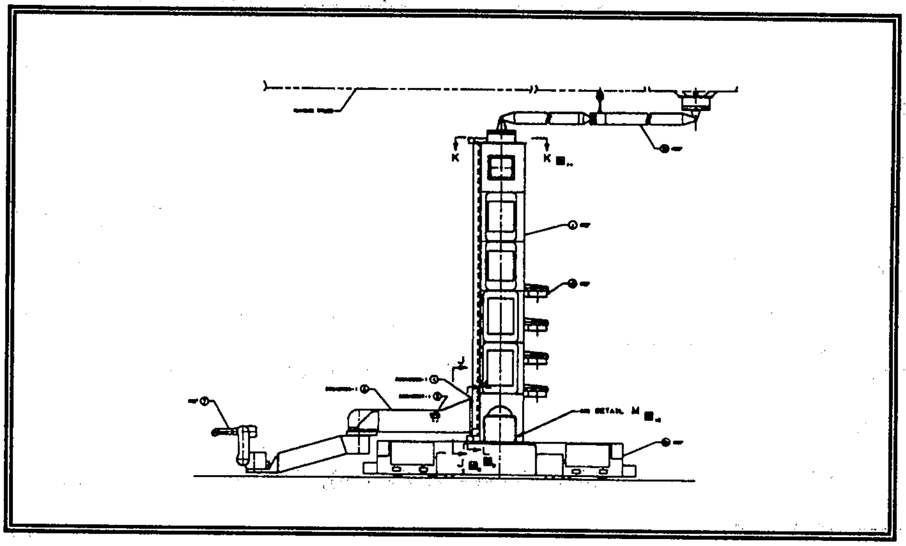

Figure 3 - Left Hand Side View

A plan view of the system in the stowed position is shown in Figure 4. The transporter can stow in any of the four quadrants. This allows optimum flexibility in movement from stop position to stop position and through limited clearance areas between the aircraft and facility. This is one example of where stringent facility requirements (due to using an older, existing facility) have driven a more flexible and "streamlined" design.

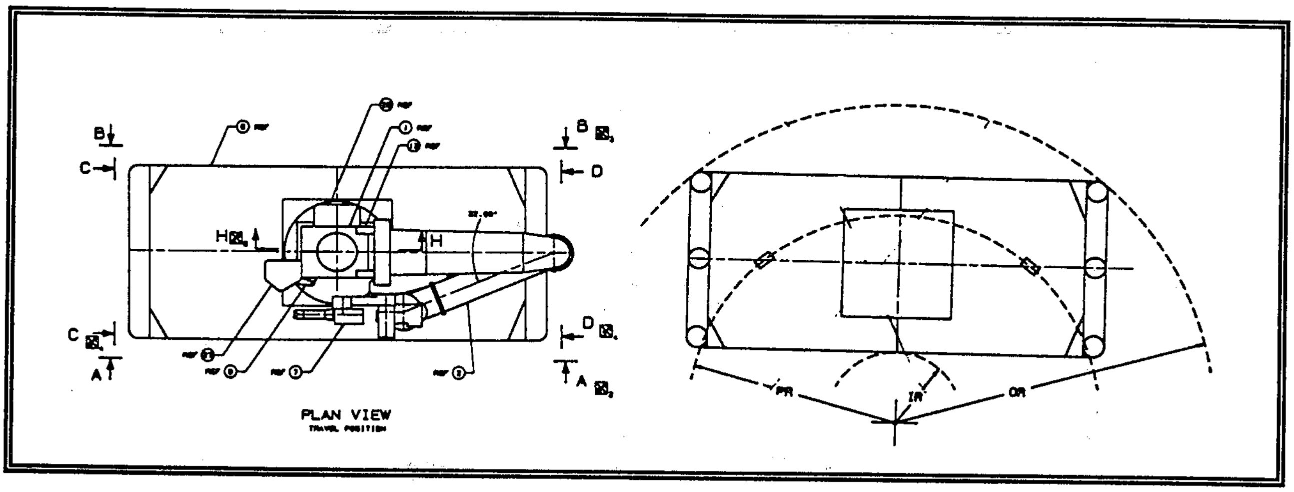

Figure 4 - Plan View

The overhead utility boom is shown in Figure 5. All utilities coming from the equipment room to the robot subsystem, and other robot subsystem mounted items, travel over this boom. The boom is supported at three points, the facility center swivel, the monorail attach point and the top of the column. The boom is not a controlled degree of freedom, but acts as a slave, following the robot subsystem from stop position to stop position.

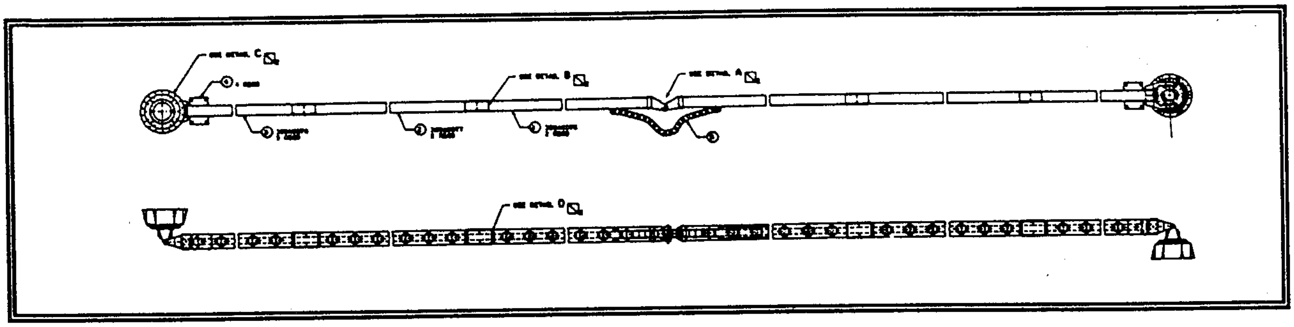

Figure 5 - Utility Boom

The column rotates on a turntable bearing located on the transporter as shown in Figure 6. This bearing is nearly six feet in diameter and supports the approximately 29,000 lbs on it at a rotation speed of up to 3 rpm. The gear is driven by two drive motors. Note also in the figure the lifting cylinders/pads supporting the robot subsystem during processing.

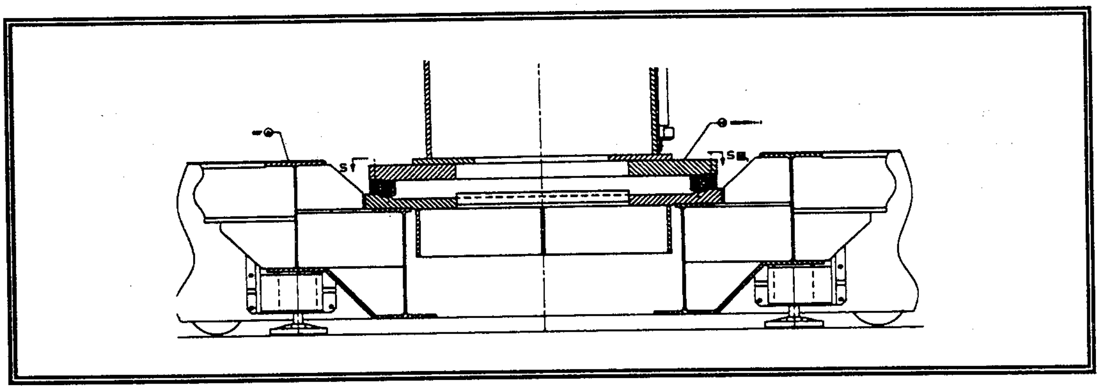

Figure 6 - Column Base Rotation

A carriage moves the SCARA up and down the front of the column. This carriage, shown in Figure 7, is also driven by two drive motors along the dual sided rack. Linear bearing rails serve to guide the carriage during movement.

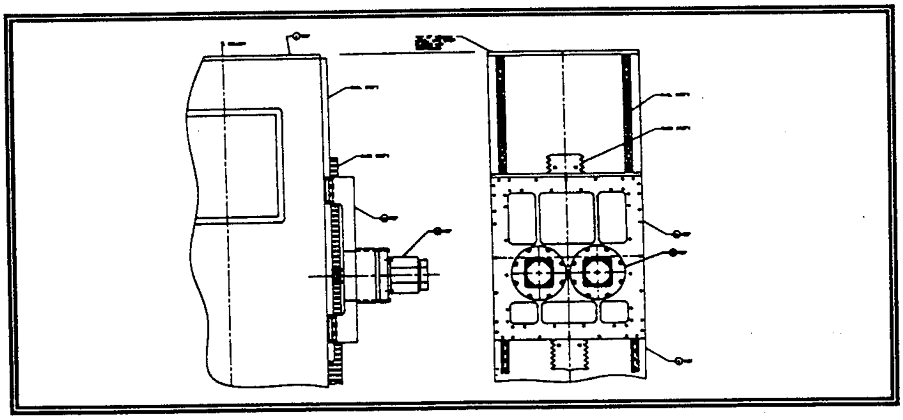

Figure 7 - Carriage

The SCARA (Figure 8) is mounted to the carriage and supports the manipulator. The SCARA has a degree of freedom at its center joint, a turntable bearing again driven by two drives. Utilities and services run from the cable carrier into the SCARA near the carriage and then travel through the SCARA to the manipulator.

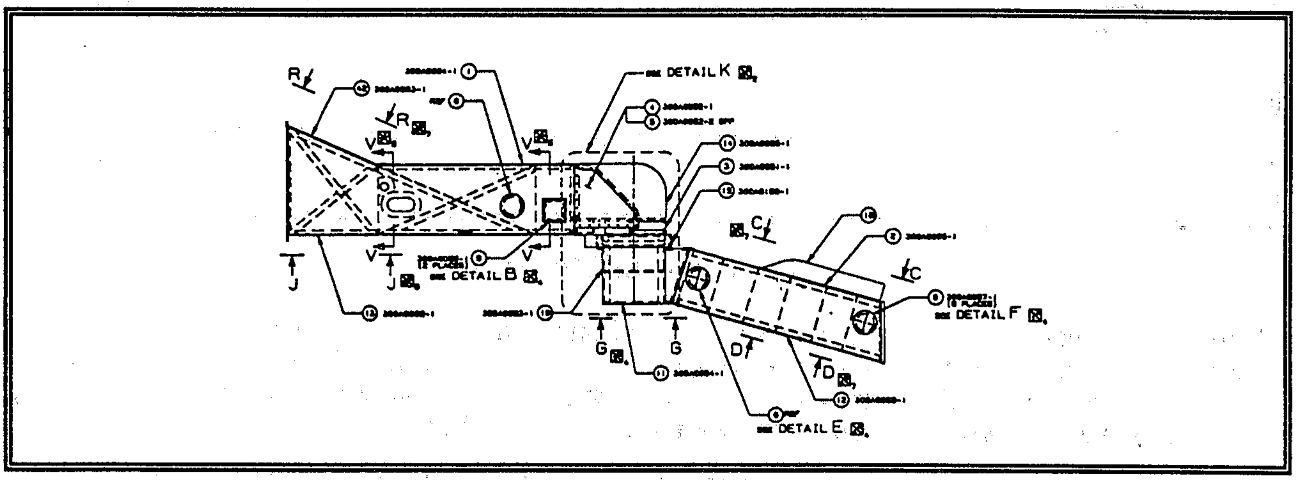

Figure 8 - SCARA

The six degree of freedom manipulator is shown in Figure 9. It combines the best of the material handling and painting robot worlds—high payload and repeatability. The manipulator has the capability of reaching below its base, essential for working over aircraft wings and fuselage.

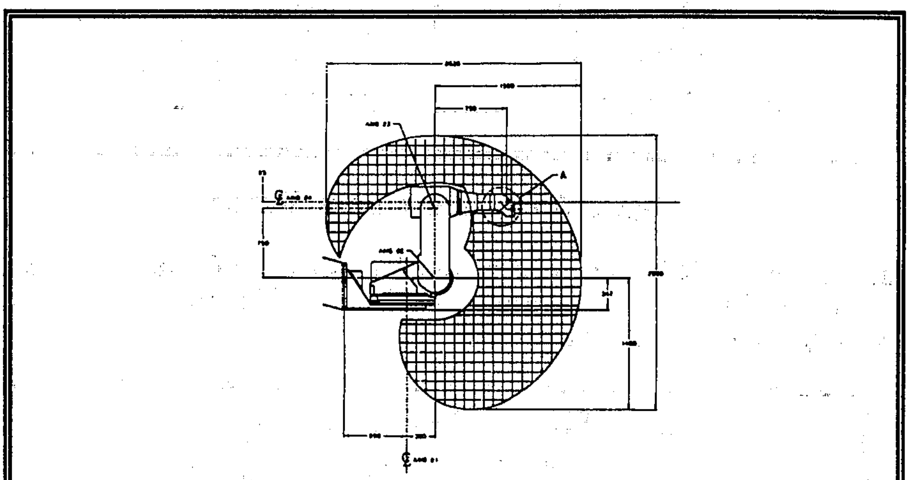

Figure 9 - Manipulator

END EFFECTORS

Mapping and paint removal end effectors are shown in Figure 10. Both mount to the robot faceplate through a quick change interface system. The mapping end effector consists of a laser contour sensor which returns a range measurement from a line equation produced by the intersection of the beam and the aircraft surface. Also mounted on the mapping end effector are color cameras. These are used to detect colored tape or other markings used to designate *exclusion* *zones*, areas which are not to be stripped and are eliminated from path planning. The mapping end effector, as well as the stripping end effector, are both surrounded by a soft collision device. This wire shade detects contact with the aircraft and puts the system in a hold mode.

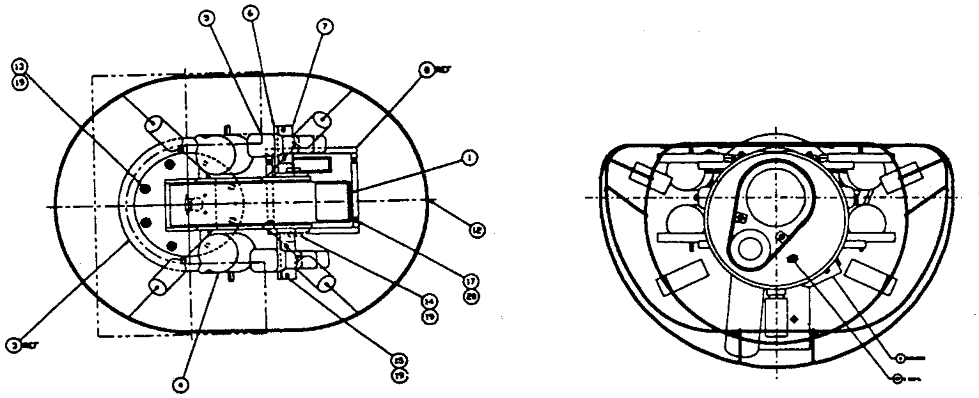

Figure 10 - End Effectors

The paint removal end effector consists of a high pressure water quick change, rotary swivel, housing and nozzle. Also mounted to the paint removal end effector is a pair of cameras and lights to provide information to the operator and process controller. A shroud surrounds the nozzle, redirecting the water plume from the cameras' line of sight.

PAINT REMOVAL SUBSYSTEM

The paint removal subsystem consists of two high pressure pumps. Only one pump is in use at any given time. Actual paint removal operations are 70% of the cycle time, however, requiring alternating between pumps to support system availability requirements. High pressure lines are routed from the equipment room approximately 350 feet to the end effector and nozzle. A combination of high pressure hard tubing and flexible line is used.

COMPUTER SUBSYSTEM

The computer subsystem includes the host computer, operator's station, access terminals and peripheral devices. The LARPS system operator will interface primarily through the operator's terminal. Most of the computer equipment will be located in operator's control room and adjacent computer room.

SENSOR SUBSYSTEM

The sensor subsystem includes the process controller, which receives input from the cameras mounted on the paint removal end effector and analyzes these for hue, saturation and intensity (HSI). This HSI data is then compared to a database of input and learned color to verify that optimal stripping is taking place. If, for example, a certain percentage of primer is being left behind, process parameters will be adjustable within the acceptable range to produce complete paint removal.

Also included in the sensor subsystem are collision avoidance sensors on the transporter (light beams, photoelectric and soft bumpers), column (light beams), and SCARA (light beams, wire shades).

GUIDANCE SUBSYSTEM

The guidance subsystem is comprised of three parts: (1) global location, (2) surface mapping and (3) path generation. At each stop position the relative location of the robot to the aircraft is established by locating 3-4 surface features. Surface mapping is then performed. Surface contour data received from the mapping end effector is routed through a board set on the process controller and back to the guidance processor. This surface is used to update the nominal path program in the aircraft database and create a new surface model of the aircraft in the hangar (this model is used on subsequent visits by the same aircraft to the LARPS hangar).

From this surface model, robot path programs are generated by zone (stop locations around the aircraft) and subzones (distinct smaller sections within each zone). Subzones can also denote exclusion zones such as windows or specially coated areas which may not require stripping.

FACILITY SUBSYSTEM

The facility subsystem consists of the modified facility, support areas, water recovery/reclamation system, monitoring cameras, door interlocks and warning lights. Modifications to the facility insure that requirements are met; requirements include:

— Floor levelness to within ±0.5 inch (±1.27 cm) over 10 feet (3.05 meters)
— Water recovery or industrial drainage system
— Overhead support for boom and monorail
— Temperature control of 60°F - 110°F (16°C - 43°C)
— 480 V, 3Ø, 360 A, 60 Hz for a single robot system and equipment
— Compressed air
— Door interlocks
— Camera and monitor system
— Ceiling clear height

AIRCRAFT COMPONENT SUBSYSTEM

The aircraft component subsystem (or ACS) will be used to remove paint from Maintenance Items Subject to Repair (MISTR) and regular PDM parts. The requirements definition task of LARPS indicated that approximately 285,000 square feet of these components were stripped in 1991. This is equivalent to 28 C-135s in total surface area. The largest part (of the approximately 160 identified) to be stripped in this workcell is the B-52 inboard flap at 31 feet 6 inches long by 8 feet 6 inches high. A computer model of the workcell is shown in Figure 11. The workcell area itself (not including the operator or equipment rooms) is approximately 20 feet by 50 feet. The system will be active in March 1994.

A trade study showed that these components should be stripped a by a separate, smaller subsystem of LARPS. The main component of this subsystem is a standard pedestal robot mounted to a servo-controlled track. This provides the work envelope for long parts. A turntable is also provided in the workcell for more cylindrical components. With the turntable and servo-controlled track integrated to the robot, the system has 8 degrees of freedom.

The same high pressure pump and similar end effector as the LARPS system will be used. Additionally, the robot controller and water recovery system are also compatible. Commonalty of components is emphasized.

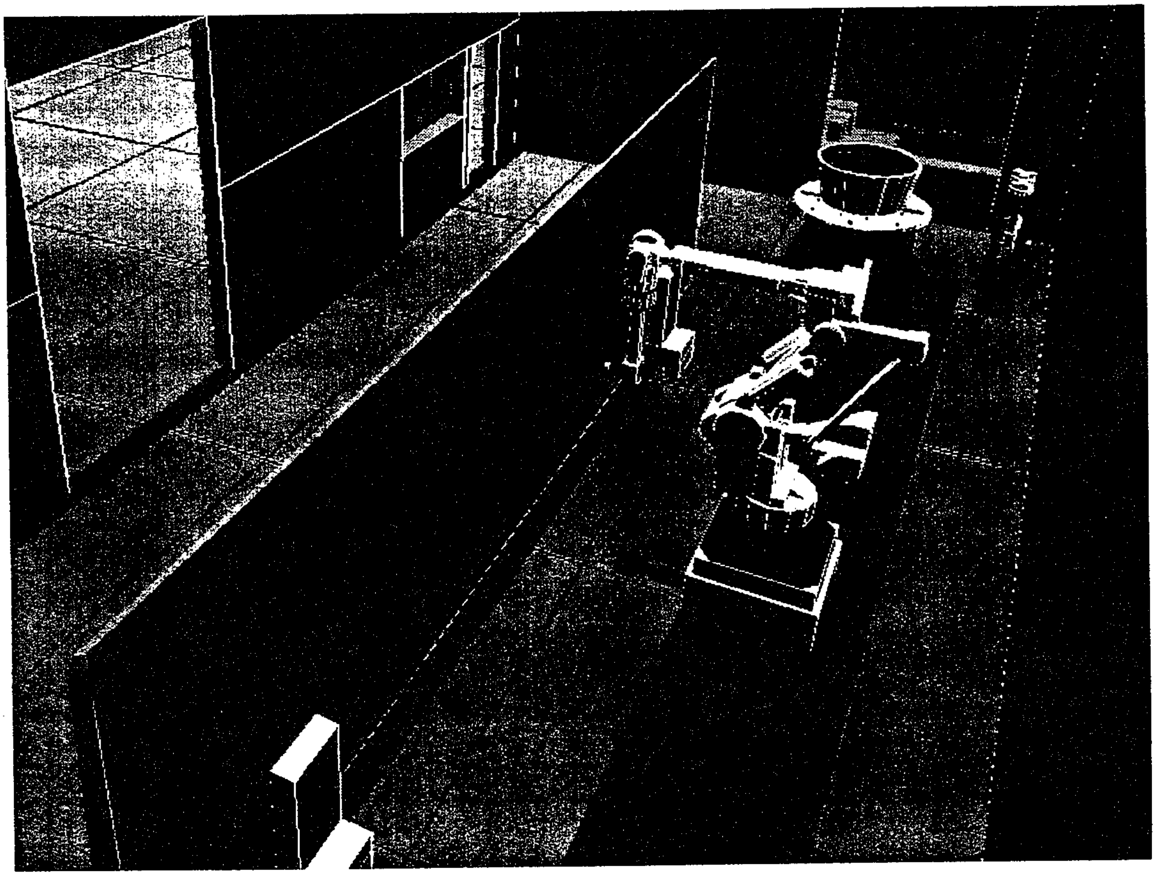

Figure 11 - ACS Layout

The operator room includes the operator interface and robot controller. The equipment room houses the pump, hydraulic unit, water reclamation system and chiller. Aircraft components will be fixtured in the cell on a cart. Fixturing will be flexible, accommodating each of the candidate parts. The cell is to be installed in Bay II of Building 2122 at the OC-ALC. The system will operate at the same process parameters as its parent LARPS system.

LARPS PROJECTED OPERATIONS

The LARPS system will be capable of accommodating each of the candidate aircraft. However, since the E-3 and B-52 do not fit into Building 3105, they will not be processed with the LARPS system at this time. Both will continue to be stripped in the same way as currently performed until such time that a new, larger facility for the LARPS system can be activated. Building 3105 is shown in Figure 12.

No changes will be required by the LARPS system in the configuration that the aircraft currently appear for paint removal (i.e., engines removed, etc.). A significant reduction in the number of masking hours is anticipated, however, based on a detailed benefits analysis.

The LARPS projected operational flow is shown in Figure 13. Preparation and masking activities will be performed, followed by system startup and transporter movement to the first stop location.

After reaching the first stop location, global location and surface mapping will occur. After completing mapping and paint removal at every stop location the transporter will be returned to its home position and the system will be shutdown.

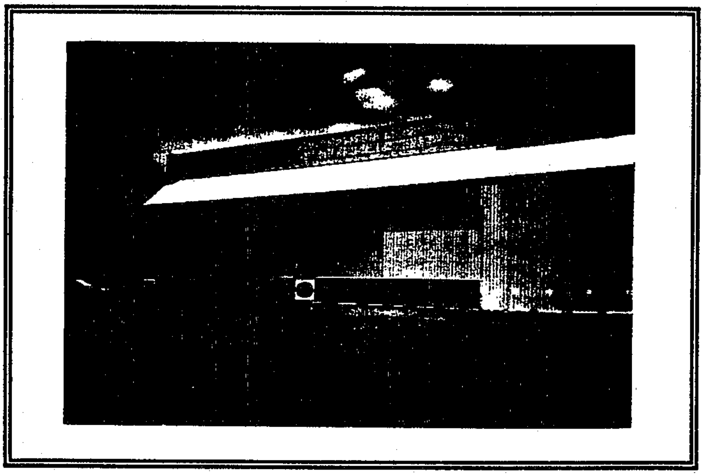

Figure 12 - Building 3105

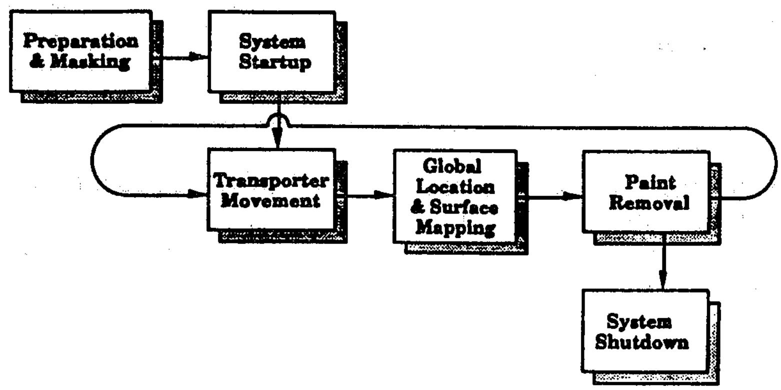

Figure 13 - LARPS Operational Flow

During preparation and masking, the aircraft will be parked in its required location within the workcell. The optimal location for the landing gear will be marked on the floor with rectangle representing the tire footprint.

After positioning the aircraft, limited masking will be performed for LARPS paint removal operations. A detailed review of the work control documents for each masking step was undertaken as part of the LARPS requirements definition and needs analysis task. For the C-135, it appears that only five masking operations will be required (15 labor hours). For the B-1B, it appears that approximately ten masking steps will be required for a total of 48-54 standard labor hours. These represent a 95% and 75% reduction in masking standard hours, respectively. Supports will be located at the wing tips to provide wing stability during processing.

The operator will be required to input information during system startup such as the aircraft tail number, aircraft type, paint type and stripping configuration. The bay will be clear of all personnel before the transporter moves to its first stop location.

During operations, the robot will move from stopping position to stopping position around the aircraft performing the surface mapping and paint removal operations each time. The projected floor layout is shown in Figure 14. The transporter will then level itself on leveling pads in the floor and then obtain the surface mapping end-effector. Depending on the complexity of the surface, fewer (or more), contour data points will be collected. The purpose of globally locating and mapping the surface of the aircraft is to:

— Account for variation in wing location and aircraft positioning
— Determine surface features that are not in the initial robot path programs
— Provide offsets to adjust robot path programs
— Accommodate overall variations between aircraft within a series

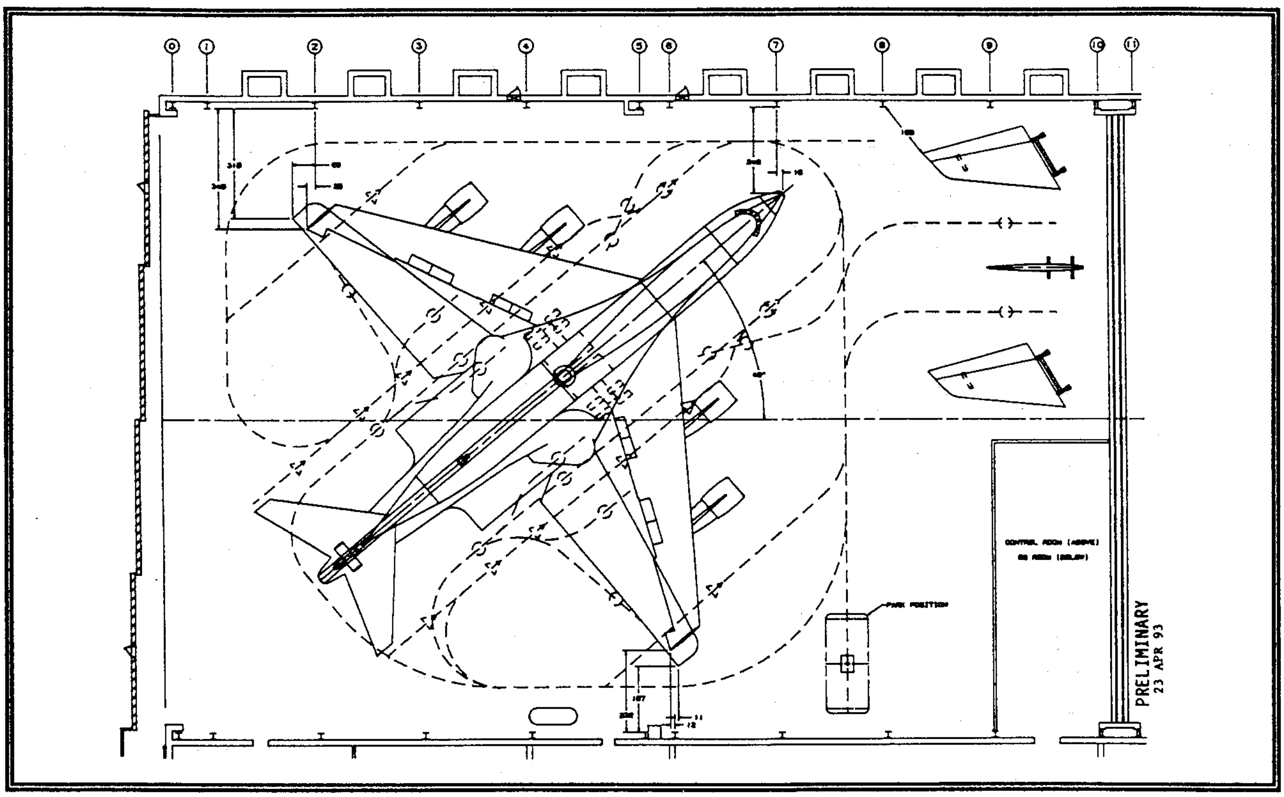

Figure 14 - Building 3105 LARPS Layout

After mapping, the end-effector will be placed back in the storage rack and the appropriate paint removal end-effector obtained. Following the updated robot path program, the end-effector will move across the surface of the aircraft, removing paint as it travels. During this time, the paint removal quality sensor will be actively monitoring the stripping process. Stripping rates are currently 80-160 square feet per hour with the four inch nozzle and projected at 120-240 square feet per hour with the six inch nozzle depending on which military paint system is being stripped.

During demasking and closeout, masking material previously applied will be removed. Any touch-up operations requiring chemical strippers will be conducted in Building 2122.

BENEFITS ANALYSIS

A 43% reduction in labor costs is projected for the LARPS system over current operations. If the E-3 and B-52 could be processed in the hangar, the reduction in labor costs would be approximately the same as the C-135, 43% on a per aircraft basis. The overall reduction in labor costs for OC-ALC would increase to 49%.

A 55% reduction in material costs is projected for the LARPS system over current operations. Processing the E-3 and B-52 would increase this reduction to 63%. A 90% reduction in waste quantities and costs is projected for the LARPS system. A 52% reduction in overall costs is projected for the LARPS system over current operations. If the E-3 and B-52 could be processed in Building 3105, the reduction in overall costs would increase to 60%.

Additional cost benefits will be realized in the areas of safety, health and costs of lost production (due to the loss of methylene chloride as a stripper, without an alternative with a comparable stripping time). These savings are projected as approximately $2.5M annually as shown in Table 15. The ACS provides similar savings, over $1M annually as shown in Figure 16.

	CURRENT ANNUAL COSTS (note 1)	LARPS PROJECTED ANNUAL COSTS	ANNUAL SAVINGS
OPERATING EXPENSES			
Labor	$1,342,000	$796,000	
Material	$998,000	$436,000	
Disposal	$365,000	$83,000	
Treatment	$30,000	$8,000	
SUB-TOTAL	$2,735,000	$1,323,000	$1,412,000
HEALTH AND SAFETY (note 2)			
Cost of Lost Days (Injury)	$7,000	$0	
Cost of Lost Days (Sickness)	$87,000	$0	
Cost of Replacement Labor	$94,000	$0	
SUB-TOTAL	$188,000	$0	$188,000
ENVIRONMENTAL			
Potential Fines (note 3)	$400,000	$0	
Cost of Lost Production (note 4)	$1,500,000	$0	
SUB-TOTAL	$1,900,000	$0	$1,900,000
TOTAL SAVINGS PER YEAR			$3,500,000

(1) Based on FY 1991 OC-ALC workload (3 B-52s, 62 C-135s, 9 E-3s, 1 B-1B); all costs in 91$
(2) Projections based on absentee rates through 3/18/92
(3) Estimated fines for not meeting EPA and OSHA guidelines by FY1995
(4) Current alternative to methylene chloride stripper is another chemical stripper which increases flow time by 50%. This means that the current workload revenues of $3M would be cut in half.
(5) E-3 and B-52 not included in projected totals since they will not fit in Building 3105

Figure 15 - LARPS Annual Savings

	CURRENT ANNUAL COSTS (note 1)		LARPS PROJECTED ANNUAL COSTS		ANNUAL SAVINGS
OPERATING EXPENSES					
Labor		$403,000		$204,000	
Material		$369,000		$119,000	
Disposal		$101,000		$10,000	
Treatment		$9,000		$1,000	
SUB-TOTAL	$882,000		$334,000		$548,000
HEALTH AND SAFETY (note 2)					
Cost of Lost Days (Injury)		$3,000		$0	
Cost of Lost Days (Sickness)		$35,000		$6,000	
Cost of Replacement Labor		$38,000		$6,000	
SUB-TOTAL	$76,000		$12,000		$64,000
ENVIRONMENTAL					
Potential Fines (note 3)		$120,000		$0	
Cost of Lost Production (note 4)		$400,000		$0	
SUB-TOTAL	$520,000		$0		$520,000
TOTAL SAVINGS PER YEAR					$1,132,000

(1) Based on FY 1991 workload of 285,000 sq. ft. of MISTR/PDM components; all costs in 91$
(2) Projections as of 3/18/92 based on absentee rates
(3) Estimated fines for not meeting EPA and OSHA guidelines by FY1995
(4) Current alternative to methylene chloride stripper is another chemical stripper which increases flow time by 50%. This means that the current workload revenues of $3M would be cut in half.

Figure 16 - ACS Annual Savings

CONCLUSION

In conclusion, the LARPS system has a unique charter—to successfully automate day-to-day manual coatings removal operations using an alternative removal process. Masking is virtually eliminated on the aircraft stripped. Annual operating costs are lower. Hazardous chemicals are eliminated. The process is totally automated and controlled.

The LARPS system is real. It is currently in fabrication with a working robot subsystem in March of 1994, an integrated system available for runoff in July 1994 and system activation date of winter 1994-1995.

The LARPS system is one part of a line of flexible large scale robot systems for removing paint from, inspecting and painting narrow and wide body commercial and military aircraft. LARPS is only the first one of these systems to be built. A second is now planned for OC-ALC.

LARPS successful implementation will provide not only a solution for OC-ALC's environmental efforts, but also a platform from which to meet the aircraft exterior refurbishment requirements for the military and commercial aviation industries.

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Paper **46**

THE PREMAJET DERUSTING AND THE ABRASIVE RECOVERY SYSTEM

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ABSTRACT

This paper will introduce the main features of the third generation derusting machine: the derusting and the abrasive recovery system and the selection of the abrasive jet parameters. The third generation deruster is characterized by its high derusting efficiency and low specific power consumption. Typically, with a working pressure of 10MPa, a water flow rate of 30 1/min and at the abrasive weight consistency of 30%, the derusting efficiency can reach as high as 16. 8m ^{2}/h, while the specific power consumption is only 1/30 of that used by the pure water jet deruster.

Organized and Sponsored by the Water Jet Technology Association.

1. Introduction

The rust corrosion of metal parts exercises bad impacts on the life span of the machine that takes metal parts as its components, on the quality of the products that the machine turns out and the production cost associated with the machine. It is well known that in the ordinary air, the annual rust corrosion rate for steel is about 0.05 – 0.15 mm. When rust corrosion depth reaches 1% of the thickness of the steel being corroded, the strength of the steel will reduce by 5 – 10%. Throughout the world, the metal rust corroded annually equals 20 – 40% of its annual production. This points to the fact that the rust prevention of metal structures is a task of paramount importance. [1] [2]

Painting metal surfaces proves to be one of the most efficient ways to prevent metal structures from being rust corroded. But to be painted, the metal surfaces should be thoroughly derusted, and derusting can help painting raise rust prevention capability by 5 times.

The pure pressure water jet derusting technology proves superior to acid cleaning, alkali cleaning and pneumatic sandblast in that it employs a fairly simple system, flexible in operation and free of any acid or alkali pollution. And for this reason, the technology deveolops rapidly. But the system warrants a rather high working pressure and hence high motor power. Typically the working pressure and the motor power can be as high as 90 MPa and 225 KW respectively. Even with those parameters, the derusting efficiency can only reach 16 m^2/h.

The injection abrasive jet system lowers the derusting working pressure and motor power in turn to 70 MPa and 75 KW respectively, but still undesirable. Moreover, with theabrasive rate of 12.5 kg/min, the derusting system can reach an efficiency of 16.7 m^2/h. Since 1987, we have been focusing our researches onthe abrasive jet derusting technology with the patented invention of rotated injection abrasive jet derusting technology and the another patented invention of the PREMAJET derusting technology. And now we have developed our third generation derusting machine.

Our first generation derusting machine employs the rotated injection abrasive jet and the second generation, the PREMAJET. The two problems with the first and the second generation derusting machine are: First, the working pressure is a little bit too low and the flow rate a little bit too high; wasting both water and abrasive; and in case of serious corrosion, the derusting efficiency reduces. Second, neither of the two machines has abrasive recovery matching system. [3] [4]

We cannot afford to neglect abrasive recovery in that in the derusting process, the jet gun consumes about 720 kg of abrasive an hour, and in 8 hours 5,760 kg of abrasive will be used. Obviously, the derusting machine without a recovery system will not be easily accepted by the customer.

The third generation machine employs the following major improvemens on the second generation:

△ The Improved abrasive feeding subsystem with higher abrasive flow control precision;

△ Working pressure properly raised, suitable parameters for abrasive jet selected, derusting efficiency raised and specific power consumption reduced;

△ A reliable abrasive recovery system added.

The abrasive jet parameters for the third generation PREMAJET machine are as follows: The working pressure, 10 MPa; the water flow rate, 30 l/min; the abrasive weight consistency, 30% ; the derusting efficiency, 16.8 m^2/h and derusting specific power consumption, the ratio of motor power to derusted area, 1/30 of that with the pure water jet system. Compared with the pure water jet and the injection abrasive jet derusting machine, our third generation machine stands out for its high derusting efficiency and low specific power consumption. The performance indexes of the three derusting machines are compared as shown in Table 1.

This paper will focuses on the introduction of the main features of the third generation derusting machine, the new PREMAJET derusting machine, that is, the introduction of the derusting and the abrasive recovery system, and the selection of the abraisve jet parameters.

2. The derusting and the abrasive recovery system

The PREMAJET derusting machine consists of the derusting system (the main body) and the abrasive recovery system (the matching device), as shown in Fig. 1.

2.1. The derusting system

The derusting system is the main body of the machine, which, as shown in Fig. 2, consists mainly of a pump station, a tank, an abrasive supply device and a jet gun.

2.1.1 The pump station

In the station, a triplex plunger pump is employed whose rated pressure and flow rate are 15 MPa and 30 l/min respectively. In the pump a safety valve is fixed.

In the station, besides the pump there are an accumulator and an automatic load relieving valve, forming a load relieving circuit. When the system is blocked, the pump can relieve the load automatically and the pump can still operate under the low pressure. A throtle valve, operated manually, is fixed in the station, through which a by-pass flows in normal circumstances. But when the jet nozzle is worn and the system pressure lowers, we can restore the system pressure to its preset value by turning down the throttle valve.

2.1.2 The tank

The tank is small in volume, only of 60 l. In the tank, there is a pilot operated float ball valve, floating up and down to turn on and turn off the flow. In the bottom, a filtre is fixed to filtre out impurities from the water.

2.1.3. The abrasive supply device

The abrasive supply device consists of an abrasive tank, a mixing chamber and a controlling circuit. Actually, there are two abrasive tanks, working alternatively so that the derusting machine can work continuously. The abrasive tank is a pressurized container, 90 1 in volume. Filled with water , the abrasive flows down under its own weight into the mixing chamber. In the tank, a dredge rod is fixed so that the abrasive flows down evenly without any block at the exit.
The mixing chamber is actually a cavity. The abrasive coming down from the tank is evenly mixed with the vortexed water, and then as slurry flows through a ten meter hose into the jet gun.
For more precise regulation of the abrasive flow rate, a by-pass is thrusted into the tank bottom to enable the abrasive in the lower part of the tank to be partially fluidized. So by adjusting the water flow rate through the by-pass, we can regulate the abrasive flow rate to the desired precision.

2.1.4 The jet gun

Rested on the gun rack, the gun takes the nozzle assembly as its main component. Made from bearing steel, the nozzle body has an internal taper of 13° . The nozzle head, made from wear resistant ceramic, has a round internal section and an extensible length twice the nozzle diameter. The nozzle head is modified by fixing a specially designed guide on the inlet of the head so that the jet comes out as a flat spray and the derusting efficiency is enhanced. In the gun rack, a gate valve is built for the emergency shut-off of the gun.

2.2. The abrasive recovery system
The machine consumes the abrasive at the rate of 720 kg/h, which greatly restricts the application of the PREMAJET derusting technology.
The abrasive used in derusting can be recovered, and our experiments demonstrate that the ordernary river sand, having been used for more than five times, can still achieve 90% of its original efficiency. N.S.Guo, H. Louis and others from Hannover University also show by their experiments that the used abrasive can be recovered. (5)
With the derusting machine the recovery system goes, consisting mainly of an abrasive collecting system, a screening system and a tank filling system and with a recovery capacity of 3,000 kg/h.

2.2.1 The abrasive collecting system

The abrasive collecting system collects the jetted-out abrasive and sends it into the settling pool. Then it is slurry pumped to the submerged vibration screen.

2.2.2 The screening system

The screening system mainly consists of a submerged vibration screen, a storage funnel and a slag discharging funnel.

Normally, the collected abrasive is wet. To screen the abrasive with ordinary screens would give rise to the increase of the washing water. Otherwise, the screens would not work efficiently. To solve the problem, we designed a special screen, submerged in water so that the screen washing process is automatically got rid of. Our experiments show that its screening capacity is quite high.
The screened abrasive falls down into the storage funnel, which connects the screen to the tank filling system.
The coarse sand on the screen glides into the slag discharging funnel and then is discharged through a discharging valve.
In collecting the abrasive, sometimes we find that some floating material goes into the abrasive. But in the process of screening, the material floats on the surface of the water. In the slag discharging funnel, we leave a long narrow mouth to discharge the material. The discharging process is automatic since when the abrasive falls into the storage funnel, the water level on the screen becomes higher and the surplus water overflows out, carrying away the floating material.

2.2.3 The tank filling system

The tank filling system feeds the abrasive tank. The system employs a slurry pump and the cycling replacement working manner. The workings of the system are as follows: Using the water in the storage funnel, the abrasive is turned into slurry near the exit of the funnel and then slurry pumped to the inlet of the abrasive tank of the derusting machine. Under the normal working conditions, the abrasive tank is all the time full of water. Having flown into the tank, the abrasive settles down, automatically separated from the water. The surplus water then returns to the storage funnel through an overflow returning hose, then it is reused to turn the abrasive in the storage funnel into slurry. This process of recycling and replacement enables the abrasive tank to be filled to its full capacity.

3. The abrasive jet parameters

The abrasive parameters include the working pressure, flow rate and abrasive weight consistency.
It is crucial to determine proper parameter for the PREMAJET derusting technology.
In selecting the parameters, we take the following as our guiding principle. In addition to the desired high derusting efficiency, the derusting quality aimed at is up to the standard set by ISO 8501−1 1987 Sa 2.5 . Meanwhile, we also aim at low specific power consumption.
The derusting efficiency for the third generation PREMAJET derusting machine, as demanded by the customers, should be up to 16 m^2/h in seriously rust corrosion conditions.
Based on our experiences with the first and the second generation derusting machine, it is necessary to increase the working pressure and decrease the flow rate. With this idea in mind, we arranged a series of experiments to track down the impacts the working pressure, flow rate and abrasive consistency exercise on the derusting efficiency. The data obtained can serve as the basis for the selction of the

PREMAJET derusting parameters.

Here we would like to redefine the specific power consumption as the ratio of jet power to derusted area.

It should be pointed out that it is very difficult to calculate precisely the derusting efficiency since we actually do not have the uniformly rusted metal surface as far as the rust degree is concerned, and then the derusting cannot be a uniform process. To ensure the reliable comparability of the experiment data, in our experiments, we hand-held the jet gun and derusted a large area on the rust uniform and seriously corroded steel sheet. We derusted for 10 minutes each time, measured the derusted area and calculated the derusting efficiency.

In the experiments, we visually determined the traverse velocity and the standoff distance (about 400 mm). The derusted surface was lustrous and the quality up to the stadard set in ISO 8501-1 1987 Sa 2.5 .

In the experiments, ordinary river sand was used with the size of less than 0.5 mm.

3.1 The pressure parameter

Experiment conditions:

Flow rate	30 l/min
Abrasive weight consistency	30%
Working pressures	2.5; 5.0; 7.5; 10; 12.5 MPa

To ensure constant flow rate, we changed nozzle diameters according to the working pressure employed.

Experiment results:

Working pressure MPa	Efficiency m^2/h	Specific power consumption $w \cdot h/m^2$
2.5	1.8	649
5	6	417
7.5	10.7	351
10	16.8	297
12.5	18	347

Variation of working pressures exercise a strong impact on the derusting efficiency and derusting specific power consumption as shown in Figs 3 and 4. It is apparent that with the increase of the working pressure, the derusting efficiency increases dramatically while the derusting specific power consumption decreases to a great extent. But when the working pressure exceeds 10 MPa, the derusting efficiencyincrease rate tends to be slower while the derusting specific power consumption tends to rise.

Based on the above mentioed experiment results and taking into consideration such factors as the size of the derusting machine and the erosion effect of the jet on the metal surface, we have finalized the selected working pressure as 10 MPa.

3.2 The flow parameter

Experiment conditions:

Working pressure	10 MPa
Abrasive weight consistency	30%
Flow rates	11; 18; 24; 30 1/min

Experiment results:

Flow rate	Efficiency	Specific power consumption
1/min	m^2/h	w • h/m^2
11	5	367
18	6.5	385
24	11.5	347
30	16.8	297

The impacts variation of water flow exercises on derusting efficiency and derusting specific power consumption are shown in Figs 5 and 6. As can be seen from the figures, with the increase of the water flow, the derusting efficiency increases while the derusting specific power consumption almost remains the same or decreases slightly.

Based on the above mentioned experiment results, for our third generation machine, we set the flow rate at 30 l/min. If higher efficiency is requried, the customer can increase either water flow rate greatly or use more jet guns or both.

3.3 The abrasive weight consistercy parameter

Experiment conditions:

Working pressure	10 MPa
Water flow rate	30 1/min
Abrasive weight consistency	0; 23.2% 30.1% 38.3%

Experiment results:

Consistency	Efficiency	Specific power consumption
%	M^2/h	w • h/m^2
0	0.7	7142
23.2	6.5	769
30.1	16.8	297
38.3	17.6	284

The impacts variation of abrasive weight consistency exercises on efficiency and specific power consumption rate are shown in Figs 7 and 8. As can be seen from the figures, with the increase of abrasive consistency, derusting efficiency increaes sharply while specific power consumption decreases dramatically. But when abrasive consistency exceeds 30.1%, the extent to which derusting efficiency increases and specific power consumption decrease tends to be slower.

Based on the above mentioned experiment results, and taking into account the aim of lowering abrasive consistency, the abrasive weight consistency is set at 30% for our third generation machine.

4. Conclusion

4. 1 Our PREMAJET technology has matured since proper parameters have been selected and the abrasive recovery system developed.

4.2 Proper parameters for our third generation machine are:

working pressure	10MPa
Flow rate	30 1/min
Abrasive weight consistency	30%

4. 3 In gravely corroded conditions , our third generation machine has achieved the efficiency of 16 m^2/h and above while the specific power consumption is 1/30 that of pure water jet derusting. So our machine is characterized by high efficiency and low specific power consumption .

Acknowledgement
Sincere thanks should be extended to Mr Xiping Wang, my Ms student, who helped me with the experiments.

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Table 1 The performance indexes of three derusting machines

Jet Type	Data Source	Pressure MPa	Power KW	Abrasive Flow Rate kg/min	Efficiency m /h	Specific Power Cousumption Kw • h/m
Pure Water	Kamat Co. Germany	90	225	0	16	14. 6
		80	90	0	14. 3	6. 25
Injection Abrasive Jet	Kamat Co. Germany	60	60	7. 6	8. 6	6. 98
		60	60	2. 7	6. 4	9. 38
	Partek USA	70	75	12. 5	16. 7	4. 01
PERMAJET	HNMI China	10	8	12	16. 8	0. 48

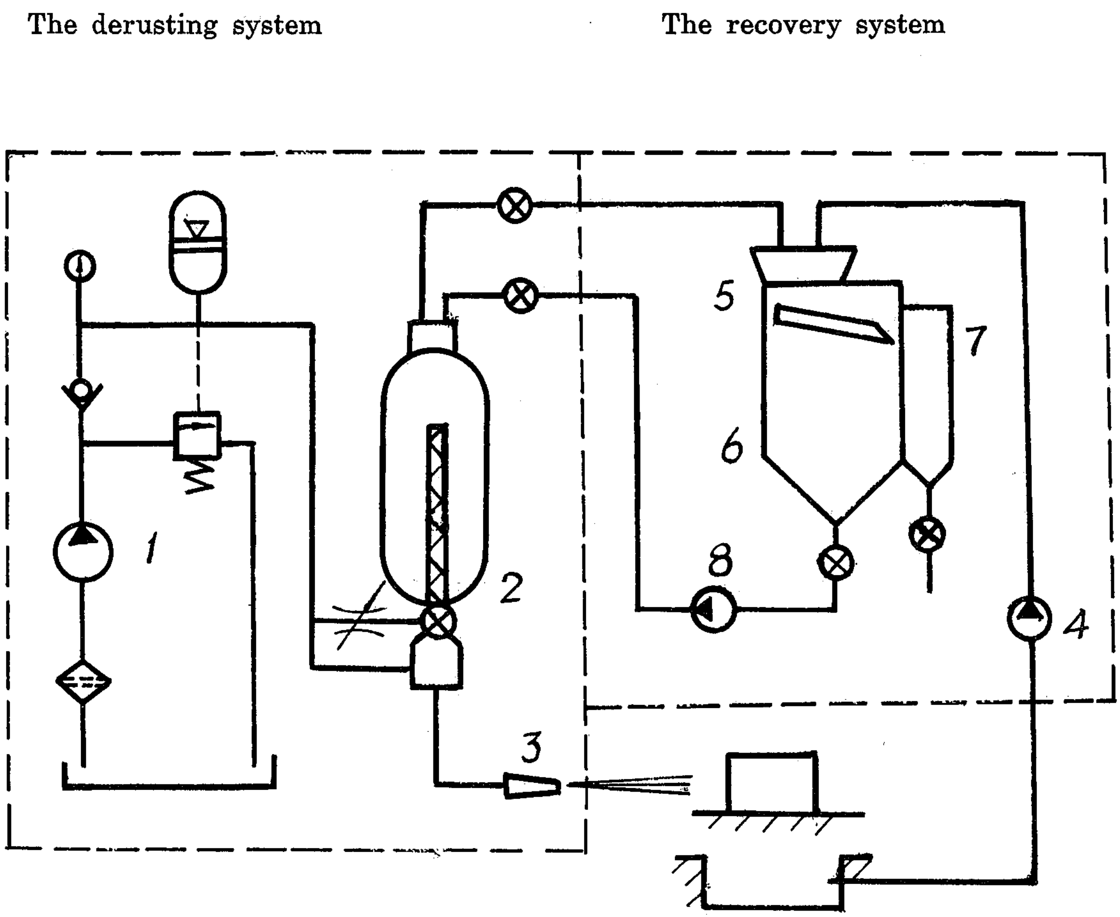

Fig 1 Derusting and abrasive recovery system
1. Pump station 2. Abrasive supply device 3. Jet gun
4. Slurry pump 5. Submerged vibratian screen 6. Storage funnel
7. Slag discharging funnel 8. Slurry pump

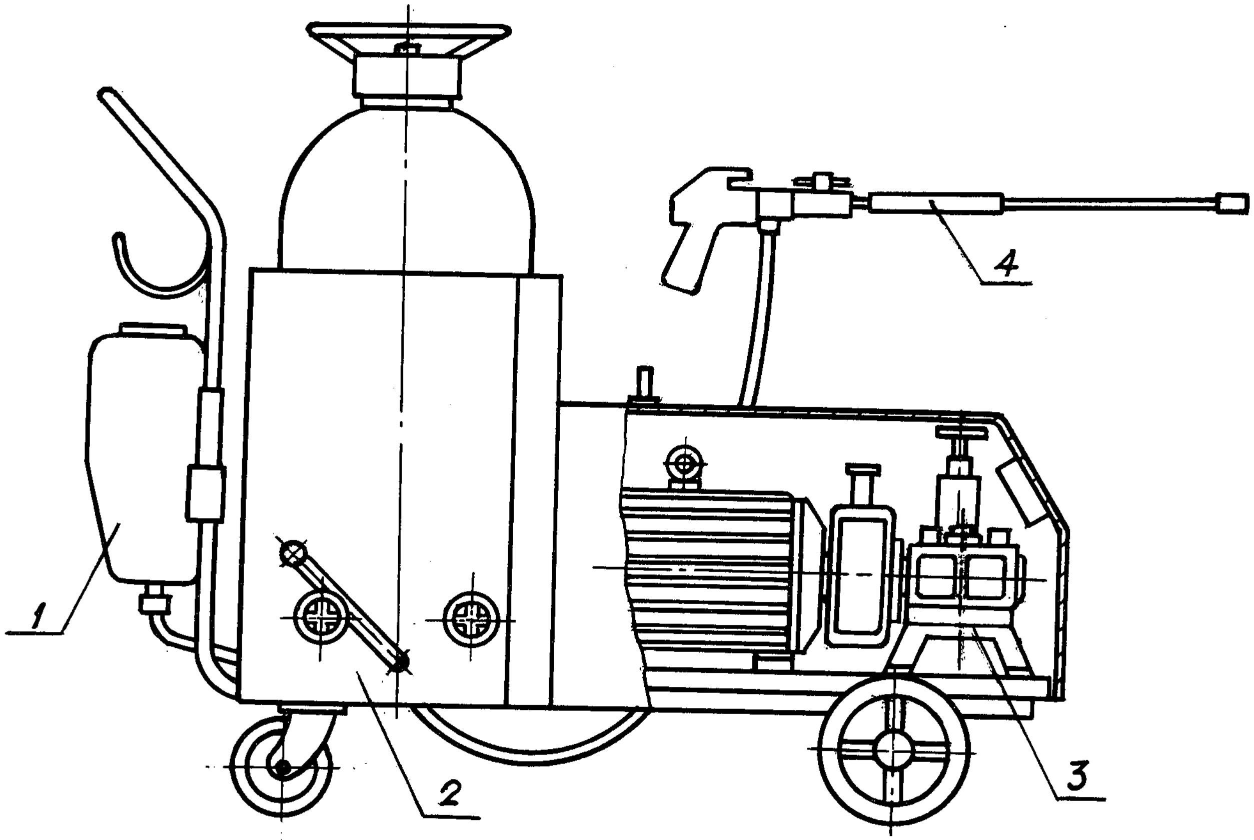

Fig 2 The main body of the derusting machine
1. Water tank 2. Abrasive supply device
3. Pump staion 4. Jet gun

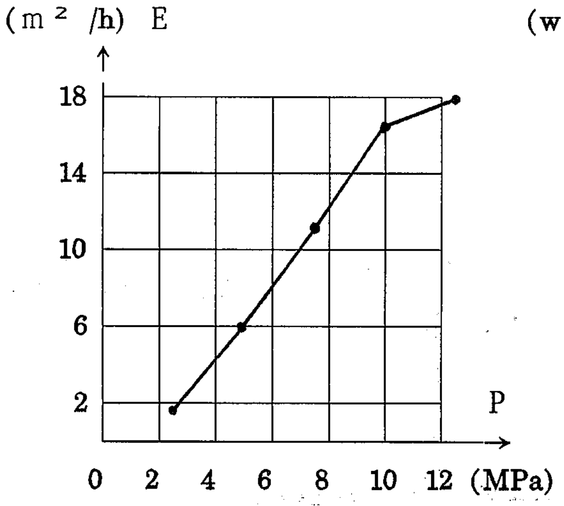

Fig 3 Impacts of pressure on derusting efficiency

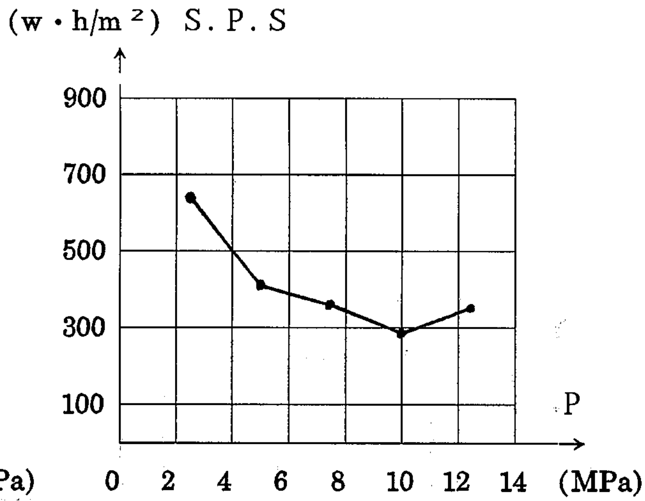

Fig4 Impacts of pressure on derusting specific power cousumption

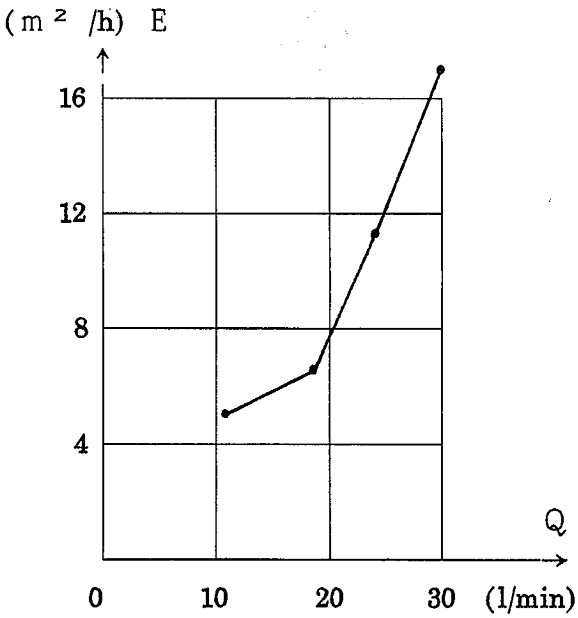

Fig 5 Impacts of flow on derusting efficiency

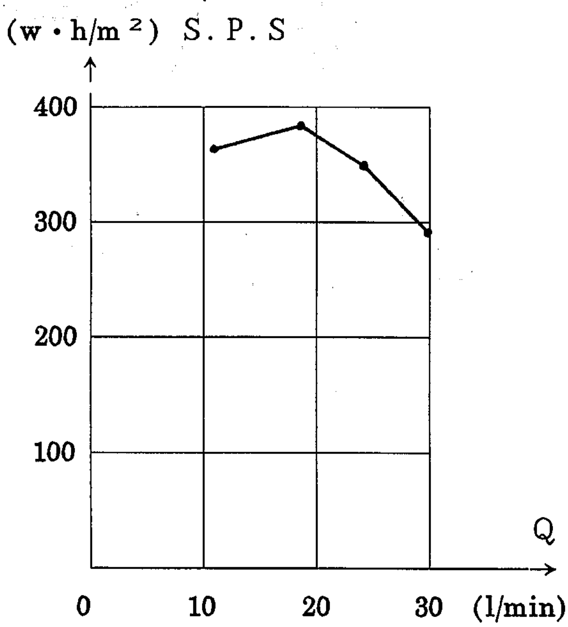

Fig 6 Impacts of flow on derusting specific power cousumption

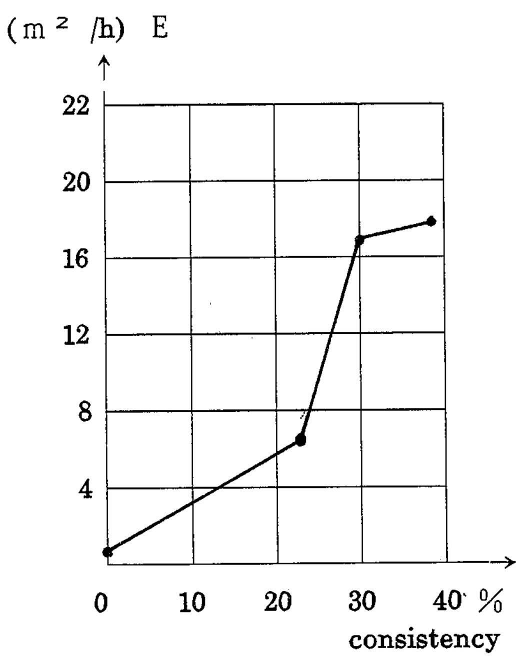

Fig 7 Impacts of abrasive weight consistency on derusting efficiency

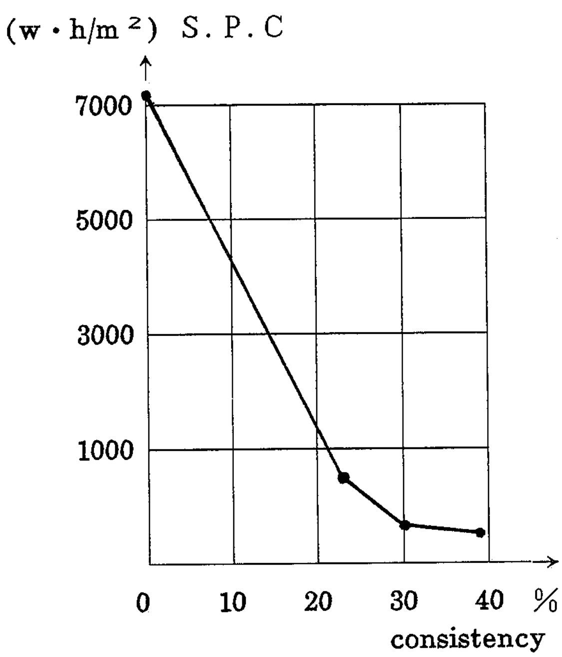

Fig 8 Impacts of abrasive weight consistency on derusting specific power consumption

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Paper 47

EXPERIMENTAL STUDY ON RUST-REMOVING WITH ABRASIVE WATERJET

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ABSTRACT

Compared with pure waterjet (PWJ), abrasive waterjet (AWJ) is more powerful and has a larger impact force. For example, a pressure of 70-100 MPa or higher is necessary when PWJ is used in rust-removing and descaling for large metal surface. However, the determinant factor is no longer the pressure but injecting and mixing of the abrasive in the case of AWJ. The experimental results show that using dry abrasive may cause problems, such as uneven abrasive flow rate, chock up and uncontrollable. Moreover, the efficiency of rust-removing is low and higher pressure is needed compared with using slurry abrasive. It is also found that higher efficiency can be achieved by injection of slurry than by suction.

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1.0 INTRODUCTION

AWJ is based on PWJ. The vertical impact force of PWJ is

$$F = A\rho_1 V_1^2 \tag{1}$$

Where, A ----------------the impacting area
ρ -----------------the density of water
V ----------------the velocity of jet

Since both the value of ρ and A are small, F can not be very large even when V_1 is relatively large.

However, if the abrasive gets energy from water, then its impacting force to the surface is

$$P = 3\rho_2 C V_2 \tag{2}$$

Where, ρ----------the density of abrasive
V------------the impacting velocity of abrasive
C------------the propagation velocity of the compressive wave in water, equal to 1500 m/s. When the impacting velocity is high enough, the wave will propagate in the form of shock wave, its velocity is far larger than the sound wave.

Both the results of test and calculation can prove that P is several ten times larger than F. So that AWJ has a better impacting effect.

However, after mixed into water, the abrasive must be accelerated. Only when all the abrasive have the same velocity with water, can the result of equation (2) be obtained. But there is not any kind of mixing way now can get this result. Why? On one hand, there is difficulty in theoretical study and calculation due to the turbulence of waterjet. On the other hand, the abrasive can only be added from the boundary layer of the waterjet. The velocity there is much smaller than the velocity at the jet center.

This paper will analyze the mixing mechanism of abrasive and make comparison between several kinds of mixing ways. As a result, the paper selects the inner mixed slurry for large-scale rust-removing.

2.0 MIXING MECHANISM OF ABRASIVE

2. 1 Longitudinal Motion of Particles

After added into water, the particles will be accelerated and move along the axial. Its motion equation is

$$\rho \frac{d^2x}{dt^2} = \frac{3}{4} \cdot \frac{dv_1^2}{dx} + \theta \cdot \frac{3}{4} \frac{C_D}{d_a}(V_1 - \frac{dx}{dt})^3 \tag{3}$$

Where, $\rho = 1/2 + \rho_2/\rho_1$

θ——symbol function

C_D——drag coefficient

d_a——the diameter of particle

It is difficult to calculate the acceleration of particles by (3). Because the velocity of water at the cross section is not uniform, and the position of particles is still unknown.

2. 2 Transverse Motion of Particles

The mixing of particles into jet and their moving towards the jet center is called the transverse motion. In fact, most particles will collide with the jet surface and then rebound. The jet surface is like a rigid body. In order to force particles mixed into jet, the following ways are used:

(1) Adjusting the incident angle of particles. The incident angle is a right angle in Figure la. It needs several times of rebounds. In Figure lb, the angle is α, it needs only 1 to 2 times and a better effect can be got.

(2) The mixing effect becomes better when the particles get closer to the convergent inlet of the nozzle. At the same time, the smoother the inner surface is, the better the effects.

(3) The nozzle diameter d is smaller than the jet diameter D, as shown in Figure 2. So that the velocity distribution of the jet becomes relatively even, and the particles within the boundary layer will enter the central part of the jet. However, d must not be smaller than a minimum value.

(4) There are a lot of particles in the jet. As shown in Figure 3, we only study the collision between two particles A and B. Assuming that $V_b > V_a$ since the particle B is closer to the center. The particle B will catch up with A and collide with it. After collision, their velocity along their central line are

$$v_A = V_a\cos\alpha + \frac{(1-e)m_b}{m_a+m_b}\cdot(V_b - V_a)\cos\alpha \tag{4}$$

$$V_B = V_b\cos\alpha + \frac{(1+e)m_a}{m_a+m_b}(V_a - V_b)\cos\alpha \tag{5}$$

Where, m_a——the mass of particle A

m——the mass of particle B

e——distance between two particles

Since $V_b > V_a$, then $V_A > V_a \cos\alpha$, $V_B < V_b \cos\alpha$. That is, particle B will move towards the axial and A towards the opposite direction after collision. Because there are less particles near the axial, particles tend to move towards the axial.

3.0 COMPARISON OF SEVERAL MIXING WAYS

Some researchers (including the author) have carried out experiments on rust-removing with PWJ, the pressure required is 70 to 100 MPa. However, only 10 to 30 MPa is needed with AWJ. The key is the mixing of abrasive.

3.1 Dry AWJ

Many researchers have studied this way, as shown in Figure 4. The dry abrasive will collide with water drops in the boundary layer. When the incident velocity of particles U is far smaller than the component velocity of the drops V, the particles will rebound. This is often the case when the jet velocity is high. After several times of rebounds, particles can be mixed into jet at the nozzle outlet. It is found that the mixing effect is very bad. The wear of nozzle is serious. Chock up is easily caused by the dry sand.

3.2 Outer Mixing of Slurry

Abrasive and water are mixed forming slurry. The slurry is ejected from a nozzle mixing with waterjet (see Figure 5). However, the jets will collide with each other at the cross point, which consumes much energy. The friction and collision between particles at that point also consumes energy. Therefore, the mixing way needs more jet energy. But the effect of rust-removing is better, its cleaning width can reach 50 to 80 mm at the metal surface.

3.3 Inner Mixing of Slurry

The mixing way takes the advantages of the former two, as shown in Figure 6. Because the particles have an initial acceleration and the incident angle is not right, the possibility of rebound is less. The nozzle generally has a convergent section. However, the author used to use a straight pipe (Figure 7) for rust-removing, the effect is good. The maximum cleaning width is 40 mm.

3.4 DIAJET

DIAJET is first put forward by BHAR, it needs a high pressure tank. Abrasive can fully mix with water. So that very good effect can be obtained with very low pressure. However, DIAJET can not work continuously for a longer time since a tank of abrasive can be used for a certain time. And it is difficult and expensive to make a very big tank.

4.0 EXPERIMENTS ON RUST-REMOVING

According to the above analysis, it is suitable to use the inner mixing of slurry for large-scale rust-removing.

4.1 Experimental System and Principle

The experimental system consists of the high pressure waterjet system, the slurry supply system and the cleaning system, see Figure 8. Water is jetting from the first nozzle forming high speed jet. The slurry is ejected by a slurry pump into a mixing chamber and jetting out with water from the second nozzle forming AWJ. The AWJ is used in rust-removing.

4. 2 Main Technique Parameters

Waterjet pressure	12 MPa, 28 MPa
Jet flow rate (each nozzle)	10 l/min, 16 l/min
Water pump flow rate	125 l/min
Slurry pressure	1.2 MPa
Sand flow rate (each nozzle)	2 to 3 kg/min
Abrasive	quartz sand
Abrasive size	60 to 80 meshes

4.3 Experimental Results

(1) Effect of waterjet pressure on the efficiency of rust-removing
It can be seen from Table 1 that the effect of waterjet pressure on the efficiency of rust-removing is little when the pressure is 10 to 30 MPa. So that it is beneficial to use a smaller pressure.

(2) Effect of waterjet flow rate on the rate of rust-removing
It can be seen from Table 2 that when the flow rate of each nozzle is increased by a factor of 4.5, the removing efficiency only increases by 30%. Therefore, it is better to use more nozzles than to use larger nozzles.

(3) Effect of distance on the efficiency of rust-removing
The cleaning width increases with the distance, as shown in Figure 9. When the distance is larger than 300 mm, the cleaning effect declines largely. So that the distance must be 150 to 300 mm.

(4) Abrasive size and flow rate

a. Size
The size of quartz sand used is 0.2 to 1 mm. The surface cleaned is coarse. When quartz sand of 40 to 80 meshes is used, the cleaning surface is very smooth.

b. Flow rate
The cleaning effect varies largely with the flow rate of abrasive. No cleaning effect is found when PWJ is used with a pressure of 12 MPa and nozzle moving speed 70 to 80 mm/s. When the sand is added gradually, it is found that cleaning effect becomes better and better. The effect is the best when the flow rate reaches 2 to 3 kg/min.

5.0 CONCLUSION

Compared with PWJ, AWJ can realize rust-removing with a lower pressure. The efficiency and effect of rust-removing mainly depend on the mixing of abrasive with waterjet. For large-scale rust-removing, it is suitable to use inner mixing of slurry.

Table 1 Effect of Pressure on Efficiency of Rust—Removing

Jet Pressure (MPa)	12	28
Jet Flow Rate (l/min)	125	125
Slurry Pressure (MPa)	1.2	1.2
Nozzle Diameter (mm)	1.2	1.2
Sand Flow Rate (kg/min)	15	15
Distance (mm)	200	200
Cleaning Width (mm)	30—35	30—35
Nozzle Number	6	6
Total Width (mm)	180—250	180—250
One Nozzle Efficiency (m^2/h)	8—9	9—10
Total Efficiency (m^2/h)	48—54	54—60
Effects	very clean	

Table 2 Effect of Flow Rate on Rate of Rust—Removing

Jet Pressure (MPa)	12	12
Jet Flow Rate (l/min)	20	90
Slurry Pressure (MPa)	1.2	1.2
Nozzle Diameter (mm)	1.2	3
Sand Flow Rate (kg/min)	3	3
Distance (mm)	200	200
Cleaning Width (mm)	30—35	35—40
Nozzle Number	1	1
Removing Rate (mm/s)	70—72	80
Efficiency (m^2/h)	8—9	10.08
Effects	very clean	

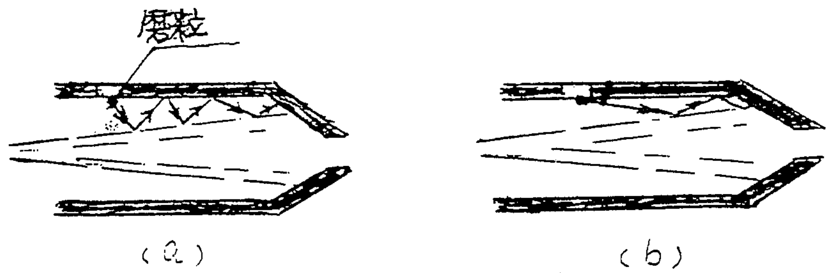

Fig. 1 Collision of Particle With Jet

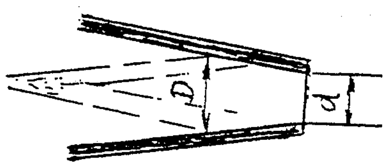

Fig. 2 Nozzle Diameter

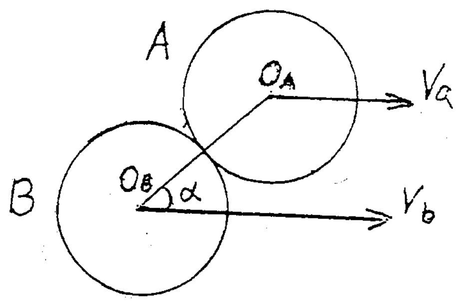

Fig. 3 Particle A And B

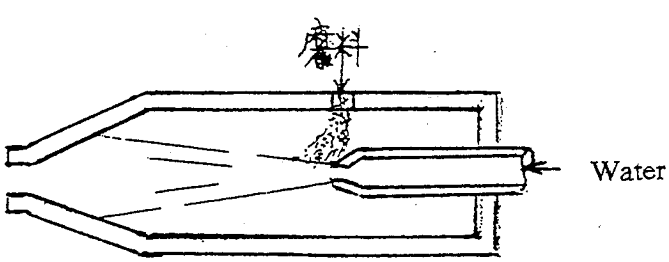

Fig. 4 Adding of Dry Abrasive

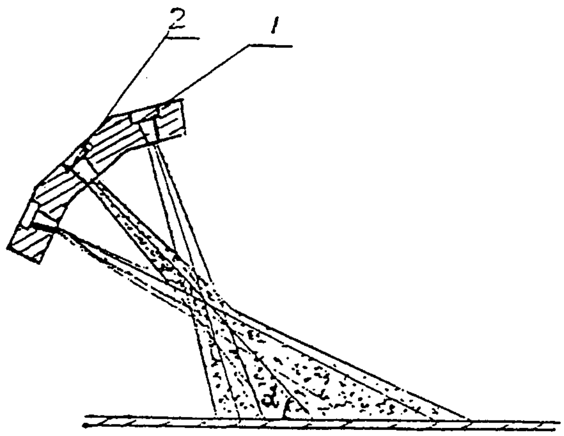

Fig. 5 Outter Mixing of Slurry

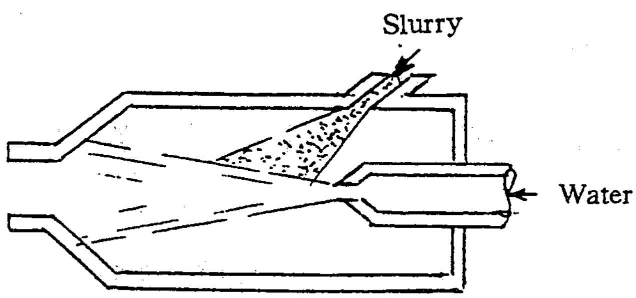

Fig. 6 Inner Mixing of Slurry

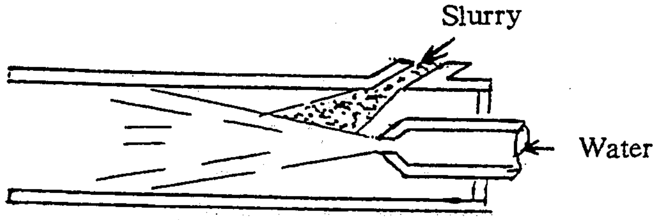

Fig. 7 A Straight Nozzle

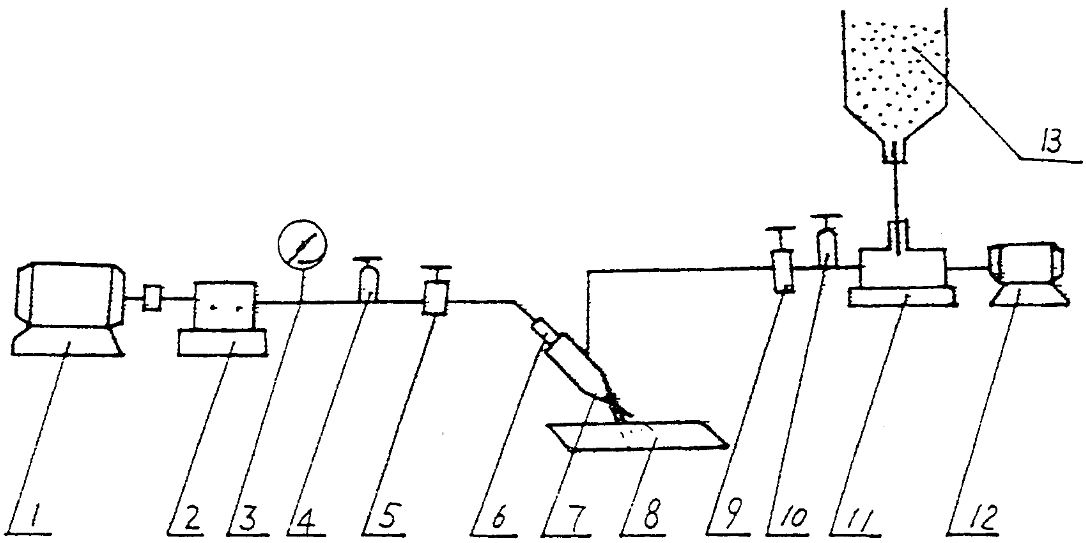

Fig. 8 · Experimental System

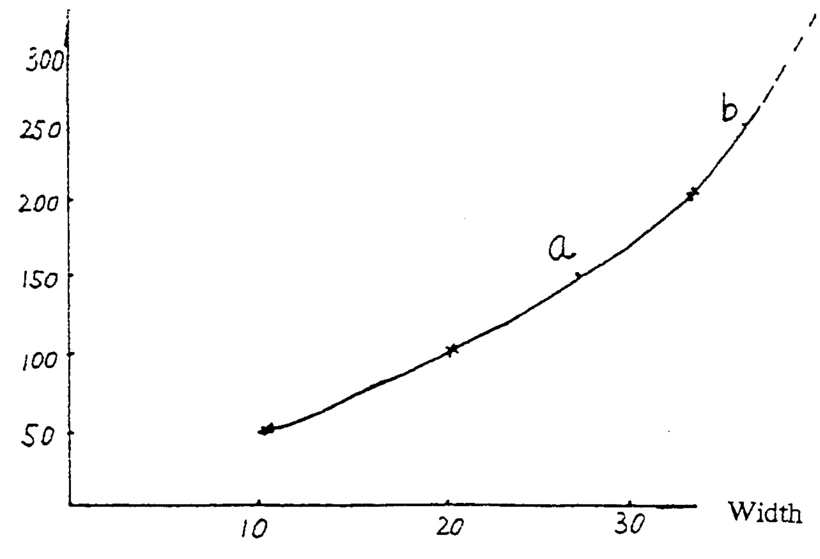

Fig. 9 Effect of Distance of Cleaning Width

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Paper 48

EQUIPMENT AND TEST RESEARCH OF HIGH PRESSURE WATER JET FOR RUST REMOVAL

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The key problems for the application of high pressure water jet in rust removal and cutting are the easy adjustment and control of high pressure water, the design of the executive mechanism and safe and reliable operation of the equipment. From the two uses of ship rust removal and stone cutting, the authors designed and manufactured a complete set of high pressure water jet equipment with 70MPa pressure, 3 m^3/h capacity and 55KW motor power. The equipment integrates technologies of high pressure pump, valve and seal, and water jet, it is composed of reciprocating pump, safety valve, pressure regulating valve, check valve, control valve, jet gun, rotary jet head, abrasive jet system and capstan, etc. Tests of rust removal on class A, B, C, D rusty steel plates and the shiphull demonstrates that the surface quality after rust removal is in accordance with Sa2.5 of ISO 8501-1:1988, while speed reaches 0.8 m^2/min., and has no pollution, so it completely meets the needs of ship repairing. At the same time, test of cutting lime stone and concrete under 100MPa pressure also show that the equipment possesses the condition of cutting application. The paper discusses the parameter optimization and the model feature of the equipment, the relation between the performance parameters and the speed of rust removal and cutting, further analyses the certain tendency that high pressure abrasive jet takes the place of sand blast for rust removal.

Organized and Sponsored by the Water Jet Technology Association.

1.0 THE COMPLETE SET OF HIGH PRESSURE WATER JET EQUIPMENT

The main parameters of the equipment are optimized under the following conditions: first, under the precondition that the surface quality reaches Sa2.5, speed of rust removal is higher than present speed 0.5 m^2/h. Secondly, the equipment should consume as little water as possible since clean water is very scarce at seaside and navy base. Thirdly, the gun must be safe and easy as operation is on a high altitude, so the design principle is high pressure, small flowrate and complete function, that is:

Discharge pressure:	7 - 100MPa
Flowrate:	2 - 1.5m^3/h
Motor power:	55KW
Pump speed:	370 min^{-1}

The complete set is designed as:

High pressure pump-pressure regulating valve-jet gun (for cleaning, cutting etc); High pressure pump-pressure regulating valve-abrasive jet (for rust removal etc); High pressure pump pressure regulating valve-control valve-jet head or rotary jet head (for the inner surface cleaning of pipe, water tank, oil tank, etc).

Figure 1 shows the complete set of model #GQ-2/70 high pressure water jet equipment.

Triplex reciprocating pump is used as the source of high pressure, hence its safety and reliability are the guarantee of continuous operation of the complete set. The key technology is the design of high pressure reciprocating seal, its sealing function as well as the service life should be ensured. Figure 2 is the seal combination of gap sleeve and packings.

Principle of the gap sleeve is that the difference between hydraulic pressure acted on the outer surface of the sleeve and that the inner side which is decreasing steadily, makes the sleeve deform and causes a gap which is difficult to machine. At the same time, end of the sleeve is connected with ball pad, and the plunger end is also connected by the floating-point contact to realize the self-alignment of the sleeve and plunger. PTFE packings are filled at the back section of the sleeve, no force is transferred directly between them. Thus, the hard and the soft help each other. The latter can remedy the former's defect of seal due to operating wear, and the former can elongate the service life and raise the sealing function of the latter. The single side gap of the sleeve is 15 μm. After 612-hour continuous operation at rated point and five month's application in the oil field, the equipment is proved to be able to continue operation only by replacing the used packings. Its reliability can completely meet the needs of continuous work of high pressure water jet.

Both the safety valve and pressure regulating valve are the structures of micro-opening butterfly spring needle valve. The safety valve is used for overload protection, and pressure regulating valve for the preset of pressure, it opens to discharge under the action of water hammer due to closing of the control], valve. As the pressure regulating valve opens too frequently to balance the regulating pressure or to respond to the outer force by the spring force only. Figure 3 shows the principle of the pressure regulation valve. Normally, high pressure fluid from pump is discharged horizontally, and across the hand control valve to the executive mechanism. While the fluid reaches the preset pressure, under the combined action of the high pressure back flow and the main flow to the valve core, it opens to unload pressure from the downstream passage. To ensure the hydraulic equilibrium of the back flow, one way is that the valve is installed at the outlet.

Function of both jet gun valve and control valve is to control the high pressure water, the key point is to solve the problems of hydraulic equilibrium; otherwise, it is impossible for the valve to open or close sensitively on]y by the spring force and the outer force from hand or foot. The authors designed a kind of combined valve structure, that is, a combination of a small-square needle valve and a large-square cone valve line contacted (See Figure 4). The cone valve which is in hydraulic equilibrium, is controlled by the needle valve which comes to balance with a small spring force, and if a very small outer force is acted to overcome the spring force, the valve can open easily, and close by the force of pressed spring.

The main problem of abrasive jet system is the injection and mixing of abrasive, to lower the consumption of abrasive and simplify the system; multihole focused ejector is used instead of pre-mixing and air pressure sand feed. Abrasive is sucked into the nozzle directly by water jet (See Figure 5). High speed water jet from multihole water nozzles converges and causes vacuum in the mixing chamber. Abrasive is sucked into the ejector from store house and mixed at the focal point with the water jet and then accelerated and ejected. The converging point of the water jet must fit the abrasive inlet. Abrasive nozzle is made of mould pressed and sintered. B_4C, its surface hardness is about HRc75. Grain size of the abrasive is about 0.5 min, both river sand and sea sand are usable. After rust removal, fine abrasive becomes mud due to collision with the surface of object and thus can be discharged with the flow without any sedimentation.

Jet head and rotary jet head are special accessories for the cleaning of pipeline, ship water tank, oil tank. Rotating power of the rotary head is the hydraulic torque which is formed by a pair of tangential jets. Non-contact gap seal is used here as the high pressure rotating seal. At the same time, relations of eccentricity, pair of friction and bearing must be considered to control the rotating speed and get the best cleaning result. The structural size of the rotary head can be serialized and can be used in combination with different auxiliary apparatus according to the space to be cleaned.

Other accessories as capstan, hand control valve, electric control cabinet, various kinds of jet heads, nozzles and support frame etc are not described here.

2.0 TEST AND APPLICATION OF RUST REMOVAL

Rust is essentially a layer of oxide which adheres on the body and has no protective function for the body. Its thickness will increase with time. The outer layer is loose while the inner one adheres tightly to the body. Rust removal is to destroy the adhering force and make the rust fall off. Ship rust removal has ever been the hard nut to crack in ship repairing. Neither with manual shovelling and hammering, nor with sand blast the problem of serious powder pollution, heavy labor intensity and high cost can be solved. The mechanism of high pressure water jet for rust removal is to apply the striking force of high speed jet. to the rust layer and the effect of water wedging caused by the high speed tangential flow which can help wedging into and expanding tiny cracks. If abrasive is equally fed in the jet, the effect of striking and tangential wedging will become more obvious. Also because of the continuity and convergence of the water jet, using this method can obtain even roughness and luster which is hardly realized by other traditional method. The quality after rust removal is comparable with that, after sand blast.

A lot of work is done in the application of high pressure water jet to ship at the beginning of the 80's in China. Pump stations equipped with 3 - 4 pumps with 250KW power for each are established in various ship-building works of CSSC. Owing to the technological limitation at that time, there is no auxiliary equipment, and the pressure of the main pump is less than 35MPa, imported equipment also has the same case. Clean water jet under this pressure can be used only for the removal of sea living things, salt, surface rust and loose paint although capacity reaches 350 l/min,i.e. it can reach the level of "heavy shovelling", not even whiteness. This can be used for the preoperation before sand blast. It is hard to clean water tank or oil tank due to the absence of inner surface cleaning jet head.

For ship rust removal, in ISO8501-1: 1988, rusty steel plates are classified into four grades A, B, C, D according to its degree of rust. Four rust removal samples Sal.5, 2, 2.5, 3 are given. Ship pretreatment requires less than Sa2.5 before painting, that is even, whiteness in a large area.

The test sample is a heavy rusty steel plate, its rust thickness is nearly 2mm, it is more serious than class D. Dried river sand with grain size 0.3-0.5 mm as abrasive, sand feed speed is 2-2.5kg/min, speed of rust removal under pressure is shown in Figure 7. The highest speed is $13.2m_2/h$, surface quality keeps Sa2.5. Many tests prove that the sand consumption is directly proportional to the, speed of rust removal under the same pressure and flowrate, and the pressure is directly proportional to the speed of rust removal at the same flowrate. Meanwhile at 70MPa pressure, while flowrate rises up to 35 1/min from 15 l/min, the speed of rust removal increases almost two times.

Whereas under the same condition, the speed of rust removal with clean water jet is only $5.4m^2/h$, yet the surface after rust removal is not evenly white.

On site ship rust removal is done in Shan Hai Guan Shipyard of CSSC, sea. sand with grain size 0.3-0.5mm is used as abrasive, and transport distance is 3m. Test sample is a steel plate of C class rust, speed of rust removal reaches $0.8m^2/min$, while surface quality gets Sa2.5.

Shiphull rust removal is performed on a high altitude operation vehicle, the speed of rust removal is very satisfactory, it is 1.5 times of that with sand blast. Figure 8 shows the worksite of shiphull rust removal.

Shiphull rust removal is high-altitude operation, reacting force of the jet gun must be limited to the range of less than 25 kg that man can bear. Figure 9 is the measured values of reacting force of the unit at different capacity under full pressure. As can be seen here when capacity increases one time, the reacting force increases almost by the same factor. The measured values are in accordance with the calculated ones.

3.0 MERITS AND DEMERITS OF ABRASIVE WATER JET FOR RUST REMOVAL

Rust removal with high pressure water jet is a, novel technology, besides the unreplaceable superiority of no powder pollution, its economic benefit is also obvious. Taking the rust removal in Shan Hai Guan Shipyard as an example, at present sand blast is used, O.7MPa compressed air is supplied specially by an air station, copper slag of 1mm grain size is used as abrasive, rust removal speed of one gun is $0.5m^2/min$ and surface quality is Sa2.5. Besides the lower speed compared to water jet for rust removal, the powder pollution to the total shipyard and the surroundings is the fatal shortcoming of this technology. Because the $Si.O_2$ ground powder which tends to cause pneumosilicosis is forbidden to use. It is replaced by the copper slag. However, the pollution is still not solved. Meanwhile, because of the reacting force of the hard grains, operator's labor intensity is heavy. Another shortcoming of sand blast for rust removal is the sand treatment after rust removal. In order not to pollute sea water, copper slag, must be buried instead of being discharged directly to the sea, this would occupy much cultivated land. Furthermore, in view of economic benefit, copper slag cost RMB 160 Yuan/T, only in Shan Hai Guan Shipyard 10,000T are needed a year, this costs 1.6 million RMB yuan, so in advanced countries, high pressure water jet is widely used for rust removal in the middle of 80's.

From the viewpoint of the process of rust removal, the shiphull surface must be cleaned completely with 35MPa clean water jet before sand blast, water jet for rust removal needn't this process, so the time for rust removal becomes shorter.

In the application of high pressure water jet for ship rust removal, the problem that the surface becomes rusty immediately after rust removal must be solved. Although the rust is very thin, it is not permitted before painting. This is ignored in the cleaning engineering of other industrial sectors because the pressure is lower and the equipment is put into operation without being painted shortly after being cleaned. To keep the hull being metallic whiteness before painting, our plan is to add 3%-5% rust preventives into the water to be jetted. It requires no environmental pollution, no effect on painting adhering force and low cost. Further test is to be done.

4.0 CUTTING TEST AND APPLICATION

High pressure water jet cutting equipment must be designed according to its use, while the common problem-cutting ability under different pressure is the main aim of this research.

Here, clean water is used as the mediurn and portable gun is as cutting head to cut limestone, red stone, concrete and refractory brick. Figure 10 is the speed curve of limestone cutting.

Tests prove that 70MPa-lOOMPa water jet is able to cut or crack some building materials. Recently some basic experimental researches have been applied to coal layer cutting, wall cutting, road breaking and bridge repairing, etc.

Cutting and breaking require different type of nozzle. Cylindrically divergent jet is used for breaking to increase the striking area, while cylindrical convergent jet is required for cutting, otherwise it will crack the hard and fragile stone into pieces.

In addition, different cutting application requires different accessory, it must be specially designed.

5.0 CONCLUSION

The application range of high pressure water jet is very wide, while the authors only developed the fundamental versatile equipment with 70MPa and 70l00MPa water jet for rust removal and cutting respectively. Through experiment it has presently been applied to shipyard, power station, sugar-making factory, paper-making mill, oil field, chemical plant etc. It is believed that further development based on this research will certainly make the novel technical achievement gain greater economic & social benefits.

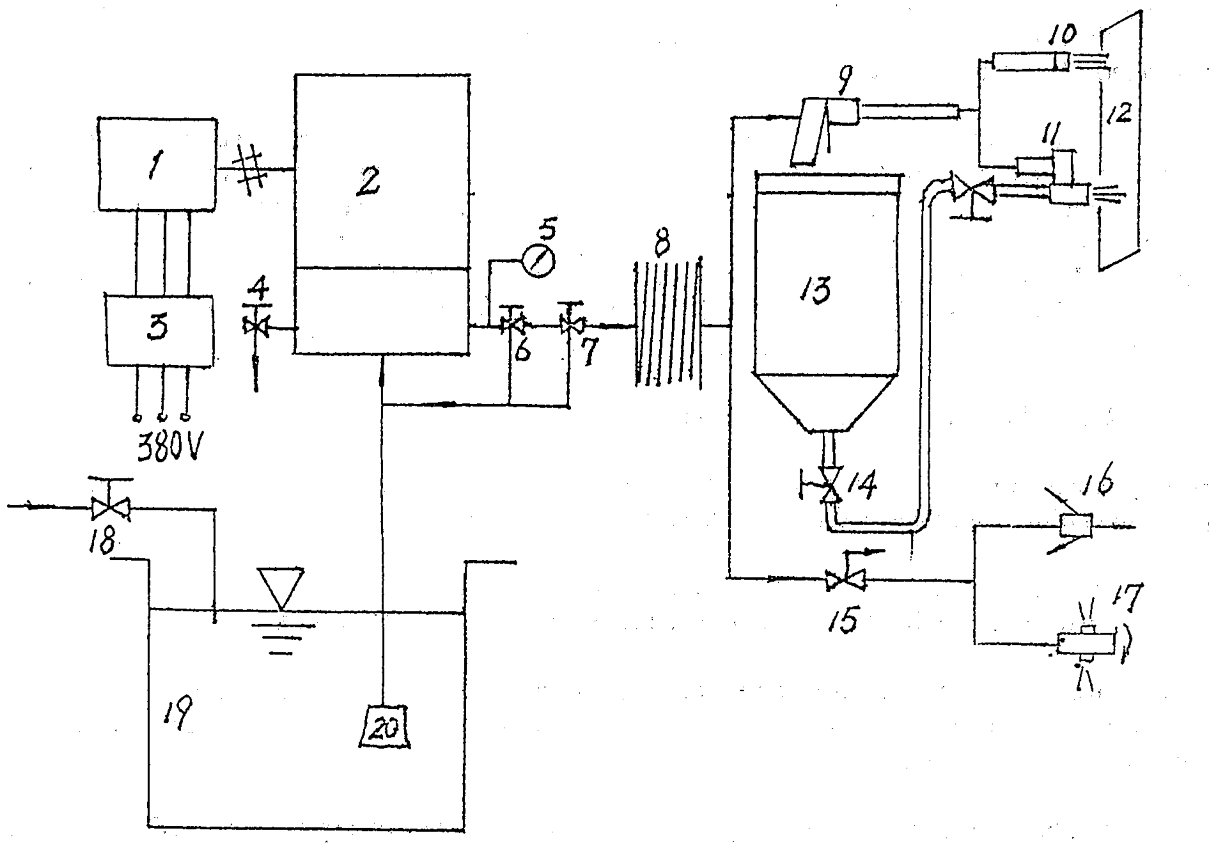

Fig.1 The complete set of high pressure water jet equipment

1. motor
2. high pressure pump
3. control cabinet
4. safety valve
5. pressure gauge
6. pressure regulating valve
7. hand control valve
8. capstan
9. jet gun
10. nozzle
11. abrasive jet nozzle
12. sample
13. sand tube
14. sand valve
15. control valve
16. jet head
17. rotary head
18. valve
19. water tank
20 filter

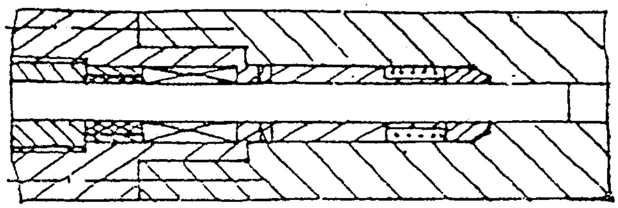

Fig.2 High pressure reciprocating seal combination

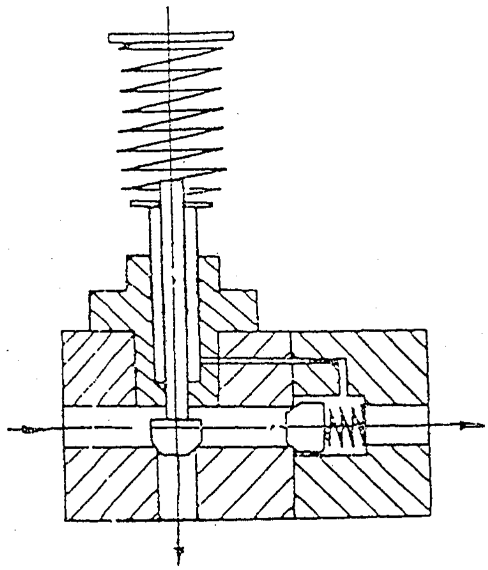

Fig.3 Sketch of the pressure regulating valve

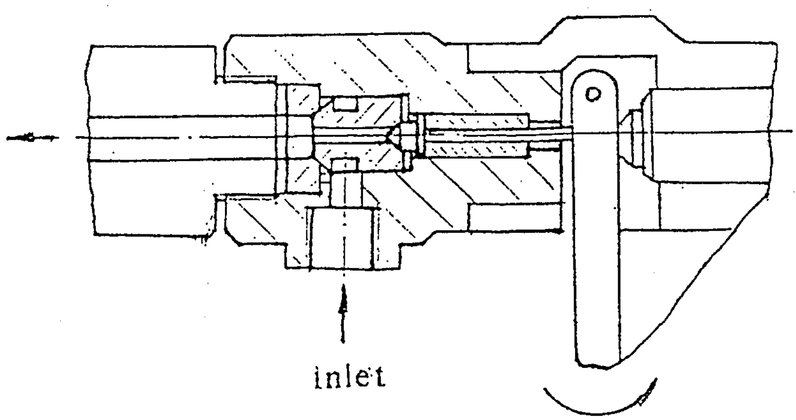

Fig.4 Principle of jet gun valve, control valve

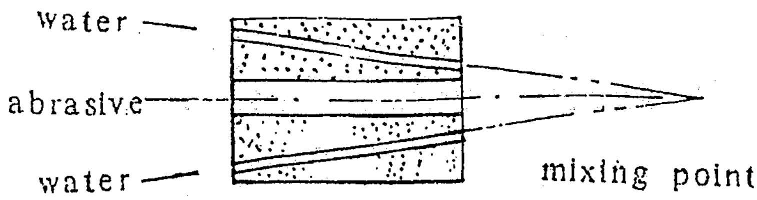

Fig.5 Principle of the abrasive nozzle

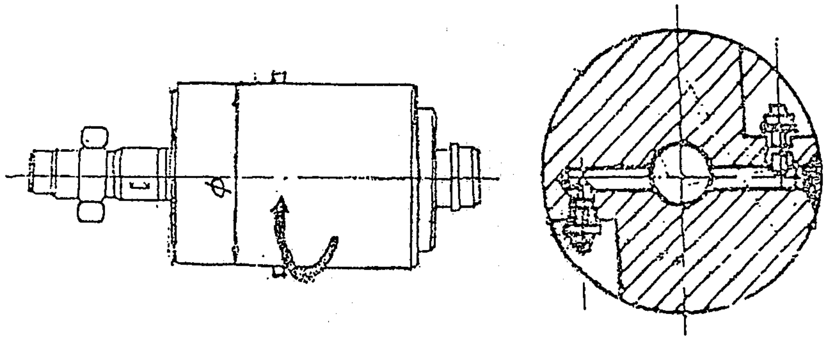

Fig.6 rotary head

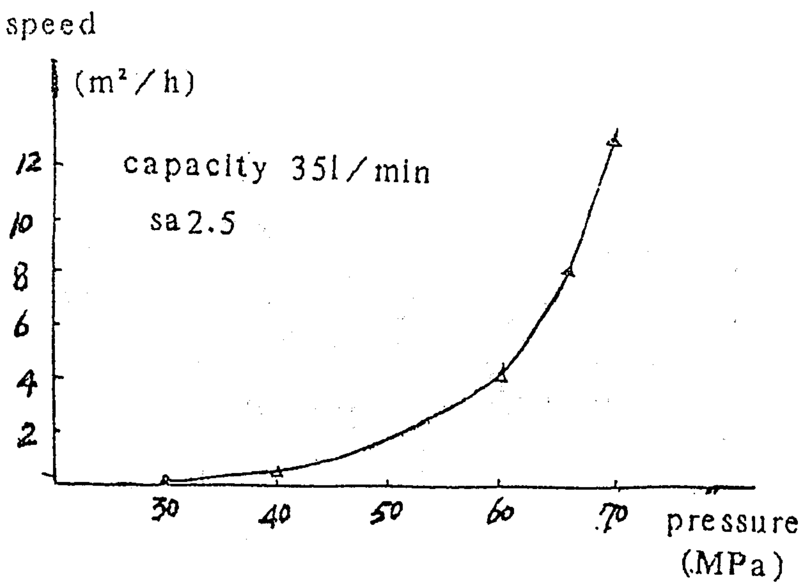

Fig.7 speed chart of abrasive jet for rust removal

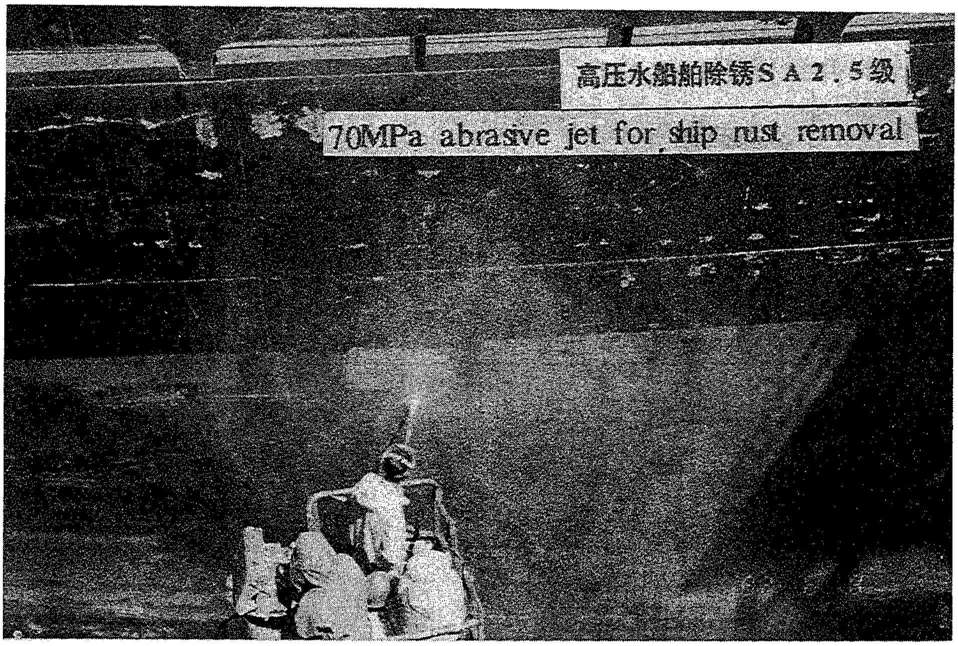

Fig.8 Worksite of shiphull rust removal

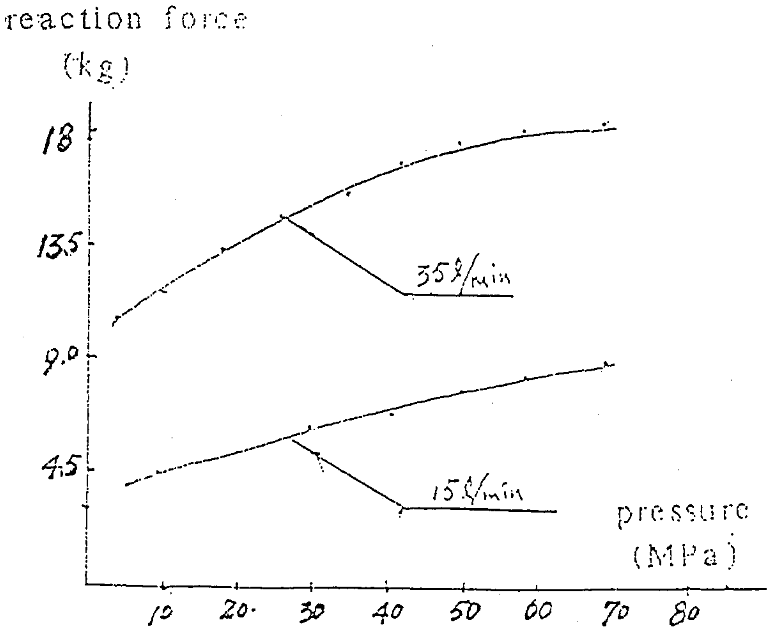

Fig.9 reacting force of jet gun

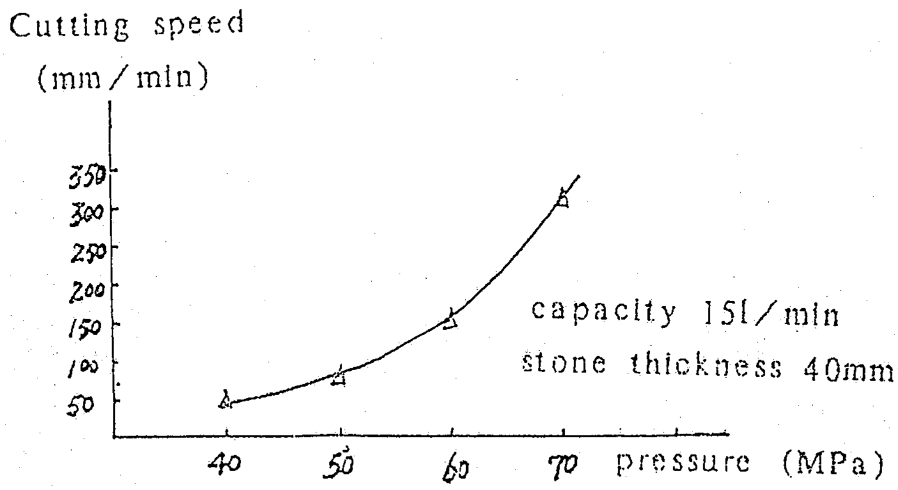

Fig.10 Speed chart of limestone cutting

7th American Water Jet Conference
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ON THE JOB

AN OVERVIEW OF OCCUPATIONAL SAFETY AND HEALTH ACT REGULATIONS, STANDARDS, AND REQUIREMENTS IN THE WORKPLACE

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ABSTRACT

Employers conducting business in a workplace in the United States of America must comply with regulations, standards, and requirements promulgated by the U. S. Department of Labor through the Occupational Safety and Health Act of 1970. The objective of this Article is to introduce the reader of some of those requirements, standards, and regulations in an attempt to draw attention to the actions necessary for compliance in hope of making a safer workplace for employees.

AUTHOR'S NOTE:

This paper is intended only to be a general introduction to the Occupational Health and Safety Act under the U. S. Department of Labor. No legal advice is intended to be given, nor is rendered in this paper. Any individual or business entity should consult with an attorney or qualified professional for advice relating to that person or business entity's specific individual circumstances relating to the Occupational Health and Safety Act.

1. The Occupational Health and Safety Act of 1970 ("the Act") was drafted by the U. S. Congress to provide uniform and comprehensive provisions for workplace safety. Congress had determined that the burden on the nation's commerce relating to lost production, wages, medical expenses, and disability compensation was enormous. In an attempt to relieve this burden, the Act was drafted and enacted. The Act is administered by the Occupational Health and Safety Administration ("OSHA") under the United States Department of Labor. OSHA's objectives are to:

- o Encourage employers and employees to reduce workplace hazards and to implement new or improve existing safety and health programs;
- o Provide for research in occupational safety and health to develop innovative ways of dealing with occupational safety and health problems.
- o Establish "separate but dependent responsibilities and rights" for employers and employees for the achievement of better safety and health conditions.
- o Maintain a reporting and recordkeeping system to monitor job- related injuries and illnesses;
- o Establish training programs to increase the number and competence of occupational safety and health personnel;
- o Develop mandatory job safety and health standards and enforce them effectively; and
- o Provide for the development, analysis, evaluation and approval of state occupational safety and health programs.

This paper will provide the reader with a basic understanding of OSHA. By understanding the Act and its purpose, employers may be more able to conform their actions with the Act and avoid costly citations from OSHA inspectors.

2. EMPLOYERS COVERED BY OSHA

OSHA or a federally approved OSHA state program provides to all employers and their employees in the fifty states, the District of Columbia, Puerto Rico, and all United States territories which fall under Federal Government jurisdiction coverage under the Act.OSHA applies to all employers and employees for employment performed in a workplace including workers employed by religious groups who perform secular jobs. A limited group of employees are not covered by OSHA, those employees are:

1. Self-employed persons;
2. Farms on which only immediate family members are employed; and
3. Workplaces which are protected by other federal agencies under other federal states.

Federal employees are covered by safety and health standards drafted by each Agency as analyzed by the Department of Labor. Many Agencies are subject to OSHA inspection. State and local governments are also outside of OSHA requirements, but those governments must draft, establish, and maintain occupational safety and health standards and programs.

3. STANDARDS

OSHA drafts and enacts legally enforceable standards so that it may carry out its duties.

OSHA has drafted specific standards for four major categories - General Industry, Maritime, Construction and Agriculture. In addition to these four major categories, the general duty clause, which reads:

Each employer "shall furnish . . . a place of employment which is free from recognized hazards that are causing or are likely to cause death or serious physical harm to his employees."

expands coverage to additional categories.

All OSHA standards are published in the Federal Register when adopted, amended, deleted, corrected, or altered. Annually, the standards are printed in the Code of Federal Regulations (CFR) under Title 29 of the CFR, parts 1900-1999.

Copies of standards can be obtained from any local OSHA Area Office or from one of the ten Regional Offices. A list of Regional Offices is provided on Attachment A, which follows this paper. Also, the OSHA Subscription Service provides current information on standards, interpretations, regulations, and procedures on loose leaf paper punched for three-ring binders. Information relating to this service can be obtained from the Government Printing Office, Washington, D.C. 20402.

4. RECORDKEEPING AND REPORTING

OSHA recordkeeping requires that employers keep records relating to workplace injuries and illnesses on OSHA-approved forms.

Specific rules control those employers who must report and those employers who are exempt from reporting. Each employer should examine their own circumstances to determine reporting requirements.

4.1 Reporting Occurrences and Employment Relationships

Records must be kept for reportable illnesses and injuries. Record information must be kept for each occupational death, each nonfatal occupational illness; and those nonfatal occupational injuries which involve one or more of the following: loss of consciousness, restriction of work or motion, transfer to another job, or medical treatment (other than first aid). Any employee employed in a pay status is subject to reportable injuries. Two charts from OSHA can assist employers in determining whether or not an injury should be recorded. Chart 1 describes whether or not a work relationship existed between the employer and the employee and Chart 2 describes the guidelines for establishing work relationships. These charts follow this paper as Attachment B.

4.2 Supplementary Records - Form: OSHA 101

Each reportable injury or illness must first be reported by the employee to the employer. Employers then must record the reportable illness or injury on an approved form. In most cases, the employer is covered by its state workers' compensation insurance. Where a state workers' compensation claim form exists, that form may be used to record the injury or illness. Where state forms are not used, the OSHA 101 Form (Attachment C) should be completed. The OSHA 101 is not as detailed as most state claim forms, but provides the information necessary for compilation on the OSHA 200 Log.

4.3 OSHA 200 Log

Each employer subject to OSHA's rules must keep and maintain an OSHA 200 Log (Attachment D). This log must be kept in an accessible place where employees may review the logs. Logs for the preceding five years must be kept together and be available for review. The 200 Log for the current or immediately preceding year should be posted along with a Job Safety and Health Protection Poster

(Attachment E) where employees can easily read the information. Most employers post these documents on an employee bulletin board. Failure to maintain an OSHA 200 Log can result in fines and/or penalties when a company is inspected by OSHA and no 200 log is maintained.

4.4 Inspection Check Lists

Many employers find that these recordkeeping requirements are tedious and then neglect their duties. With a small amount of time investment, the required forms can be established and maintained. Attachments F and G are copies of the Inspection Checklists for Employees and Management, respectively, covered by OSHA inspectors. These Checklists can help employers review their own systems of recordkeeping in compliance with OSHA's regulations.

5. TRAINING REQUIREMENTS

OSHA has developed voluntary training requirements within more than 100 current standards. At present, it does not appear that OSHA intends to make these training guidelines mandatory. Employers are recommended to educate and train their employees within the training guidelines for their specific job and work related tasks. Most of OSHA's training guidelines follow this model:

(1) Determine if training is necessary;
(2) Identify that training;
(3) Identify goals and objectives for the training;
(4) Develop learning activities for training;
(5) Conduct training activities;
(6) Evaluate training program; and
(7) Work to improve training program.

Training should be matched with employees who have priority needs for specific training activities relating to job related tasks. All employees and their jobs should be evaluated by the employer and training fitting with the OSHA model should be provided where necessary.

6. WORKPLACE HAZARDS

Hazards in the workplace occur on almost every job. OSHA specifically addresses many workplace hazards in an attempt to reduce worker injuries and illnesses arising from such hazards. In this paper, hazards relating to confined spaces and stored energy (Lockout/Tagout) will be addressed. These areas of workplace hazard are so severe that they deserve special attention.

6.1 Confined Spaces

Worker entries into confined spaces have been the cause of numerous fatalities. Many of those fatalities included other workers or passers-by who attempted a rescue without proper training and equipment. A confined space is identified as a space:

(1) not designed for continuous worker occupancy;
(2) which has limited exits and openings; and
(3) which has unfavorable natural ventilation.

In many cases, OSHA requires that employers obtain a permit before workers may enter and work inside of a confined space. Provisions must be made to ensure worker safety by testing the atmosphere inside of the space at several depth levels within the space, providing proper ventilation, protecting against flammable atmospheres, providing workers with proper respiration devices, evaluating the physical hazards of the space and surrounding environment, and providing a standby worker and an established rescue plan.

Countless lives have been unnecessarily lost due to non-compliance with OSHA regulations relating to confined spaces. If an employer has a confined space in which workers are expected to enter, the employer should take all steps to comply with the OSHA requirements for confined spaces.

6.2 Lock-Out/Tag-Out - Stored Energy

Employees who work with or close to machinery in the workplace encounter hazards relating to those machines. OSHA has promulgated standards governing machinery maintenance and stored energy in machinery. Stored energy can originate from a power source which unexpectedly activates the machinery during maintenance or from within the machinery itself. Unique hazards exist while machinery is being maintained or serviced. OSHA claims that almost ten percent (10%) of all serious accidents arise from failure to control stored energy.

OSHA requires that a written Lockout/Tagout procedure be drafted and implemented by employers. Specific attention must be given to servicing and maintenance activities for controlling hazardous stored energy.

When employees are directed to service and maintain machinery, precautions must be taken to ensure that they machinery will not unexpectedly engage while the service or maintenance is underway. Locks and tags must be placed on power sources to prevent other employees from engaging the machinery. 29 CFR Section 1910.147 should be read thoroughly to ensure that workers are protected from unexpected machinery activation.

Lockout/Tagout procedures are intended to work together with other regulations relating to service and/or maintenance which takes place under normal production operations. Employers should also note that OSHA regulations address machinery guards and protectors for use while machinery is in operation.

Many times, merely cutting off a power source or shutting down a piece of machinery will not totally control stored energy. Potential energy can be stored within the machinery and create a hazardous condition for workers.

Stored energy within machinery can exist in the form of residual energy - such as that energy stored in springs under tension or compression or by the atmospheric pressure of gases or liquids. The release of residual energy can cause injury and precautions should be taken to ensure that the energy is released or that it is guarded so that no energy is released before repairs and maintenance commence. Machinery should be positioned in a neutral state and effective locks and tags should be placed to prevent other movement and/or warn of the work being undertaken.

Lockout/Tagout procedures are vitally important for protecting workers, and employers should maintain the required written policy, along with procedures for lockout/tagout and the locks and tags necessary to protect their employees.

7. WORKPLACE SIGNS, LABELS, AND MARKINGS

Title 29 of the Code of Federal Regulations has specific requirements relating to labels, signs, and markings required in the workplace. Some of the topics addressed are: WALKING WORKING SURFACES (29 CFR Section 1910.22(b)(2); (d)(1)); MEANS OF EGRESS (29 CFR Section 1910.37(q)); POWERED PLATFORMS, MANLIFTS, AND VEHICLE-MOUNTED WORK PLATFORMS (29 CFR Section 1910.66(f)(3); (f)(15), (f)(7), (i)(2)); and OCCUPATIONAL HEALTH AND ENVIRONMENTAL CONTROL (29 CFR Section 1910.96(e)(1-6). An important regulation concerns Hazardous Materials (HAZMAT) (29 CFR Section 1910.103(b)(1)(i), (v); (c)(1)(iii), (2)(i)). All hazardous materials must be handled in accordance with OSHA regulations and must be labeled in compliance thereto. The particular rules for labeling are beyond the scope of this Article and any employer handling any hazardous material should consult OSHA regulations for proper handling and labeling. Proper signs and markings should also be posted as required.

8. MATERIAL SAFETY DATA SHEETS

Under 29 CFR Section 1910.1200, OSHA requires that any hazardous material in the workplace be recorded by a Material Safety Data Sheet ("MSDS Sheet"). MSDS sheets must be kept for employees to review at any time. Manufacturers of materials so designated as hazardous will provide MSDS sheets for filing.

Many obvious materials are considered hazardous and require an MSDS sheet to be on file, however, other more subtle products such as liquid paper, copy machine toner, and floor wax require a MSDS sheet.

Failure to maintain MSDS sheets is a common violation during an OSHA inspection. Employers should work towards maintaining an up to date MSDS sheet file in a place where it is readily accessible by employees. Keeping the file as required by OSHA regulations can ensure one less violation in the event that OSHA comes to inspect your workplace.

9. CONCLUSION

Employers may be reluctant to comply with OSHA regulations under which their workplaces are governed, but those employers should keep in mind the purpose behind the regulations. The Department of Labor and the Occupational Safety and Health Administration promulgate the regulations in an attempt to protect workers on the job. Compliance with the many OSHA regulations should be effectuated by the cooperation of employers and employees. When working together, persons at the workplace can make that workplace a healthier and safer place to work.

ATTACHMENT "A"

Ten Regional Offices

If you are unable to contact your local OSHA Area Office, you may contact the appropriate OSHA Regional Office for information and/or assistance.

Region I
(CT,* MA, ME, NH, RI, VT*)
133 Portland Street
1st Floor
Boston, MA 02114
Telephone: (617) 565-7164

Region II
(NJ, NY,* PR,* VI*)
201 Varick Street
Room 670
New York, NY 10014
Telephone: (212) 337-2378

Region III
(DC, DE, MD,* PA, VA,* WV)
Gateway Building, Suite 2100
3535 Market Street
Philadelphia, PA 19104
Telephone: (215) 596-1201

Region IV
(AL, FL, GA, KY,* MS, NC,* SC,* TN*)
1375 Peachtree Street, N.E.
Suite 587
Atlanta, GA 30367
Telephone: (404) 347-3573

Region V
(IL, IN,* MI,* MN,* OH, WI)
230 South Dearborn Street
Room 3244
Chicago, IL 60604
Telephone: (312) 353-2220

Region VI
(AR, LA, NM,* OK, TX)
525 Griffin Street
Room 602
Dallas, TX 75202
Telephone: (214) 767-4731

Region VII
(IA,* KS, MO, NE)
911 Walnut Street
Room 406
Kansas City, MO 64106
Telephone: (816) 426-5861

Region VIII
(CO, MT, ND, SD, UT,* WY*)
Federal Building, Room 1576
1961 Stout Street
Denver, CO 80294
Telephone:(303) 844-3061

Region IX
(American Samoa, AZ,* CA,* Guam, HI,* NV,* Trust Territories of the Pacific)
71 Stevenson Street
Room 415
San Francisco, CA 94105
Telephone: (415) 744-6670

Region X
(AK,* ID, OR,* WA*)
1111 Third Avenue, Suite 715
Seattle, WA 98101-3212
Telephone: (206) 442-5930

*These states and territories operate their own OSHA-approved job safety and health programs (Connecticut and New York plans cover public employees only). States with approved programs must have a standard that is identical to, or at least as effective as, the federal standard.

ATTACHMENT "B"

Chart 1. Guide to recordability of cases under the Occupational Safety and Health Act

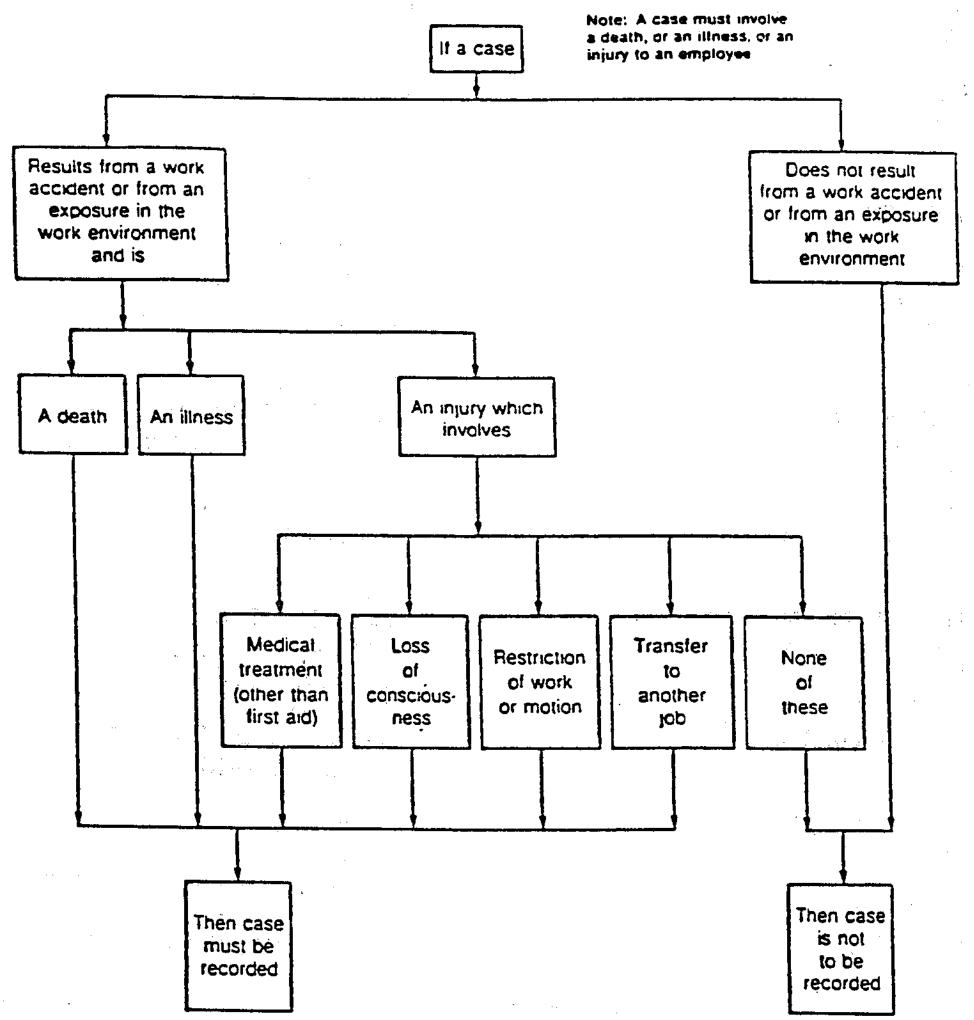
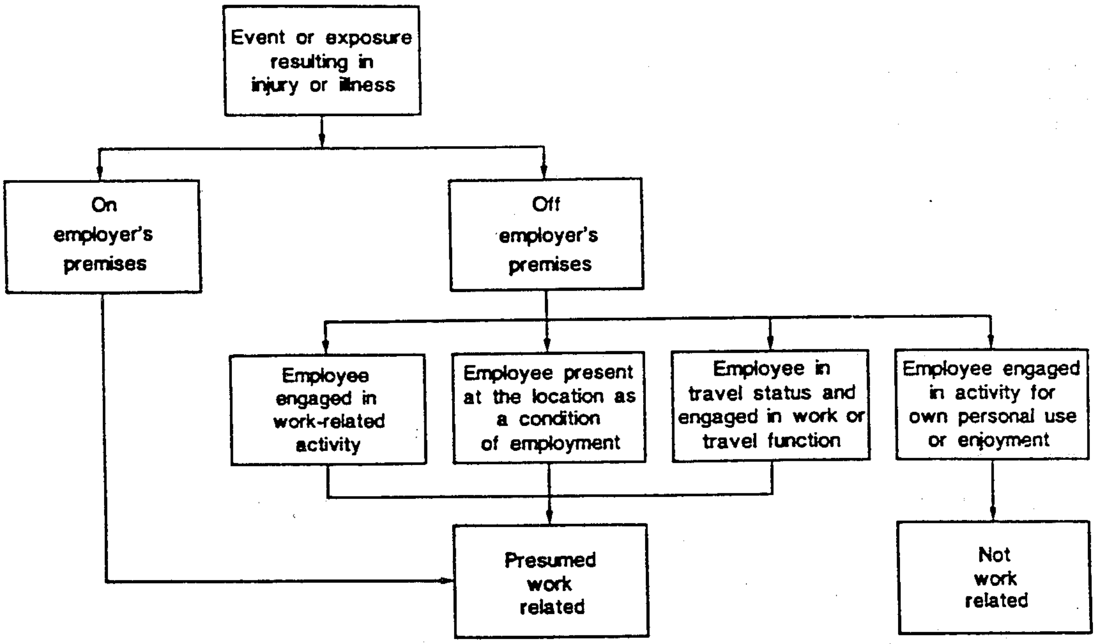


Chart 2. Guidelines for establishing work relationship



ATTACHMENT "C"

SUPPLEMENTARY RECORD OF OCCUPATIONAL INJURIES AND ILLNESSES (OSHA No. 101)

To supplement the Log and Summary of Occupational Injuries and Illnesses (OSHA No. 200), each establishment must maintain a record of each recordable occupational injury or illness. Worker's compensation, insurance, or other reports are acceptable as records if they contain all facts listed below or are supplemented to do so. If no suitable report is made for other purposes, this form (OSHA No. 101) may be used or the necessary facts can be listed on a separate plain sheet of paper. These records must also be available in the establishment without delay and at reasonable times for examination by representatives of the Department of Labor and the Department of Health and Human Services, and States accorded jurisdiction under the Act. The records must be maintained for a period of not less than five years following the end of the calendar year to which they relate.

Such records must contain at least the following facts:

1) *About the employer* - Name, mail address, and location if different from mail address.

2) *About the injured or ill employee* - name, social security number, home address, age, sex, occupation, and department.

3) *About the accident or exposure to occupational illness* - place of accident or exposure, whether it was on employer's premises, what the employee was doing when injured, and how the accident occurred.

4) *About the occupational injury or illness* - description of the injury or illness, including part of body affected; name of the object or substance which directly injured the employee; and date of injury or diagnosis of illness.

5) *Other* - name and address of physician; if hospitalized, name and address of hospital; date of report; and name and position of person preparing the report.

SEE *DEFINITIONS* ON THE BACK OF OSHA FORM 200.

Bureau of Labor Statistics
Supplementary Record of
Occupational Injuries and Illnesses

U.S. Department of Labor

This form is required by Public Law 91-596 and must be kept in the establishment for 5 years. Failure to maintain can result in the issuance of citations and assessment of penalties.	Case or File No.	Form Approved O.M.B. No. 1220-0029

Employer

1. Name

2. Mail address *(No. and street, city or town, State, and zip code)*

3. Location, if different from mail address

Injured or Ill Employee

4. Name *(First, middle, and last)* — Social Security No.

5. Home address *(No. and street, city or town, State, and zip code)*

6. Age — 7. Sex: *(Check one)* Male ☐ Female ☐

8. Occupation *(Enter regular job title, not the specific activity he was performing at time of injury.)*

9. Department *(Enter name of department or division in which the injured person is regularly employed, even though he may have been temporarily working in another department at the time of injury.)*

The Accident or Exposure to Occupational Illness

If accident or exposure occurred on employer's premises, give address of plant or establishment in which it occurred. Do not indicate department or division within the plant or establishment. If accident occurred outside employer's premises at an identifiable address, give that address. If it occurred on a public highway or at any other place which cannot be identified by number and street, please provide place references locating the place of injury as accurately as possible.

10. Place of accident or exposure *(No. and street, city or town, State, and zip code)*

11. Was place of accident or exposure on employer's premises? Yes ☐ No ☐

12. What was the employee doing when injured? *(Be specific. If he was using tools or equipment or handling material, name them and tell what he was doing with them.)*

13. How did the accident occur? *(Describe fully the events which resulted in the injury or occupational illness. Tell what happened and how it happened. Name any objects or substances involved and tell how they were involved. Give full details on all factors which led or contributed to the accident. Use separate sheet for additional space.)*

Occupational Injury or Occupational Illness

14. Describe the injury or illness in detail and indicate the part of body affected. *(E.g., amputation of right index finger at second joint; fracture of ribs; lead poisoning; dermatitis of left hand, etc.)*

15. Name the object or substance which directly injured the employee. *(For example, the machine or thing he struck against or which struck him; the vapor or poison he inhaled or swallowed; the chemical or radiation which irritated his skin; or in cases of strains, hernias, etc., the thing he was lifting, pulling, etc.)*

16. Date of injury or initial diagnosis of occupational illness — 17. Did employee die? *(Check one)* Yes ☐ No ☐

Other

18. Name and address of physician

19. If hospitalized, name and address of hospital

Date of report	Prepared by	Official position

OSHA No. 101 (Feb. 1981)

ATTACHMENT "D"

Public reporting burden for this collection of information is estimated to vary from 8 to 30 minutes per line entry, including time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding the burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to the Office of Information Management, Department of Labor, Room N-1301, 200 Constitution Avenue, NW, Washington, DC 20210; and to the Office of Information and Regulatory Affairs, Office of Management and Budget, Washington, DC 20503.

Instructions for OSHA No. 200

I. Log and Summary of Occupational Injuries and Illnesses

Each employer who is subject to the recordkeeping requirements of the Occupational Safety and Health Act of 1970 must maintain for each establishment a log of all recordable occupational injuries and illnesses. This form (OSHA No. 200) may be used for that purpose. A substitute for the OSHA No. 200 is acceptable if it is as detailed, easily readable, and understandable as the OSHA No. 200.

Enter each recordable case on the log within six (6) workdays after learning of its occurrence. Although other records must be maintained at the establishment to which they refer, it is possible to prepare and maintain the log at another location, using data processing equipment if desired. If the log is prepared elsewhere, a copy updated to within 45 calendar days must be present at all times in the establishment.

Logs must be maintained and retained for five (5) years following the end of the calendar year to which they relate. Logs must be available (normally at the establishment) for inspection and copying by representatives of the Department of Labor, or the Department of Health and Human Services, or States accorded jurisdiction under the Act. Access to the log is also provided to employees, former employees and their representatives.

II. Changes in Extent of or Outcome of Injury or Illness

If, during the 5-year period the log must be retained, there is a change in an extent and outcome of an injury or illness which affects entries in columns 1, 2, 6, 8, 9, or 13, the first entry should be lined out and a new entry made. For example, if an injured employee at first required only medical treatment but later lost workdays away from work, the check in column 6 should be lined out, and checks entered in columns 2 and 3 and the number of lost workdays entered in column 4.

In another example, if an employee with an occupational illness lost workdays, returned to work, and then died of the illness, any entries in columns 9 through 12 should be lined out and the date of death entered in column 8.

The entire entry for an injury or illness should be lined out if later found to be nonrecordable. For example an injury which is later determined not to be work related, or which was initially thought to involve medical treatment but later was determined to have involved only first aid.

III. Posting Requirements

A copy of the totals and information following the fold line of the last page for the year must be posted at each establishment in the place or places where notices to employees are customarily posted. This copy must be posted no later than *February 1 and must remain in place until March 1.*

Even though there were no injuries or illnesses during the year, zeros must be entered on the totals line, and the form posted.

The person responsible for the *annual summary totals* shall certify that the totals are true and complete by signing at the bottom of the form.

IV. Instructions for Completing Log and Summary of Occupational Injuries and Illnesses

Column A – CASE OR FILE NUMBER. Self-explanatory.

Column B – DATE OF INJURY OR ONSET OF ILLNESS.
For occupational injuries, enter the date of the work accident which resulted in injury. For occupational illnesses, enter the date of initial diagnosis of illness, or, if absence from work occurred before diagnosis, enter the first day of the absence attributable to the illness which was later diagnosed or recognized.

Columns C through F – Self-explanatory.

Columns 1 and 8 – INJURY OR ILLNESS-RELATED DEATHS.
Self-explanatory.

Columns 2 and 9 – INJURIES OR ILLNESSES WITH LOST WORKDAYS.
Self-explanatory.

Any injury which involves days away from work, or days of restricted work activity, or both must be recorded since it always involves one or more of the criteria for recordability.

Columns 3 and 10 – INJURIES OR ILLNESSES INVOLVING DAYS AWAY FROM WORK. Self-explanatory.

Columns 4 and 11 – LOST WORKDAYS—DAYS AWAY FROM WORK.
Enter the number of workdays (consecutive or not) on which the employee would have worked but could not because of occupational injury or illness. The number of lost workdays should not include the day of injury or onset of illness or any days on which the employee would not have worked even though able to work.
NOTE: For employees not having a regularly scheduled shift, such as certain truck drivers, construction workers, farm labor, casual labor, part-time employees, etc., it may be necessary to estimate the number of lost workdays. Estimates of lost workdays shall be based on prior work history of the employee AND days worked by employees, not ill or injured, working in the department and/or occupation of the ill or injured employee.

Columns 5 and 12 – LOST WORKDAYS—DAYS OF RESTRICTED WORK ACTIVITY.
Enter the number of workdays (consecutive or not) on which because of injury or illness:

(1) the employee was assigned to another job on a temporary basis; or
(2) the employee worked at a permanent job less than full time, or
(3) the employee worked at a permanently assigned job but could not perform all duties normally connected with it.

The number of lost workdays should not include the day of injury or onset of illness or any days on which the employee would not have worked even though able to work.

U.S. GOVERNMENT PRINTING OFFICE : 1982 O - 227-655

Columns
6 and 13 – INJURIES OR ILLNESSES WITHOUT LOST WORKDAYS. Self-explanatory.

Columns 7a
through 7g – TYPE OF ILLNESS.
Enter a check in only *one* column for each illness.

TERMINATION OR PERMANENT TRANSFER—Place an asterisk to the right of the entry in columns 7a through 7g (type of illness) which represented a termination of employment or permanent transfer.

V. Totals

Add number of entries in columns 1 and 8.
Add number of checks in columns 2, 3, 6, 7, 9, 10, and 13.
Add number of days in columns 4, 5, 11, and 12.
Yearly totals for each column (1-13) are required for posting. Running or page totals may be generated at the discretion of the employer.

If an employee's loss of workdays is continuing at the time the totals are summarized, estimate the number of future workdays the employee will lose and add that estimate to the workdays already lost and include this figure in the annual totals. No further entries are to be made with respect to such cases in the next year's log.

VI. Definitions

OCCUPATIONAL INJURY is any injury such as a cut, fracture, sprain, amputation, etc., which results from a work accident or from an exposure involving a single incident in the work environment.
NOTE: Conditions resulting from animal bites, such as insect or snake bites or from one-time exposure to chemicals, are considered to be injuries.

OCCUPATIONAL ILLNESS of an employee is any abnormal condition or disorder, other than one resulting from an occupational injury, caused by exposure to environmental factors associated with employment. It includes acute and chronic illnesses or diseases which may be caused by inhalation, absorption, ingestion, or direct contact.

The following listing gives the categories of occupational illnesses and disorders that will be utilized for the purpose of classifying recordable illnesses. For purposes of information, examples of each category are given. These are typical examples, however, and are not to be considered the complete listing of the types of illnesses and disorders that are to be counted under each category.

7a. Occupational Skin Diseases or Disorders
Examples: Contact dermatitis, eczema, or rash caused by primary irritants and sensitizers or poisonous plants, oil acne; chrome ulcers; chemical burns or inflammations; etc.

7b. Dust Diseases of the Lungs (Pneumoconioses)
Examples: Silicosis, asbestosis and other asbestos-related diseases, coal worker's pneumoconiosis, byssinosis, siderosis, and other pneumoconioses.

7c. Respiratory Conditions Due to Toxic Agents
Examples: Pneumonitis, pharyngitis, rhinitis or acute congestion due to chemicals, dusts, gases, or fumes; farmer's lung, etc.

7d. Poisoning (Systemic Effect of Toxic Materials)
Examples: Poisoning by lead, mercury, cadmium, arsenic, other metals; poisoning by carbon monoxide, hydrogen sulfi[illegible] or other gases; poisoning by benzol, carbon tetrachloride, other organic solvents; poisoning by insecticide sprays such [illegible] parathion, lead arsenate; poisoning by other chemicals such [illegible] formaldehyde, plastics, and resins; etc.

7e. Disorders Due to Physical Agents (Other than Toxic Materi[illegible]
Examples: Heatstroke, sunstroke, heat exhaustion, and ot[illegible] effects of environmental heat; freezing, frostbite, and effects [illegible] exposure to low temperatures; caisson disease; effects of ioniz[illegible] radiation (isotopes, X-rays, radium); effects of nonionizing radi[illegible]tion (welding flash, ultraviolet rays, microwaves, sunburn); et[illegible]

7f. Disorders Associated With Repeated Trauma
Examples: Noise-induced hearing loss; synovitis, tenosynoviti[illegible] and bursitis; Raynaud's phenomena; and other conditions du[illegible] repeated motion, vibration, or pressure.

7g. All Other Occupational Illnesses
Examples: Anthrax, brucellosis, infectious hepatitis, malignan[illegible] and benign tumors, food poisoning, histoplasmosis, coccidioi[illegible] mycosis, etc.

MEDICAL TREATMENT includes treatment (other than first aid) admi[illegible]istered by a physician or by registered professional personnel under th[illegible] standing orders of a physician. Medical treatment does NOT include fir[illegible] aid treatment (one-time treatment and subsequent observation of mi[illegible] scratches, cuts, burns, splinters, and so forth, which do not ordinaril[illegible] quire medical care) even though provided by a physician or regist[illegible] professional personnel.

ESTABLISHMENT: A single physical location where business is condu[illegible]ed or where services or industrial operations are performed (for examp[illegible] a factory, mill, store, hotel, restaurant, movie theater, farm, ranch, ba[illegible] sales office, warehouse, or central administrative office). Where distin[illegible] separate activities are performed at a single physical location, such as c[illegible]struction activities operated from the same physical location as a lumbe[illegible] yard, each activity shall be treated as a separate establishment.

For firms engaged in activities which may be physically dispersed, such a[illegible] agriculture; construction; transportation; communications; and electri[illegible] gas, and sanitary services, records may be maintained at a place to whi[illegible] employees report each day.

Records for personnel who do not primarily report or work at a sin[illegible] establishment, such as traveling salesmen, technicians, engineers, etc., sh[illegible] be maintained at the location from which they are paid or the base fr[illegible] which personnel operate to carry out their activities.

WORK ENVIRONMENT is comprised of the physical location, equipme[illegible] materials processed or used, and the kinds of operations performed in [illegible] course of an employee's work, whether on or off the employer's premi[illegible]

Bureau of Labor Statistics
Log and Summary of Occupational
Injuries and Illnesses

NOTE: **This form is required by Public Law 91-596 and must be kept in the establishment for 5 years. Failure to maintain and post can result in the issuance of citations and assessment of penalties.** ***(See posting requirements on the other side of form.)***

RECORDABLE CASES: You are required to record information about every occupational death, every nonfatal occupational illness; and those nonfatal occupational injuries which involve one or more of the following: loss of consciousness, restriction of work or motion, transfer to another job, or medical treatment (other than first aid). ***(See definitions on the other side of form.)***

Company Name

Establishment Nar

Establishment Add

Case or File Number Enter a nonduplicating number which will facilitate comparisons with supplementary records. (A)	Date of Injury or Onset of Illness Enter Mo./day. (B)	Employee's Name Enter first name or initial, middle initial, last name. (C)	Occupation Enter regular job title, not activity employee was performing when injured or at onset of illness. In the absence of a formal title, enter a brief description of the employee's duties. (D)	Department Enter department in which the employee is regularly employed or a description of normal workplace to which employee is assigned, even though temporarily working in another department at the time of injury or illness. (E)	Description of Injury or Illness Enter a brief description of the injury or illness and indicate the part or parts of body affected. Typical entries for this column might be: Amputation of 1st joint right forefinger; Strain of lower back; Contact dermatitis on both hands, Electrocution—body. (F)	Extent of and Outc Fatalities Injury Related Enter DATE of death. Mo./day/yr. (1)	Nonf Injun Enter CHEC if inj involv days from work, days restri work activi or bo (2)
					PREVIOUS PAGE TOTALS →		
					TOTALS (Instructions on other side of form.) →		

OSHA No. 200

☆U.S. GOVERNMENT PRINTING OFFICE: 1989 241-374/08097

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OSHA No. 20(

S. Department of Labor

For Calendar Year 19 ______ Page ___ of ___

Form Approved
O.M.B. No. 1220-0029
See OMB Disclosure Statement on reverse.

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ome of INJURY					Type, Extent of, and Outcome of ILLNESS													
atal Injuries					Type of Illness							Fatalities	Nonfatal Illnesses					
es With Lost Workdays				Injuries Without Lost Workdays	CHECK Only One Column for Each Illness (See other side of form for terminations or permanent transfers.)							Illness Related	Illnesses With Lost Workdays					Illnesses Without Lost Workdays
a CK ry res away or of cted ty, th.	Enter a CHECK if injury involves days away from work.	Enter number of DAYS away from work.	Enter number of DAYS of restricted work activity.	Enter a CHECK if no entry was made in columns 1 or 2 but the injury is recordable as defined above.	Occupational skin diseases or disorders	Dust diseases of the lungs	Respiratory conditions due to toxic agents	Poisoning (systemic effects of toxic materials)	Disorders due to physical agents	Disorders associated with repeated trauma	All other occupational illnesses	Enter DATE of death. Mo./day/yr.	Enter a CHECK if illness involves days away from work, or days of restricted work activity, or both.	Enter a CHECK if illness involves days away from work.	Enter number of DAYS away from work.	Enter number of DAYS of restricted work activity.	Enter a CHECK if no entry was made in columns 8 or 9.
	(3)	(4)	(5)	(6)	(7) (a)	(b)	(c)	(d)	(e)	(f)	(g)	(8)	(9)	(10)	(11)	(12)	(13)

INJURIES

ILLNESSES

Annual Summary Totals By ______________________ Title ______________________ Date ______________

POST ONLY THIS PORTION OF THE LAST PAGE NO LATER THAN FEBRUARY 1.

ATTACHMENT "E"

JOB SAFETY & HEALTH PROTECTION

The Occupational Safety and Health Act of 1970 provides job safety and health protection for workers by promoting safe and healthful working conditions throughout the Nation. Provisions of the Act include the following:

Employers

All employers must furnish to employees employment and a place of employment free from recognized hazards that are causing or are likely to cause death or serious harm to employees. Employers must comply with occupational safety and health standards issued under the Act.

Employees

Employees must comply with all occupational safety and health standards, rules, regulations and orders issued under the Act that apply to their own actions and conduct on the job.

The Occupational Safety and Health Administration (OSHA) of the U.S. Department of Labor has the primary responsibility for administering the Act. OSHA issues occupational safety and health standards, and its Compliance Safety and Health Officers conduct jobsite inspections to help ensure compliance with the Act.

Proposed Penalty

The Act provides for mandatory penalties against employers of up to $1,000 for each serious violation and for optional penalties of up to $1,000 for each nonserious violation. Penalties of up to $1,000 per day may be proposed for failure to correct violations within the proposed time period. Also, any employer who willfully or repeatedly violates the Act may be assessed penalties of up to $10,000 for each such violation.

There are also provisions for criminal penalties. Any willful violation resulting in death of an employee, upon conviction, is punishable by a fine of up to $250,000 (or $500,000 if the employer is a corporation), or by imprisonment for up to six months, or both. A second conviction of an employer doubles the possible term of imprisonment.

Voluntary Activity

While providing penalties for violations, the Act also encourages efforts by labor and management, before an OSHA inspection, to reduce workplace hazards voluntarily and to develop and improve safety and

Inspection

The Act requires that a representative of the employer and a representative authorized by the employees be given an opportunity to accompany the OSHA inspector for the purpose of aiding the inspection.

Where there is no authorized employee representative, the OSHA Compliance Officer must consult with a reasonable number of employees concerning safety and health conditions in the workplace.

Complaint

Employees or their representatives have the right to file a complaint with the nearest OSHA office requesting an inspection if they believe unsafe or unhealthful conditions exist in their workplace. OSHA will withhold, on request, names of employees complaining.

The Act provides that employees may not be discharged or discriminated against in any way for filing safety and health complaints or for otherwise exercising their rights under the Act.

Employees who believe they have been discriminated against may file a complaint with their nearest OSHA office within 30 days of the alleged discriminatory action.

Citation

If upon inspection OSHA believes an employer has violated the Act, a citation alleging such violations will be issued to the employer. Each citation will specify a time period within which the alleged violation must be corrected.

The OSHA citation must be prominently displayed at or near the place of alleged violation for three days, or until it is corrected, whichever is later, to warn employees of dangers that may exist there.

health programs in all workplaces and industries. OSHA's Voluntary Protection Programs recognize outstanding efforts of this nature.

OSHA has published Safety and Health Program Management Guidelines to assist employers in establishing or perfecting programs to prevent or control employee exposure to workplace hazards. There are many public and private organizations that can provide information and assistance in this effort, if requested. Also, your local OSHA office can provide considerable help and advice on solving safety and health problems or can refer you to other sources for help such as training.

Consultation

Free assistance in identifying and correcting hazards and in improving safety and health management is available to employers, without citation or penalty, through OSHA-supported programs in each State. These programs are usually administered by the State Labor or Health department or a State university.

Posting Instructions

Employers in States operating OSHA approved State Plans should obtain and post the State's equivalent poster.

Under provisions of Title 29,Code of Federal Regulations, Part 1903.2(a)(1) employers must post this notice (or facsimile) in a conspicuous place where notices to employees are customarily posted.

More Information

Additional information and copies of the Act, specific OSHA safety and health standards, and other applicable regulations may be obtained from your employer or from the nearest OSHA Regional Office in the following locations:

Atlanta	(404) 347-3573
Boston	(617) 565-7164
Chicago	(312) 353-2220
Dallas	(214) 767-4731
Denver	(303) 844-3061
Kansas	(816) 426-5861
New York	(212) 337-2325
Philadelphia	(215) 596-1201
San Francisco	(415) 995-5672
Seattle	(206) 442-5930

Elizabeth Dole

Elizabeth Dole, Secretary of Labor

Washington, D.C.
1989 (Revised)
OSHA 2203

U.S. Department of Labor

Occupational Safety and Health Administration

ATTACHMENT "F"

Inspection Checklist for Employees

U.S. DEPARTMENT OF LABOR
Occupational Safety and Health Administration

CSHO NAME	INSPECTION NUMBER
INTERPRETER'S NAME (If Any)	INTERVIEW DATE

EMPLOYEE DATA

NAME (FIRST) (MIDDLE) (LAST)	
OCCUPATION	NUMBER OF YEARS
EMPLOYMENT (DEPT./DIVISION WHERE REGULARLY EMPLOYED)	

EMPLOYEE QUESTIONAIRE

(Y) (N) (If additional space is needed, continue on reverse or on a separate sheet of paper.)

☐ ☐ 1. HAVE YOU EVER SEEN AN OSHA 200 FOR YOUR ESTABLISHMENT? *IF YES, CHECK THOSE (a or b) THAT APPLY:*

☐ a. VIEWED THE SUMMARY PORTION OF THE LOG POSTED BY THE EMPLOYER.

☐ b. REQUESTED ACCESS TO VIEW THE ENTIRE OSHA 200 LOG.

☐ ☐ 2. DID YOU EXPERIENCE AN INJURY OR ILLNESS DURING THIS YEAR OR LAST YEAR THAT WAS CAUSED OR AGGRAVATED BY AN EVENT OR EXPOSURE IN YOUR WORK ENVIRONMENT? *IF YES, ANSWER a THROUGH e BELOW.*

a. BRIEFLY DESCRIBE THE INJURIES AND ILLNESSES. ______________

____

____

☐ ☐ b. DID YOU REPORT THE INJURIES OR ILLNESSES TO YOUR EMPLOYER?

☐ ☐ c. WERE THE INJURIES OR ILLNESSES RECORDED ON THE OSHA LOG?

☐ ☐ d. HAVE YOU OR YOUR EMPLOYER FILED FOR WORKERS' COMPENSATION FOR THESE INJURIES OR ILLNESSES?

☐ ☐ e. DID YOUR INJURIES AND/OR ILLNESSES INVOLVE ANY DAYS AWAY FROM WORK OR DAYS OF RESTRICTED WORK ACTIVITY? IF YES, HOW MANY WORKDAYS WERE LOST OR RESTRICTED? ______ DAYS.

EXPLAIN. ______________

____

☐ ☐ 3. ARE YOU AWARE IF ANY OF YOUR CO-WORKERS EXPERIENCED A JOB-RELATED INJURY OR ILLNESS DURING THIS YEAR OR LAST YEAR? IF YES, EXPLAIN WHO SUFFERED THE INJURY OR ILLNESS, WHAT KIND OF INJURY OR ILLNESS AND HOW IT WAS CAUSED.

____

____

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(Y) (N)

☐ ☐ 5. ARE DECISIONS MADE DIFFERENTLY IN BORDERLINE CASES? *IF YES, EXPLAIN.* ....

....

6. HOW IS ASSISTANCE OBTAINED IF NEEDED? ....

....

7. WHEN AND WHERE DO YOU POST THE YEAR-END SUMMARY? ....

....

8. WHO REVIEWS THE LOG FOR ACCURACY? ....

....

9. WHO CERTIFIES THE ACCURACY OF THE LOGS? ....

....

E. EMPLOYER/RECORDKEEPER UNDERSTANDING OF RECORDKEEPING CONCEPTS

☐ ☐ 1. DO YOU DETERMINE IF A CASE IS RECORDABLE? *IF NOT, SPECIFY WHO DOES.* ....

....

2. HOW DO YOU DETERMINE IF A CASE IS WORK-RELATED? ....

....

☐ ☐ 3. DO YOU RECORD CASES ON OSHA FORMS WHICH ARE NOT COMPENSABLE UNDER WORKER'S COMPENSATION? *(IF YES, EXPLAIN.)* ....

....

4. HOW DO YOU DISTINGUISH BETWEEN AN INJURY AND ILLNESS, MEDICAL TREATMENT, AND FIRST AID? ....

....

....

5. WHEN DOES A CASE INVOLVE LOST WORKDAYS? ....

....

6. WHAT CONSTITUTES RESTRICTED WORK ACTIVITY? ....

....

*U.S. Government Printing Office: 1991 — 282-118/20069

ATTACHMENT "G"

Inspection Checklist for Management

U.S. DEPARTMENT OF LABOR
Occupational Safety and Health Administration

CSHO NAME	INSPECTION NUMBER

A. MANAGERS INTERVIEWED

NAME	TITLE	INTERVIEW DATE

B. MANAGER QUESTIONS

(Y) (N)

☐ ☐ 1. DOES YOUR FIRM KEEP OSHA RECORDS? *IF YES, CHECK ALL BELOW THAT ARE USED.*

- ☐ a. INSTRUCTIONS ON OSH FORMS.
- ☐ b. BLS GUIDELINES.
- ☐ c. TRADE ASSOCIATION GUIDELINES.
- ☐ d. INSURER'S GUIDELINES.
- ☐ e. OTHER. *(LIST)* ____________________

____

(Y) (N)

☐ ☐ 2. DO YOU HAVE A COMPUTERIZED RECORDKEEPING SYSTEM?

☐ ☐ 3. IS THIS A MULTI-ESTABLISHMENT FIRM?

☐ ☐ 4. DO YOU USE CENTRALIZED RECORDKEEPING?

DO NOT WRITE IN THIS SPACE

C. RECORDKEEPER INTERVIEWED

	JOB TITLE	INTERVIEW DATE
PRIMARY RECORDKEEPER		
OTHER RECORDKEEPER		

D. RECORDKEEPER QUESTIONS

☐ ☐ 1. DO YOU HAVE A COMPLETED OSHA 200 LOG FOR LAST CALENDAR YEAR?

☐ ☐ 2. DO YOU HAVE A COMPLETED SUPPLEMENTARY RECORD FOR EACH CASE ENTERED ON AN OSHA 200 LOG? *CHECK BELOW THOSE USED AS A SUPPLEMENTARY RECORD.*

- ☐ a. OSHA 101.
- ☐ b. STATE WORKERS COMPENSATION FORM.
- ☐ c. INSURER'S FORM.
- ☐ d. OTHER *(LIST)* ____________________

____

____

3. AFTER THE INJURY OR ILLNESS OCCURS, HOW LONG DOES IT TAKE TO ENTER IT ON THE LOG?

____

4. WHO DECIDES WHETHER OR NOT A CASE IS RECORDABLE?

____

____

DO NOT WRITE IN THIS SPACE

OSHA FORM 186 Jan. 1991 edition

ATTACHMENT "H"

Material Safety Data Sheet
May be used to comply with OSHA's Hazard Communication Standard, 29 CFR 1910.1200. Standard must be consulted for specific requirements.

U.S. Department of Labor
Occupational Safety and Health Administration
(Non-Mandatory Form)
Form Approved
OMB No. 1218-0072

IDENTITY (As Used on Label and List)

Note: Blank spaces are not permitted. If any item is not applicable, or no information is available, the space must be marked to indicate that.

Section I

Manufacturer's Name	Emergency Telephone Number
Address (Number, Street, City, State, and ZIP Code)	Telephone Number for Information
	Date Prepared
	Signature of Preparer (optional)

Section II — Hazardous Ingredients/Identity Information

Hazardous Components (Specific Chemical Identity; Common Name(s))	OSHA PEL	ACGIH TLV	Other Limits Recommended	% (optional)

Section III — Physical/Chemical Characteristics

Boiling Point		Specific Gravity (H_2O = 1)	
Vapor Pressure (mm Hg.)		Melting Point	
Vapor Density (AIR = 1)		Evaporation Rate (Butyl Acetate = 1)	

Solubility in Water

Appearance and Odor

Section IV — Fire and Explosion Hazard Data

Flash Point (Method Used)	Flammable Limits	LEL	UEL

Extinguishing Media

Special Fire Fighting Procedures

Unusual Fire and Explosion Hazards

(Reproduce locally)

Section V — Reactivity Data

Stability	Unstable		Conditions to Avoid
	Stable		

Incompatibility (Materials to Avoid)

Hazardous Decomposition or Byproducts

Hazardous Polymerization	May Occur		Conditions to Avoid
	Will Not Occur		

Section VI — Health Hazard Data

Route(s) of Entry: Inhalation? Skin? Ingestion?

Health Hazards (Acute and Chronic)

Carcinogenicity: NTP? IARC Monographs? OSHA Regulated?

Signs and Symptoms of Exposure

Medical Conditions Generally Aggravated by Exposure

Emergency and First Aid Procedures

Section VII — Precautions for Safe Handling and Use

Steps to Be Taken in Case Material Is Released or Spilled

Waste Disposal Method

Precautions to Be Taken in Handling and Storing

Other Precautions

Section VIII — Control Measures

Respiratory Protection (Specify Type)

Ventilation	Local Exhaust	Special
	Mechanical (General)	Other

Protective Gloves	Eye Protection

Other Protective Clothing or Equipment

Work/Hygienic Practices

U.S.G.P.O. 1986-491-529/45775

7th American Water Jet Technology Conference
August 28-31, 1993: Seattle, Washington

Paper 50

WATER AS A TOOL: ALTERNATIVE METHODS OF REDUCING THE ENVIRONMENTAL AND HUMAN HEALTH RISKS IN PAINT STRIPPING

Frank E. Scharwat
WOMA Corporation
Everett, Washington

1.0 INTRODUCTION

"Water as a tool" is used in many markets and applications, not only as a paint stripping medium, but also in cleaning other environmental and safety conscious applications. Since there are numerous applications, we have chosen the paint stripping of aircraft for today's presentation.

2.0 TYPICAL APPLICATIONS IN MARKETS FOR PRESSURIZED WATER AS A TOOL

The following industries typically use pressurized water as a tool:

- Agriculture
- Airline
- Automotive
- Beverage
- Building and Concrete
- Cellulose and Paper
- Cement
- Chemical
- Energy
- Engineering
- Food
- Glass, Porcelain, and Ceramic
- Iron, Steel, and Metal
- Military Fields
- Mining
- Municipal Services
- Painting
- Plastics Manufacturing
- Public Transport
- Railroads

- Shipbuilding
- Wood

Pressurized water can be used to reduce the risk to man and the environment in aircraft paint stripping applications. Lufthansa Airlines has made a substantial investment in a procedure the Germans call aqua stripping. This approach utilizes pressurized water up to 500 bar/7,250 pounds per square inch for the safe and environmentally sound removal of paint from aircraft. Lufthansa estimates that this new procedure could save them initially DM 10 million per year, as compared to the previous methods utilizing caustic chemicals.

Aircraft have to be completely overhauled every five to eight years. Each "D-check," as it is called, lasts a good four weeks and usually takes 30,000 manhours to complete. An important part of such an overhaul involves renewing the paint job. After thousands of flight hours, even the best paint Is dull, brittle, and cracked. Before, a strong corrosive agent containing phenol methylene chloride and other substances was applied, which caused the paint to swell and loosen its hold on the surface. The paint was then scraped off by hand. This process was repeated until the surface was cleaned.

This procedure has several drawbacks. Phenol is toxic and highly caustic. Safety regulations require workers to wear protective clothing and gas masks (both of which have to be thrown away after a single use). These two materials cost Lufthansa approximately DM 1 million per year. Protective coverings on the aircraft and surrounding areas also have to be used and discarded. The residues, clothing, and coverings have to be disposed of as toxic waste at great expense. Several tons of waste material accumulate from stripping the paint off a single aircraft. The waste material is typically disposed of by incineration, which pollutes the environment.

Methylene chloride, highly volatile and known to cause cancer, is hardly a less critical substance than phenol. Like all other chlorinated hydrocarbons, it damages the earth's ozone layer. Milder corrosives are not capable of removing the type of airplane paint currently in use. Aircraft paint must meet very high durability standards, withstand scorching heat, and yet be crack-resistant at such low temperatures as 60°C. Year after year it must stand up to an intense ultraviolet radiation at altitudes of 10,000 meters.

How can airplane paint which is invulnerable to such extreme conditions be removed without inflicting damage on the environment? Chemicals are not the answer.

Water as a tool, however, is a perfect solution as recently demonstrated at the Lufthansa hangar in Hamburg. After three years of testing, conducted in conjunction with WOMA Corporation using pressurized water up to 500 bar/7,250 psi, computer evaluation of the test data results revealed certain regularities. If you determine the type, thickness, and age of the paint used, you can use a formula developed to calculate the appropriate pressure and temperature. The appropriate pump and tools used to apply water at the appropriate pressure and temperature will strip off a layer of paint only one-tenth of a millimeter thick without damaging the aircraft. Sometimes a chemical swelling agent is applied to thicken the paint coat to make it more vulnerable to the pressurized water spray. Benzyl alcohol is a perfect swelling agent. It is biodegradable and completely nonpoisonous. The time required for the agent to achieve the desired effect is calculated precisely. If the softening agent is left on for a longer period, pressurized water spray also will remove the primer coat.

In testing this application it had to be proven that the vibrations and pressures created by the pressurized jet of water spray did not subject the airplane's thin aluminum skin to undue stress or damage. A series of tests were carried out by independent institutions under the supervision of

Boeing Aircraft Company. The vibrations and stresses were measured with lasers and a variety of other testing equipment, and these values were compared to those resulting from the mechanical stress of orbital sanders and polishing machines. All misgivings were dispelled, and in late 1989, Boeing gave the go-ahead for the procedure using pressurized water in paint stripping.

Boeing is looking for an alternative to harsh chemical paint stripping in Seattle, Washington. However, they are placing their hopes on a kind of shock therapy that calls for spraying aircraft with a barrage of dry ice crystals. Cold shock causes the paint to peel off and drop to the floor with crystals of dry ice. The crystals of frozen carbon dioxide (extracted from the air) vaporize completely, leaving behind only the paint particles on the floor. That, at least, is how it works in theory. This technique was once a favorite of some of Lufthansa's engineering staff. But like so many other approaches, this one is plagued by nasty drawbacks. The refrigeration machine and dry ice blower are voracious consumers of energy. Personnel have to wear heavy protective clothing similar to that used in sandblasting. Not least of all, the cleaning area must be equipped with an elaborate ventilation system to prevent workers from being knocked unconscious by carbon dioxide vapors. Furthermore, it has been observed that the heavy artillery of ice crystals dents the thin aluminum sheets, leaving the planes' outer skin wavy.

The same problem occurs when the plane is sprayed with granulated plastic. Boeing has approved this technique of paint removal on its aircraft, but only one such treatment is allowed per plane. Stringent safety precautions must be taken, since the fine dust cloud of plastic and paint particles can combine with air to form an explosive mixture.

Paint stripping with laser beams is still at the laboratory stage. In this application, the laser would heat the paint to a point of vaporization. Many are critical of this approach since problems such as filtration of the resulting gas have not been thought out.

Water as a tool in paint stripping has none of these disadvantages. At the beginning of the decade, water as a tool was successfully used, and each day we learn a little bit more. This technique is not only ecologically safer than chemical paint removal, but it typically costs less and takes less time.

A new paint stripping facility is being built by Lufthansa on the edge of the Hamburg airport complex. When it begins operation in 1992, the era of chemical paint removal for Lufthansa will have drawn to a close. In this new facility, large remote control units located on platforms and equipped with six rotating jets will take on the task of stripping paint from the entire aircraft. In a single work cycle, they will lay bare a swath nearly one meter wide. It is anticipated that only a few isolated spots on the airplane will require manual water stripping. A processing facility will filter the paint particles out of the circulating water, reducing the amount of hazardous material to be disposed of and allowing the water to be reused.

The total investment with this new technology will have paid for itself in a year's time. But more important than earnings and the competitive edge gained by Lufthansa, since aircraft planes from throughout the world are overhauled in Hamburg, is the growing sensitivity to environmental problems. Water as a tool addresses problems by offering an ideal mix of economy and ecology.

Before you launch any project utilizing pressurized water as a tool, be sure to seek a professional in the field. I'm sure you will find them helpful - some companies have more than 30 years of experience. There are variables such as pressure, flow rate, standoff, speed, and determining what power source or tools are required, that have to be considered to accomplish the task. In many years of experience in this field, I have seen many people waste a lot of time and money misapplying water as a tool. If you take advantage of the resources available to you, I am confident you will find pressurized water can solve many problems, save money, and be a friend to the environment as well. Paint removal is just one of many applications for which you may choose to use water as a tool.

7th American Water Jet Conference
August 28-31, 1993: Seattle, Washington

Paper 51

ENVIRONMENTAL PROTECTION IN HIGH PRESSURE WATERBLASTING

Michael T. Gracey, P.E.
Hydro Environmental Services Limited Partnership
Missouri City, Texas, U.S.A.

ABSTRACT

High pressure waterblasting is used in the cleaning of process equipment including heat exchangers, reactor vessels, towers and piping. In the past, the water used in these operations was allowed to flow to sewers or to the ground along with the products and materials removed. New equipment and procedures will be discussed in this paper that are helping to contain the contaminated effluent and allow the re-use of much of the water that was heretofore wasted. The paper includes illustrations of the equipment and procedures.

Organized and Sponsored by the Water Jet Technology Association.

1.0 INTRODUCTION

In times gone by, if you washed a vehicle or if you did high pressure waterblasting in an industrial plant, the water and dirt/debris was of little concern to you. The rules have changed and the Environmental Protection Agency (EPA) dictates that no contaminated water will leave the premises. There is the problem of water permits, regulations and possible fines for noncompliance. There are forms and procedures for local agencies; there is the cost of processing the used water and then there is the cost of liquid waste hauling and disposal. All of these are legitimate concerns and are currently being discussed in the water jetting industry. The petrochemical plants where most of the high pressure waterblasting is being done along the Gulf of Mexico, usually receive and process the water used by contractors to clean their heat exchangers, towers and process equipment. This paper discusses how the contractor can be part of the solution to the problem of wastewater disposal and some of the equipment that is available to save the customer money while making the jobs safer and more efficient.

2.0 THE PROBLEM OF WATERBLASTING EFFLUENT

The large and /or long waterblasting jobs that are done in the petrochemical plants, require large amounts of water to operate portable equipment. The procedure has been to connect to the customer's service water system and allow the effluent to run to their sewers that are supposed to run to their wastewater treatment systems. This has worked well for the last 20 years, but the cost of processing the wastewater and the enforcement of new rules and regulations has prompted the development of portable equipment to re-circulate the effluent and re-use it for the waterblasting operation.

Another problem for the plant and the contractor, involves dangerously contaminated items like heat exchangers. The product may tend to cause cancer, heart and respiratory problems, or liver damage. Personal protective clothing was developed called "acid suits" to enable waterblasting personnel to work on the "hot" bundles or tanks. The operation is expensive and uncomfortable; sometimes the clothes have to be disposed of, after the work. This type of work has prompted the development of a portable containment system to control the liquid effluent and the gases produced in the cleaning operation. A tube bundle can be placed inside a roll-on/roll-off enclosure that has been designed for tube lancing and shell side cleaning operations.

Sand blasting for surface preparation and hard material removal is another area that produces debris and a used product. A bio-degradable media has been developed that was first used for cosmetic cleaning but now is moving into the area reserved for conventional abrasive blasting. It can be as aggressive as sandblasting without the clean up or breathing hazards. The following paragraphs will discuss these recent developments that are showing promise in the battle to protect the environment while accomplishing high pressure waterblasting in heavy industry.

3.0 HEAT EXCHANGER CLEANING CONTAINMENT SYSTEMS

Waterblast cleaning of heat exchangers generally involves removing material deposits from the tube side or shell side of a tube bundle. It was first done and continues to be done using hand held waterblast guns and lances (flexible or rigid). The water and debris usually falls to the ground and runs off into the sewers or soaks into the ground. Some plants have a special area for cleaning exchangers and process equipment which includes a concrete slab and curbs to contain the water and debris. The plant can then process the effluent in their wastewater treatment system, but it is an expensive proposition when there may be as much as 30 to 130 gallons of water per minute being used during the cleaning operation. The physical cleaning operation is made more efficient by using powered lances and automated shell side cleaning equipment, but the water usage is still a factor as well as the exposure of personnel to the material being removed or the gases being released.

Equipment has been newly developed that encloses the heat exchanger cleaning operation as shown in Figure I. The hazardous material containment system was first developed for heat exchangers that were contaminated with benzene or phosgene because it controls the effluent and the toxic gases. The water can be filtered and re-circulated while the toxic gases are processed before being exhausted to the atmosphere. The obvious benefits of reducing the amount of water used, the reduction of human exposure to chemicals and the automated features of this system have proven valuable for non-toxic heat exchangers and other process equipment as well as the dangerous ones.

4.0 TOWER CLEANING WATER RE-CIRCULATION

The field of "Water Recovery", "Water Recycling" and "Water Treatment" has become a rapidly growing part of the water jetting industry. Much of the efforts at this time are found in developing and marketing water processing equipment using various filtration methods, reverse osmosis, oil separators, coalescing media and chemicals. These packages are available for installation into equipment washing operations and are especially suited for fixed truck and car washing systems. The purpose of this discussion is to promote the reusing of waterblasting water to reduce the amount of wastewater, possible soil contamination and air pollution. Lancaster (1991) covers in more detail, the treatment of wastewater by discussing the volume of water, types of disposal, the chemicals involved and the filters used in the process.

The high pressure waterblast cleaning of towers, reactors and tanks has been improved by the various types of hardware developed in recent years. Rotating nozzles, cleaning heads and other labor saving mechanisms as indicated in Figure II, make the jobs safer and faster. These operations also make it easier to capture the water and reuse it because the effluent usually runs out of a drain or access. If a waterblaster produces only 20 gallons per minute, a 10 hour operation could use as much as 12,000 gallons of water. A recirculating filtration unit can process the effluent for reuse while concentrating non-soluble debris and contaminants for more economical disposal. This equipment was developed for the petrochemical process equipment such as towers and heat exchangers, but can be adapted to ship cleaning, rail car cleaning and tank truck washing to name a few other applications.

5.0 PROCESS EQUIPMENT CLEANING EFFLUENT CAPTURE

Process equipment such as vertical heat exchangers are another type of job where the effluent can be captured as shown in Figure III. Water consumption can be reduced by as much as 1800 gallons of water per hour and disposal is greatly simplified. The solids are separated from the water and the personnel are exposed to less of the effluent than with the previous methods used for water jet cleaning.

6.0 NEW BLAST MEDIA FOR COSMETIC CLEANING

Several companies have begun to market a waterblast media system to use with conventional high pressure waterblast pumps and pressure washers. The media is used like wet/abrasive sandblasting to remove stains, light buildups, discolorations and graffiti where sandblasting is too aggressive or not allowed. The system uses a non-toxic, non-hazardous, biodegradable, water soluble media powder as discussed by Gracey (1992). One of these medias is called BIO-BLAST, but the main idea is to do the many types of cleaning jobs with a substance that does not harm the environment. Figure IV shows one of these wet/abrasive system that uses the special media.

The media is abrasive, non-sparking, environmentally safe, dust free, requires no clean up, increases production, can be used with low & high pressure equipment and leaves no residue. It does a better job on stain removal from concrete, brightening aluminum, polishing stainless steel, removing graffiti and surface preparation than water alone.

The BIO-BLAST system and the other types of environmentally safe systems that are now available for use in the industry are examples of the concern for the effects of cleaning operations on the health of the worker and the impact on our surroundings.

7.0 CONCLUSIONS & FUTURE DEVELOPMENTS

Waterblasting operations will probably become more automated in the future and if the systems are in a fixed location, they will be more suitable for capturing the effluent and processing it for re-use. Conn (1992) discusses in-plant applications for water jetting and there are uses in almost every industry that lend themselves to automated systems.

Portable equipment to contain the water, debris, and gases for some of the various waterblasting jobs has been developed. Figure V shows the HAZ-CON^{SM} unit that is used to contain the contaminates while cleaning the shell side and tube side of heat exchangers. Figure VI shows a portable re-circulation system to separate and filter the effluent. These recently developed systems, along with the continual development of new ideas, will assure greater environmental protection for waterblasting operations in the future.

8.0 ACKNOWLEDGMENTS

The author wants to thank the employees of Hydro Environmental Services for help with the illustrations and the valuable input concerning the protection of our environment.

9.0 REFERENCES

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2. Gracey, M.T., "Bio-Blast Media for Cosmetic Cleaning," *CLEANER TIMES*, March 1992.
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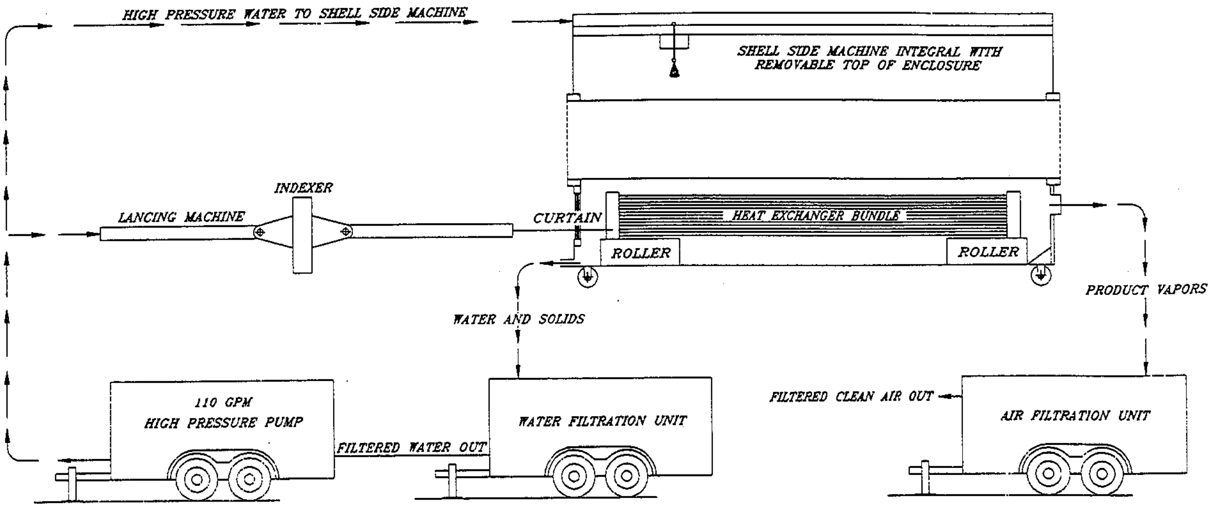

Figure I – Hazardous Material Containment System

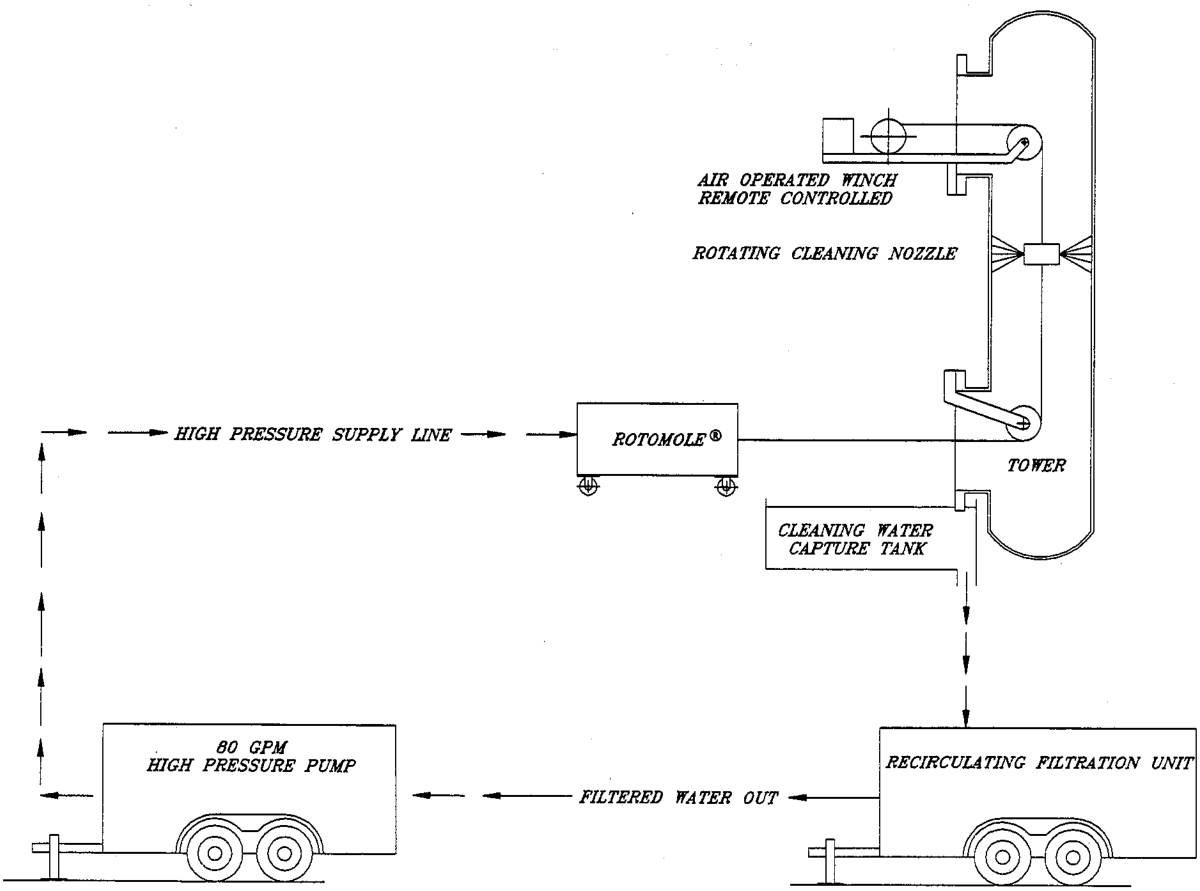

Figure II – Effluent Re-Use In Tower Cleaning

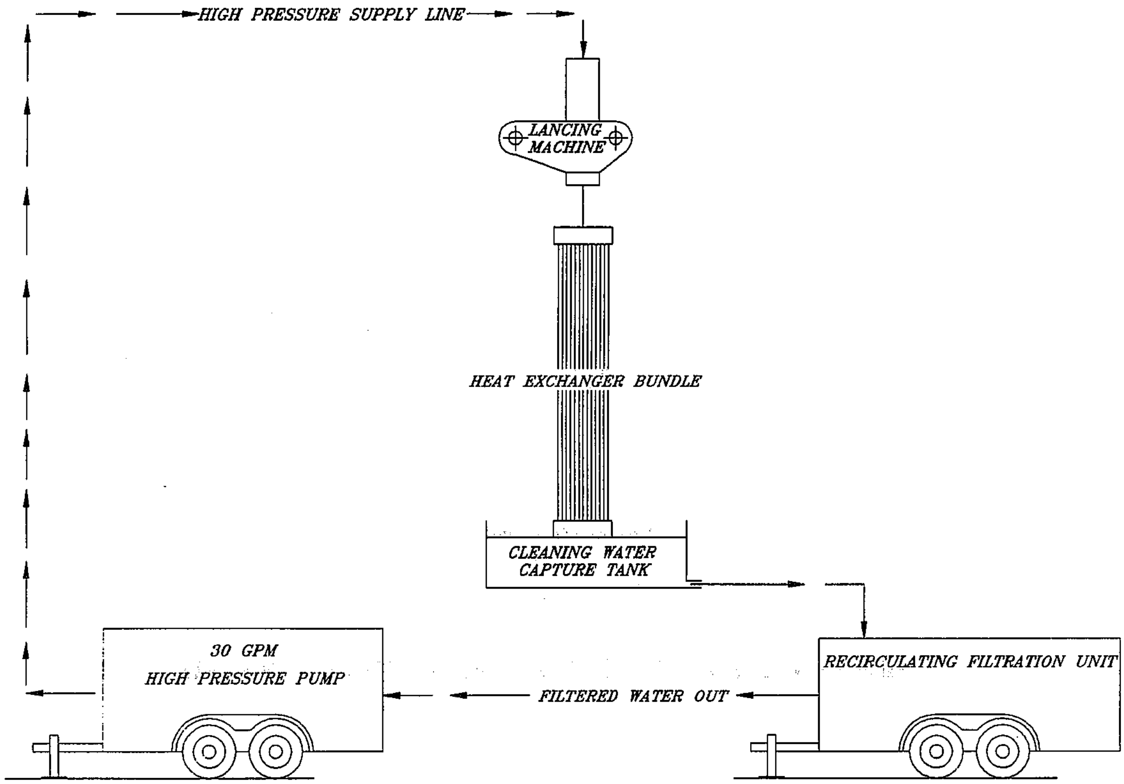

Figure III – Process Equipment Cleaning

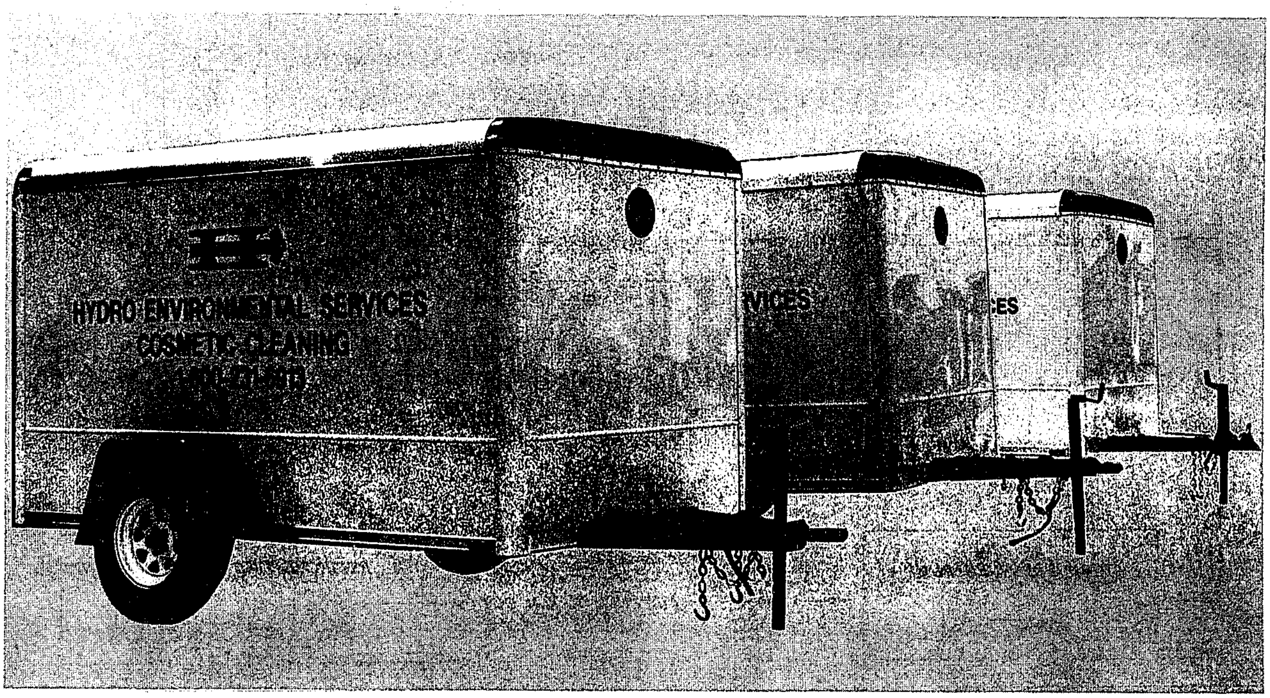

Figure IV – Bio-Blast System Using Non-Hazardous Media

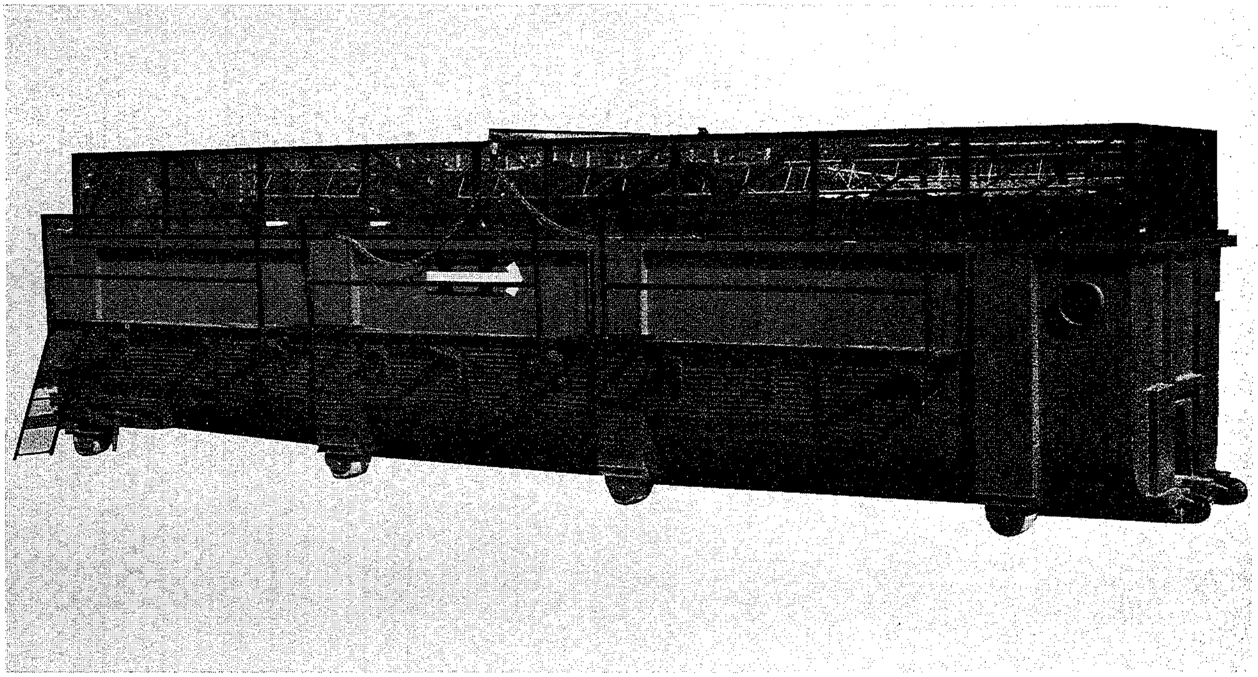

Figure V – Haz-Con℠ Hazardous Material Cleaning System

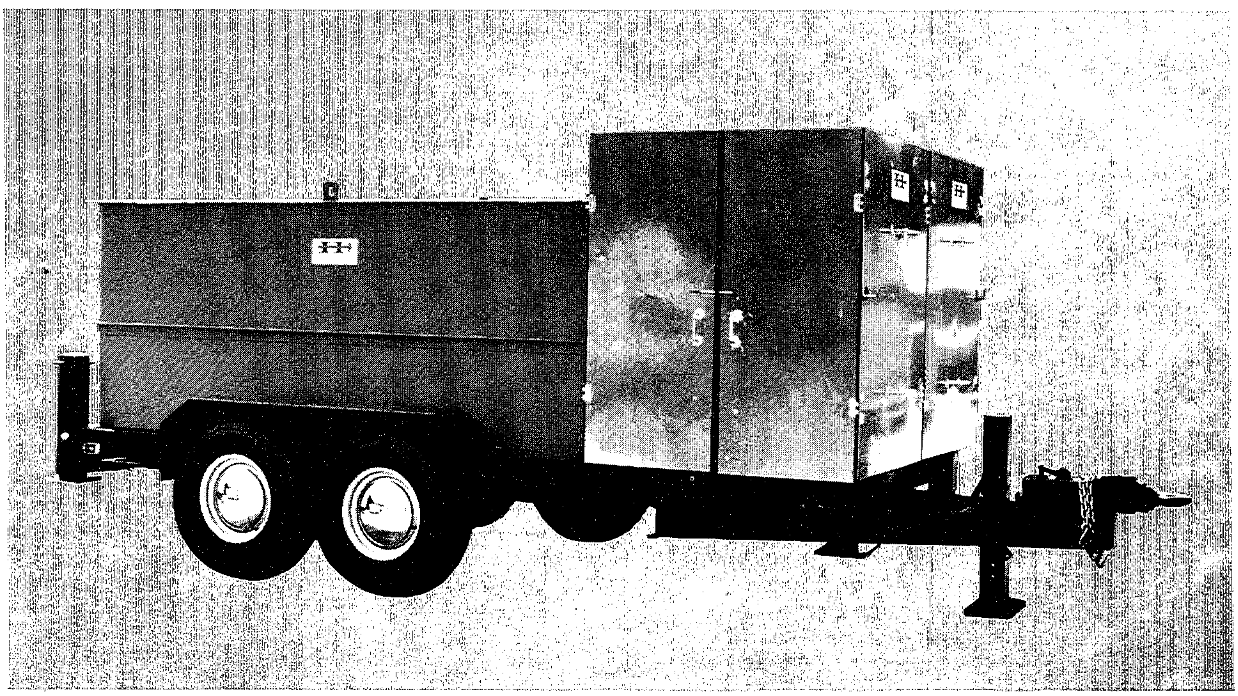

Figure VI – WRCS Water Re-Circulation System

7th American Water Jet Conference
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Paper 52

ENVIRONMENTAL AND SAFETY ATTRIBUTES OF WATERJET CUTTING

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ABSTRACT

KEY WORDS: Environment, Operator Safety, Equipment & Machinery

The inherent characteristics of ultrahigh-pressure waterjet technology resolve many of today's concerns over both environmental and operator safety in the work place. Advances in waterjet cleaning provide an alternative solution to today's environmental processing problems. This paper examines the environmental and safety attributes of waterjet cutting as an alternative to other conventional and non-conventional methods.

The conventional methods of cutting material such as paper or fiberglass can create an inordinate amount of airborne dust. Cutoff saws used to de-gate metal castings can create a dense fog of airborne particulate. Cutting these materials as well as an endless list of others with waterjet or abrasive waterjet (AWJ) virtually eliminates this hazard. The waterjet stream traveling at three times the speed of sound pulls the potential airbound kerf material into itself and safely deposits it in a catcher.

Plasma arc and lasers burn materials which can create heat-affected zones and emit toxic fumes. The abrasive waterjet can cut heat-sensitive materials such as aluminum, steel, titanium, and nickel alloys without risking heat damage. Fume extractors are not required on waterjet or AWJ systems.

Potentially hazardous chemical coolants and lubricants required with conventional cutting tools are not needed with waterjet processing.

The latest ultrahigh-pressure waterjet systems utilize closed-loop water recirculation systems minimizing water consumption, noise-abatement techniques keeping sound levels below 75 db, and waste disposal systems that separate the kerf material from the water simplifying the disposal process.

1. ULTRAHIGH-PRESSURE WATERJETS AND ABRASIVEJETS OFFER CLEAN CUTTING TECHNOLOGY

The inherent characteristics of ultrahigh-pressure waterjet technology resolve many of today's mounting concerns with the environment and worker safety. Advances in waterjet and abrasive waterjet cutting extend an alternative solution to environmentally unsound methods presently in use. These advances affect both those working with the machinery, and the population living in surrounding residential areas. This paper examines the environmental aspect of waterjet and abrasive waterjet and discusses their use as alternatives to conventional methods.

The industrial world faces a dilemma concerning traditional methods used for cutting advanced materials. OSHA and the Environmental Protection Agency (EPA) demand manufacturers utilize processes that are operator safe and environmentally sound. The agencies have targeted several hazards as areas of concern. They include:

- Toxic fumes;
- chemicals and lubricants;
- waste discharge and disposal;
- airborne dust;
- noise.

A number of recent advancements in waterjet and abrasive waterjet technology establish it as an operator safe and environmentally sound cutting process. While achieving these objectives, waterjet and abrasive waterjet offer manufacturers the capability to cut a diverse range of advanced materials.

1.1 Toxic Fumes

Several technologies utilize thermal processes for cutting materials. For example, laser cutting and plasma arc remove material via heating and melting. They create a heat-affected zone (HAZ) that, depending on the workpiece material, may emit toxic fumes when cutting metals and plastics. The toxic fumes present a hazard or annoyance to workers operating the machinery and can pollute the air. In order to contain the fumes, many companies are forced to purchase expensive shrouds and vacuums.

Waterjets and abrasivejets generate no heat during the cutting process. The systems can cut all metals, composites, glass, stone, and plastic without generating toxic fumes. The operator can safely operate the machinery without wearing breathing apparatus. And the system requires no shrouds or vacuums, reducing capital equipment and operating cost of the machinery.

1.2 Chemicals

Waterjet technology also eliminates the need to use lubricants and coolants when cutting materials. Milling, routing, turning, grinding and other processes that involve shearing or tearing action require lubricants and coolants to produce satisfactory surfaces. The lubricants are composed of numerous chemicals, which can cause costly disposal problems. Sometimes, the chemical's toxicity requires that the materials be processed before disposal.

The waterjet machines material by a supersonic grinding process. Each grain of sand acts as a micro-cutting tool. As water surrounds the sand particles, it provides a lubricant to alleviate friction and abate noise.

1.3 Waste Disposal

With pure waterjet processing (no abrasive added), there are two distinct types of waste generated: solid and liquid. Solids consist of the kerf material. The liquid waste is composed of purified water (usually 0.05 to 1.0 gallons per minute).

Waterjets minimize the amount of solid discharge generated during the cutting process by reducing kerf width. The kerf width from the waterjet stream is minimal, ranging from 0.003" to 0.10". As a result, the user has less waste to dispose.

Abrasive waterjet processing adds an abrasive media to the waterjet stream. Kerf width associated with abrasive waterjets is slightly larger than that of waterjets, ranging from .030" to .060".

Abrasive used in the cutting process makes up an additional solid waste. A majority of users utilize garnet for their abrasive waterjet cutting systems. Garnet provides a safe and inert abrasive, easing disposal concerns. Garnet is used in quantities of 0.5 to 1.5 lbs./min.

Solid waste composed of garnet abrasive and a small amount of kerf material can be disposed of in a clean landfill. Only when cutting hazardous materials such as lead must a user dispose of the solid or liquid material in a hazardous waste facility.

1.4 Airborne Dust

Another growing concern stems from the threat of airborne dust. Several cutting techniques, such as high-speed routers, produce a significant amount of airborne dust during the cutting of advanced composites and fiberglass. Despite attempts to contain the dust, no preventive measure appears to fully control its release. Not only does this material threaten the environment, but also the operator. Some fear that airborne dust from routing graphite/epoxy composites and other relatively new materials may cause severe harm to the operator's respiratory system.

Waterjets create little airborne dust during the cutting process. The waterjet stream travels at three times the speed of sound, and creates a localized vacuum. As water mixes with the air, the water carries the air downward. The result is that the vast majority of the kerf material (and abrasive, if used) is deposited directly into the catcher tanks.

1.5 Noise

Government agencies also have begun to regulate the amount of noise generated by industrial tools. Federal, state and local agencies typically allow for a maximum of 85 db for industrial machinery. High speed routing and several other traditional forms of cutting may operate in the vicinity of 85 db.

Without following proper operating procedures, waterjets too can create substantial amounts of noise. The amount of sound emitted from a waterjet or abrasivejet depends on the distance that the stream is exposed to open air. If the jet stream is exposed to air for distances exceeding those outlined by manufacturers, the sound generated by a waterjet can exceed 85 db. The latest in waterjet and abrasive waterjet systems routinely operate under 75dbA. Cutting under water reduces cutting noise to virtually zero.

Most pumps manufactured for use with waterjet systems employ some type of limited sound-abatement equipment. A new pump from Flow International Corporation, the 20X, features significantly more power than its predecessors, while operating at 75 db, a full 10 decibels below previous models. For the human ear, reducing the decibel level from 85 to 75 will reduce the noise by about half.

1.6. Water Recirculation

Recently, new advanced equipment has been introduced for waterjet and abrasive waterjet systems that will meet the next wave of environmental regulations. Closed-loop water recirculation systems eliminate any water discharge to drain. The system removes all solids from the water through an advanced filtration system down to .05 micron. Solids are collected in a bag filter or 55-gallon drum for easy disposal.

After the water recirculation system filters out the solids, the purified water recirculates to the intensifier system for reuse. The recirculation of the water reduces water consumption and cost. The system requires only a small amount of water to compensate for evaporation. The recirculation process also increases the equipment's product life by using water purified to industry standards.

1.7 Summary

In summary, the public's concern for protecting the environment, and the need for a safe workplace for machine tool operators, necessitates the move toward new, environmentally sound technologies. Waterjet technology is positioned to meet the ever tightening environmental requirements. Future developments promise to keep waterjet technology one step ahead.

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Paper 53

"PERSONNEL AND ENVIRONMENTAL RISK REDUCTION THROUGH HIGH PRESSURE JET CLEANING OF NORM"

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ABSTRACT

Naturally Occurring Radioactive Material (NORM) has been found as an unwanted scale or sludge in a number of industries. The fertilizer, power and oil and gas industries have been dealing with their NORM issues in various ways. This paper will detail the development of high pressure water jetting systems for cleaning, processing and disposing of NORM from a wide range of equipment contaminated during oil and gas production and processing.

Over the past 12 years the issue of Naturally Occurring Radioactive Material (NORM) in the oil and gas industry has been evaluated and found to be an ingestion/inhalation hazard to personnel but primarily an environmental contamination problem.

The NORM is made up from Radium-226, Radium-228, and their daughter isotope products which includes Radon gas. Many of these isotopes emit alpha and beta particles in addition to the relatively low levels of gamma radiation. Ingestion/inhalation of the alpha/beta particles is the greatest single hazard to personnel from this low level NORM. These long half life (1620 years) isotopes have long term impact on the environment.

To avoid the creation of airborne alpha and beta particles in the decontamination systems used, the most effective cleaning medium has been found to be high pressure water jetting systems. In addition to water jetting, it is also necessary to minimize the creation of aerosols from the cleaning process and use operational procedures which reduce or eliminate all unplanned accumulations of NORM which could become a distributed airborne hazard should it dry out and blow around. This airborne distribution would also result in wide spread environmental contamination.

The paper will outline the application of high pressure water jetting techniques which reduce the risk of personnel contamination and produce a water based NORM slurry which can be processed and injected into suitable underground strata, thus solving the difficult and costly disposal problem while resolving the environmental contamination issue.

The author has designed 3 major NORM Cleaning Facilities in Scotland, Louisiana and Alaska. The Scottish facility has been in operation for over 10 years, the Louisiana facility for 2 years, and the Alaska facility was commissioned in the Spring of 1993.

A brief comparison of these 3 facilities will illustrate the great flexibility of high pressure water jetting as a cleaning technology to reduce the personnel and environmental risk which occurs in all radioactive decontamination work.

1 Introduction

Naturally Occurring Radioactive Materials (NORM) has been identified with oil and gas production since 1904 (ref 1). Much of the early oil bearing geological evaluation used the radioactive emanations to both identify and evaluate the oil production capabilities of the strata. While the existence of this radioactive phenomenon was well known, it was not identified as a potentially significant problem until studies were begun in the US gas industry in the mid 1960's (ref 2). Further studies were carried out in Germany in the 1970's and 1980's (ref 3 & 4) and a major initiative followed the identification of wide spread NORM in the UK oil and gas industry in 1981 (ref 6).

NORM is found in many geological formations all over the earth and as a natural phenomenon, it cannot be avoided. While radiation has an effect on all living cells, it is not certain at what level the effect may become detrimental. Hence, the principle of keeping all additional manmade enhanced exposures to as low as reasonably achievable above natural background levels continues to be one of the main principles of radiation protection.

Oil and gas are found in many geological formations deep underground in association with water formations which have been trapped together for millions of years. These natural formations also contain other materials, some of which are radioactive. Barium is a heavy metal which is often found in ionic form in the connate waters under the oil and gas. In many oil fields huge quantities of sea water are injected to force oil and gas from the reservoir. Sulfate ions are often found in these injected sea waters and when the barium and sulfate ions combine, they form barium sulfate which is virtually insoluble to all but a few very complex chemical solvents. Associated with these compounds, we also find other heavy metals such radium 226 and radium 228 which are radioactive. When the barium sulphate forms in association with oil and gas production, it often carries with it these radium isotopes which form part of the scale making it radioactive (ref 6). This is the NORM material found as scale and sludge associated with oil and gas production.

The radium found in this NORM comes from the chemical families produced by Uranium 235, 238, and Thorium 232 (figures 1, 2, & 3). The figures show that these parent isotopes have very long half lives over 10^8 years each, hence it is likely that the oil and gas production will always have some associated NORM. The main isotopes found in the NORM scale are radium 226 which has a 1620 year half life and radium 228, which while it has a 6.7 year half life, is the daughter of the thorium 232 with a 1.4×10^{10} year half life. Once produced, they will be around for a very long time. Consequently, their identification proper management and disposal is critical for personal and environmental protection from contamination.

Radium decays to form a chain of daughter isotopes through the emission of alpha particles, beta particles, and gamma rays. Radon gas as the isotopes radon 219, 220 and 222 is found in all three decay chains, hence, the problem is common to the gas production and processing industries as well as the oil industry. Since we consider all radiation above the natural background as potentially dangerous, we need to evaluate the levels in the oil and gas industry and manage the operations to reflect the real risks present (ref 8).

Radiation from the NORM material contained within operating equipment is emitted in the form of alpha and beta particles and gamma rays which are attenuated by the steel from which the equipment is made. The alpha and beta particles are contained within the steel process items.

The real risk from NORM occurs when the material must be cleaned from the contaminated item and the NORM handled and disposed. The cleaning personnel are exposed to contamination through working with the NORM. Inhalation of radon gas and/or NORM as dust or aerosol vapor together with ingestion through using contaminated wipes, eating contaminated food, sweets or tobacco, and egress through skin cuts or wounds must be prevented. The small pieces of NORM which could lodge in the body emit alpha particles which will severely damage all living body tissue with which they collide.

Alpha particles can be stopped by the external skin of the body and washed off. By preventing the inhalation and/or ingestion of NORM particulate and Radon gas, the major risk can be avoided. The risk to people and the environment can be managed through good personal hygiene and safe systems of work which minimize the generation of airborne radioactive materials. High pressure jetting has been found to be very effective in this regard. The water/NORM aerosols make the particulate NORM more easily managed and prevent the emission of alpha or beta particles while greatly alleviating the already low levels of gamma radiation.

2 NORM in the Oil and Gas Industry

Norm in the oil and gas industries has been reported by the author[5], Dr. A.L. Smith[6], Dr. Peter Gray[7], and many others. Table 1 (ref 6) reports some data for NORM found in oil production equipment in the UK North Sea. While dose rates up to 300 micro Sv/h (30 mR/h) have been found in the North Sea platforms, these levels are well above the US oil industry average range which is in the 0.5 - 5.0 microSv/h (50 - 500 microR/h).

NORM scale within operating gas production and processing equipment is very difficult to detect and measure accurately (ref 7) due to the low gamma ray energy emitted by the gas NORM. Table 3[7] lists priority areas in gas and NGL facilities which should be surveyed using a detector suitable for low energy gamma rays in the range 35 - 50 kev.

In gas production and processing, the radon gas and daughter products,(Table 2)[7] can be detected while the equipment is in service and higher energy gamma radiation is being given off. Table 3 lists the priority areas for checking an operational gas plant for NORM. When gas plants are shut down and new gas stops flowing, the Radon parent supply stops and the short half life daughter isotopes of the Radon gas quickly decay. After 3 days only lead 210 with a 22 year half life can be detected within the equipment as a NORM scale. Lead 210 has a weak gamma ray of 46.2 kev which is quickly stopped by process steel. Hence, it is essential to survey the inside of gas equipment which has been shut down for NORM to be effectively detected.

Unfortunately, lead 210 decays through Bismuth 210 to form the isotope polonium 210 which emits a high energy alpha particle which will cause significant localized tissue damage to the body cells around its location should it become lodged within the body. Since alpha particles can be stopped by a sheet of paper and NORM from gas plants has only a low gamma energy 46.2 kev from lead 210, it is virtually impossible to detect ingested, inhaled gas NORM particles within the body. Hence, it is essential that all exposures be kept as low as reasonably achievable and inhalation ingestion of all particulate NORM be prevented.

Managing the removal of NORM from oil field equipment throughout the US presents a wide range of problems due to the equipment diversity, geographical distribution and historical practices. While the oil industry is moving rapidly to put safe systems of work in place, more work is required to define the real occurrence and risks from NORM especially in the gas industry. Little real survey data is available for NORM surveys of gas and gas condensate facilities.

NORM has been found as hard scale on virtually all operating and processing equipment used in the production and processing of oil and especially produced water systems[6]. Fortunately the bulk of the oilfield NORM is low in specific activity and in many cases, is only slightly above the natural background. This low dose rate 0.2 - 0.5 micro Sv/h (20 - 50 microR/h) scale is found in the lower pressure equipment in large volumes[6]. The associated specific activities are correspondingly low in the range 0.5 - 50 Bq/g (13 -1350 pico Ci/g)[6]. Large accumulations of this low level NORM can still result in significant dose rates and repeated disposal in the same location will build up a major environmental contamination problem.

Where the NORM scale accumulates as a more crystalline barium sulfate as occurs in higher pressure well heads flow lines, down hole tubulars, and well completion equipment associated with oil production, the dose rates 120 - 300 microSv/h (12-30 mR/h) and specific activity 37 - 15170 Bq/g (1000 - 41000 pico Ci/g) can be much higher. This higher level NORM requires much more care as it can be a significant hazard to operating personnel, especially during removal and disposal. Safe systems of work must be used and detailed records kept of all operations.

Existing produced water injection wells from oil and gas production have been handling the injection of low levels of dissolved and micro fine suspensions of NORM for many years and this return of NORM to the strata from which it was produced can be accurately described as "RESTORING THE GEOLOGICAL EQUILIBRIUM" of the reservoir. This is one way to maintain the natural balance while disposing of NORM.

The author recently commissioned a cradle to grave NORM facility to service the entire North Slope. This operation provides total containment of all NORM from the start of cleaning operations through to and including the injection of the NORM into a Class II injection well which has been permitted for NORM disposal.

3. The Real Risks of NORM

NORM material can become lodged within the body through inhalation and/or ingestion of particulate NORM or Radon gas. The alpha particles emitted by the NORM cause damage to the body tissue around the location in which the NORM becomes lodged.

The radiation dose rate given off by NORM in equipment or the environment in the form of alpha, beta and gamma rays is relatively low and presents little risk to personnel. During clean up operations the NORM can contaminate the cleaning personnel and/or the working environment. The barium and radium found in the NORM, should it be ingested or inhaled into the body, may be treated by the body as though it were calcium and transferred to the bone marrow where it is deposited. It could also become lodged within the lung tissue for particles of respirable size. In either case, the following describes what happens.

The isotopes in the NORM decay chain (see Figures 1, 2 & 3) change from one isotope to the next lower in the chain by emitting various combinations of alpha, beta and gamma radiation as shown in the following two examples.

Example of NORM Isotope Decay

e.g.:

Oil Scale (Radium parent 1620 years)

	Half Life	Decay	Half Life
Radium 226	(1620y)	alpha particle at 4.7 Mev	Radon 222 (3.8 d)

Gas Scale (Lead parent 22 years)

Polonium 210	(138d)	alpha particle ——————— at 5.3 Mev	Lead 206 (stable)

Half Lives in (years y,days d)

Lead 210 with a 22 year half life decays through Bismuth 210 to produce polonium 210 which in turn decays to stable lead 206 through the emission of high energy alpha particles having an energy level of 5.3 Mev. The higher the alpha particle energy, the more damaging it will be to body tissue. Hence, NORM in gas equipment while more difficult to detect, especially in out of service equipment, is at least as significant an inhalation/ingestion hazard as oilfield NORM.

NORM in Oil and Gas operations continues to be studied as a potential personnel and environmental contaminant and health hazard.

Actual personnel exposures of NORM cleaning workers given in Table 4[8modified] were obtained through the use of government approved radiation badge monitoring programs. The mean external doses average 0.03 mSv/y (3 mRem/y) for safety personnel and 0.23 mSv/y (23 mRem/y) for cleaning personnel who work at NORM cleaning facilities full time. (ref[8]) The UK offshore workers show a slightly higher range of exposures due to the higher dose rates found in NORM in the UK North Sea compared to the Gulf of Mexico.

These employees are also subject to other exposures[8] which arise from the inhalation and ingestion of radon gas, its daughter products and airborne NORM dust. The example given[8] for the cleaning of an oilfield separator when extrapolated for a full year concludes that in a worst case the worker could receive up to 0.034 Sv/y (3.4 Rems/y) which is two thirds of the annual dose limit allowed for a monitored radiation worker. In practice the highest reading obtained from a NORM worker working full time in a NORM cleaning facility was 0.8 mSv/y (80 mRem/y) in the US and 1.3 mSv/y (130) mRem/y) in the UK. Safe work procedures are designed to reduce the personnel exposure to a reasonable level and these actual exposures show how effectively they work.

Dose rates of up to 0.03 mSv/h (30 mRem/h) have been found on oilfield tubulars and up to 0.055 mSv/h (55 mRem/h) found on gas condensate separators in West Texas. These dose rates are very significant and would quickly result in exposures over the allowable limits for radiation workers of 1.25 mSv/quarter (1250 mRem/quarter). Fortunately oilfield and NORM maintenance personnel do not spend significant amounts of time close to these or similar items and actual exposures are kept to a low level. Should dose rates over 0.02 mSv/h (2 mRem/h) be measured, the radiation regulations require a barrier to be set up with warning signs to prevent inadvertent access to radiation fields above 0.02 mSv/h (2 mRem/h). It is also a regulatory requirement under OSHA that personnel radiation exposure monitoring at dose rates above 625 microSv/h (0.625 mRem/h)

The real risk of inhalation/ingestion of NORM material can be avoided through the use of effective respiratory protection which recognizes the potential for Radon gas being present. Good personal hygiene and safe systems of work are essential to prevent the inadvertent spread of NORM and the resultant environmental contamination.

4 Cleaning Technologies Compared[5]

The single greatest risk associated with NORM cleaning is the inhalation and ingestion risk resulting from radon gas and airborne NORM dust and aerosols. The gamma ray exposure dose rates are relatively small and, with the use of safe systems of work, do not present a significant risk to NORM cleaning personnel in the oil and gas industry. Hence, the minimization of airborne dust and the management of inhalation ingestion risks is the single most important factor.

Table 5 lists the main cleaning techniques used for NORM removal. All cleaning that does not use water as the cleaning medium has a higher potential for the creation of airborne particulate NORM should their containment systems fail.

The use of high pressure water for cleaning NORM can result in the creation of aerosol sprays which could spread NORM in a similar way to other cleaning methods. However, the aerosols are more easily managed due to their wetting characteristic which facilitates containment of the NORM particles and the subsequent pumping of the NORM in a wet slurry. Where NORM disposal by down hole injection is available, the wet NORM slurry can be continuously processed and provided the aerosols have been eliminated, the issue of NORM ingestion and inhalation has been eliminated completely.

Scaled Equipment

1 Hand cleaning requires direct contact with the NORM and causes contamination of work clothes, hand tools, work bench and area. This method is usually applicable to small components with limited NORM, however, the accumulation over time, should the NORM not be collected after each work session, would result in dry NORM and dust which would spread over the entire work area. Work clothing contamination would also spread the NORM into the home and collect in washing machines and clothes dryers. In NORM cleaning facilities the lint trap of the clothes dryers has been found to be contaminated.

Hand cleaning requires the use of full personnel and respiratory protection to avoid dust and the spread of contamination. The work must be carried out within a contained monitored area and all work clothes surveyed before leaving the area.

2 Power tools, like hand tools, will result in the spread of NORM and the creation of airborne particulate would be faster and spread over a larger area. The inhalation/ingestion risk will also be greater than hand cleaning and even wetting down the NORM will still result in contamination of the entire work area and the workers clothing.

Full respiratory and personnel protection is required with work carried out in a controlled monitored area in which the NORM is collected and contained in an appropriate manner.

3 Air driven tools are one stage more severe than mechanically powered hand tools in that the compressed air discharge increases the probability for the production of airborne particulate which must be collected in some way. Recent advances in surface blast and vacuum combinations are effective for large flat surfaces, but do not work so well for pieces of equipment and sections which have odd shaped surfaces.

Full respiratory and personnel protection equipment needs to be backed up by using vacuum collection of airborne material. All work must be carried out in a monitored area. The blast medium (e.g. steel shot, sand, etc.) will becomes NORM contaminated and increased the disposal costs significantly.

4 Chemical cleaning can be very effective provided the NORM has a reactive component such as barium carbonate. Most NORM has a high percentage of barium sulfate which is highly insoluble in all but a few complex expensive chemicals. The removal of NORM by chemical reaction can result in a mixed NORM chemical solution. This mixed waste cannot be disposed of without further separation to remove the radioactive NORM waste. In addition, the residual chemicals are often a hazardous waste and require controlled disposal.

Chemical cleaning of complex high value items such as down hole valves completions and equipment in oil producing wells may be the only way to recover the equipment or return a well to production. However, careful consideration should be given in advance as to how the effluents and potentially "mixed wastes" will be further treated for disposal. The removed mixed waste requires all personnel to be fully protected and work in a monitored area. Vapors from the chemicals could present a significant increase in personnel exposure risk and respiratory protection including supplied breathing air may be required.

5 Water jet cleaning of NORM minimizes the production of NORM dust and greatly reduces the inhalation ingestion risks associated with other forms of NORM cleaning. Vapor aerosols because of their larger size (compared to airborne NORM dust) are more manageable through vapor extraction systems. Aerosols from NORM cleaning have been extensively sampled and found to be free of NORM.

The remote cleaning systems developed for water jetting separate the worker from the equipment being cleaned and the NORM material it contains virtually eliminating all worker exposure. The jet cleaning water covering the NORM reduces the already low gamma dose rates and further enhances this cleaning methodology.

NORM removed in a controlled way using jetting techniques can be easily pumped and processed in entirely closed systems which fully contain or eliminate the creation of all aerosols, dust, and Radon gas providing the maximum achievable worker protection during NORM cleaning. NORM is often found as a complex sulfate compound which is virtually insoluble in water leaving the only problem which is the potential build up of sub micron colloidal NORM in the cleaning water especially if the water is recycled for reuse in a closed system.

All water filtration recovery systems for NORM work need to be self cleaning and not generate any contaminated disposable filter elements or other solid wastes.

NORM removed by water jetting has been successfully processed into particle size controlled slurry and injected into a Class II injection well. The entire NORM cleaning processing and injection was made possible through the use of water jet cleaning techniques. Cleaning personnel were totally separated from the NORM throughout the entire process and all exposure risks minimized.

Therefore, it is true to conclude that the use of high pressure water jetting for cleaning NORM is the best technology available for radiation exposure and inhalation/ingestion risk reduction.

Sludge Removal from Vessels

1 Pumped sludge removal is only possible with light weight solids. Solids agitation will increase the amount of material removed but still leave the heavy solidified material which requires mechanical removal.

Water oil Separation can result in significant problems in pumping and necessitate the use of oil water and solid separators to handle the removed effluent.

NORM sludge is generally quite low in specific activity 22 - 28 Bk/g (594 - 756 pCi/g)[6]. Despite this low specific activity, the large volumes which accumulate can produce significant dose rates greater than 20 µSv/h (2mRem/h). Worker contamination is generally very limited due to the contained NORM fluid pumping systems.

2 Hand shoveled sludge removal is normally combined with the pumped fluid removal and requires the NORM worker to be in intimate contact with the NORM sludge. Severe personal contamination results and full supplied breathing air is required to protect from hazardous organic fumes and Radon gas emitted by the NORM.

This method is slow and although the equipment is cheap, the total cost will be higher than using water jet assisted sludge cleaning techniques. It also increases the cleaning worker exposure due to direct contact with the NORM.

3 High pressure jetting combined with pump removal of sludge can provide the physical separation required to protect the NORM workers from severe contamination and personal exposure.

The high pressure jetting can break up the settled solids and when combined with water powered vacuum units can emulsify the sludge oil and water and greatly increase the solid carrying capacity of the fluid. This in turn allows the contained processing of the slurry emulsion and provides an efficient system which minimizes NORM worker exposure.

5 Comparison of Three NORM Facilities[5]

The author has been responsible for the design, procurement, construction and operational start up of three NORM cleaning facilities in Scotland, Louisiana and Alaska. Figures 4, 5, & 6 and (Table 6) show single line diagrams of each system. The development of each facility was in response to the common needs of NORM as an operational problem in the oil and gas industry.

Structure of the Oil and Gas Industry US and UK

The UK oil and gas production is a relatively new industry and because of the offshore nature of the facilities the support and maintenance bases are concentrated in a few locations which are adjacent to the shipping ports and major refineries which in turn are connected by pipelines to major production fields.

In the US the oil and gas industry has been established for many years and is widely distributed throughout the country. Extensive pipeline systems link oil and gas producing and processing facilities from the north slope of Alaska to the Gulf of Mexico. The complexity and age of many pipeline systems in the US results in a much more wide spread potential NORM problem area in the US. Louisiana and Texas have extensive historical oil and gas production areas which have been abandoned but which still may require NORM remediation services.

Relative Size of Oil and Gas Industry

The UK has some 1800 - 2000 producing oil and gas wells producing some 2 million barrels of oil per day. The US has 650,000 oil wells producing about 8 million barrels per day. The UK average oil well produces 2500 barrels per day while the US average well is <10 barrels per day. This results in a huge difference in the number and size of oil well production tubulars. The UK tubulars are 5 1/2" OD and 45 feet long while the most common size in the US is 2 3/8" OD and 32 feet long. The depth of the UK oil is also some 9000 feet on average with the US being at 3750 feet. The net result is that the UK uses relatively few larger tubulars lengths while the US uses very large numbers of smaller sized lengths. These are generalized numbers for comparison.

Regulatory Drivers US and UK

The development of the UK production processing support and maintenance services was required to meet a detailed set of health, safety and environmental regulations. Despite this, the industry was caught short in 1981 when NORM was found in the Piper field in the North Sea. The UK regulations which were applicable had been developed for the nuclear power industry. Fortunately, the regulations were under revision at that time and the 1985 Ionizing Radiation Regulations included provisions for dealing with NORM[9].

The UK has one set of regulations for the entire country including the offshore territorial waters. While different government departments were responsible for some parts of the industry,the industries response to meet the regulatory requirements was applicable to all operations.

In the US, a similar but much more complex situation existed and still exists today. The Federal Nuclear Regulatory Commission (NRC) regulations were developed to cover the nuclear power and defense industries. The EPA, despite having been formed more recently, did not have the remit to deal with radioactive materials in the environment when NORM in oil and gas production was first raised as a legal issue in 1986 in Mississippi. The NRC/EPA debate has resulted in the NORM issue being primarily assigned to the EPA for regulation but has yet to issue any draft NORM regulation.

The conference for Radiation control Program Directors (CRCPD) initiates the development of radiation regulations in the US. New regulations for NORM are now in their seventh draft. Some states have gone ahead with state NORM regulations, Louisiana being the one which has had them in effect since 1989 with Mississippi following in 1992. Other states which are close to implementation are Texas, Illinois, and Michigan. On the federal side, the Mineral Management Services is providing operational guidance using the draft CRCPD regulations to operators in the federal waters of the Gulf of Mexico. NORM has been processed and injected into wells being abandoned in the Gulf of Mexico.

Disposal

UK regulations allow for the disposal of NORM into the sea in a diffuse highly dilute form. NORM is already found in the sea. Radium extraction from the sea was one of the early sources of radium production. In addition, the offshore platforms are permitted to dispose of NORM into the North Sea provided the particle size is less that 1 mm.

The UK has one low level burial site and NORM contaminated items which are not cleaned are disposed of at the Drigg facility in England.

NORM burial disposal in the US is limited to one permitted disposal location in Utah. NORM solids and contaminated tubulars have also been placed into wells and cemented in place as part of the plug and well abandonment program.

One company has developed a NORM slurry injection disposal system into a permitted Class II injection well in Alaska. This unique process is the first multi company use disposal operation for bulk NORM injection in the US.

In the US, disposal of solid NORM above the controlled level of 30 pico Ci/g into the sea or uncontrolled land or waters is not allowed at this time.

Geographical Factors UK

1 UK weather is temperate. Operational experience has shown this means heavy cold rain in winter and lighter warmer rain in summer. Seldom really hot above 20^{0}C (70^{0}F) or below 0^{0}C (32^{0}F).

Hence, and outdoor rain washed NORM cleaning facility is ideal to minimize contamination. The development of a 5 acre concrete covered storage and operational area required a complete set of special drains which collect all spilled NORM materials. Oil water separators for all processed fluids are an essential feature of the NORM disposal equipment.

The unique feature of the UK NORM facility is the governmental approval which allows the discharge of NORM material into the North Sea. Removed NORM is processed to reduce particle size then de-oiled prior to injection into a bulk sea/fresh water pipe line. Strict control of particle size and dilution concentrations are backed up by third party monitoring of the sea outfall of the pipe line. This continuous disposal prevents the accumulation of NORM and the consequent build up of significant dose rates that occur in NORM accumulation in drums.

Personnel protection is achieved through the use of full protective clothing and use of a 3 stage decontamination procedure for access to and from the controlled storage and cleaning areas and an effective "Safe System of NORM Work".

Geographical Factors US

2 US Louisiana presents a very different environment geographical problem. High water table, together with high temperatures and the possibility of hurricane flooding results in significant problems for a NORM operational and storage facility designer.

The NORM cleaning area must be strong enough to withstand tidal flood conditions while the NORM accumulation systems must also be physically secure to contain all NORM at all time.

High ground water ideally requires complete concrete coverage to prevent even small NORM spills from entering the water table. Torrential rains require overhead protection to prevent unmanageable amounts of contaminated surface water. High temperatures require shade for both manpower and equipment.

Opensided roof protection over heavy bermed concrete bays allow for spill containment while allowing natural air circulation. Wind blown rain requires some side protection to avoid excessive water accumulations into the contained areas.

Flood conditions are the most significant potential problem and NORM facility sited in the Gulf Coast in Louisiana will virtually always be within a 100 year flood plain.

Ground conditions are dependent on the back fill used to form the facility work areas with oyster shell being the historically favored fill material. Today continuous addition of gravel and other fill to the site could quickly result in NORM accumulation in depth should all accidental spills not be immediately collected.

NORM disposal at this time requires the collection and storage in approved drums. The drummed NORM can be sent for burial in the Utah permitted site. It may also be taken offshore and injected into an oil or gas well as part of the well plug and abandonment program.

3 US Alaska North Slope conditions of wind, cold and rain requires enclosed protection virtually year round. Process equipment must be inside heated buildings and modules and secondary and tertiary spillage protection employed. Temperatures from +70^{0}F to -60^{0}F with winds to 60 m.p.h. are common.

The terrestrial environmental background radiation levels are extremely low partially explained by the absence of Radon gas which is contained by the perma frost. Hence, any spilled NORM can be easily detected.

Fully contained NORM cleaning processing transport and injection systems must address every conceivable spill response scenario. Enclosed process vessels prevent aerosols and radon discharge through the use of vacuum ventilation and external air vents.

The NORM cleaning operation within buildings requires greater attention to safe work procedures, spill detection and collection.

The transport of NORM in a slurry requires the use of a mechanically closed system. Spillage of the NORM will require a rupture of the transportation vessel. The removed NORM is virtually insoluble in the cleaning water hence, spill collection is easily monitored by hand held radiation detection instrumentation.

<u>Summary</u> The common factor of all 3 facilities is the use of high pressure jetting and water based slurry processing to minimize the work exposure risk while eliminating inhalation/ingestion risks.

UK and US governmental inspection agencies have approved these jet cleaning systems which have proven records of safe operation in cleaning processing and disposing of Naturally Occurring Radioactive Materials

6 Water Jet Cleaning of NORM The Preferred Solution

The use of a water jetting system for the cleaning and removal of NORM scale and sludge has been shown in this report and in extensive field experience to be preferred method because it addresses the following:

1 Radiation dose rate alleviation through water coverage of removed NORM.

2 Elimination of dust and airborne NORM particulate and the associated inhalation/ingestion risk.

3 Fast effective removal of hard scale NORM from complex forms.

4 Minimal damage to the complex high value equipment being cleaned.

5 Separation of the cleaning personnel from the NORM material through the use of remote cleaning systems provides the most effective radiation protection possible by increasing the distance between them.

6 NORM processing in a water based slurry facilitates a wide range of processing options with many of the advantages listed above.

7 The injection of NORM in the cleaning water ensures maximum the reduction of concentration of NORM which close to the levels found in deep geological strata. In these instances, the return of NORM through injection can be reasonable described as the "RESTORATION OF THE GEOLOGICAL EQUILIBRIUM".

7 Acknowledgements

The author wishes to express his thanks to Aqua Dyne, Inc. for their extensive support in the development of the innovative high pressure jetting systems and their supply of first class equipment at all stages of this project.

In addition, I wish to thank ARCO Alaska, Inc. and BPX Alaska, Inc. for their financial support but more importantly, the significant contribution made by their personnel.

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PRINCIPAL DECAY SCHEME OF URANIUM - 238

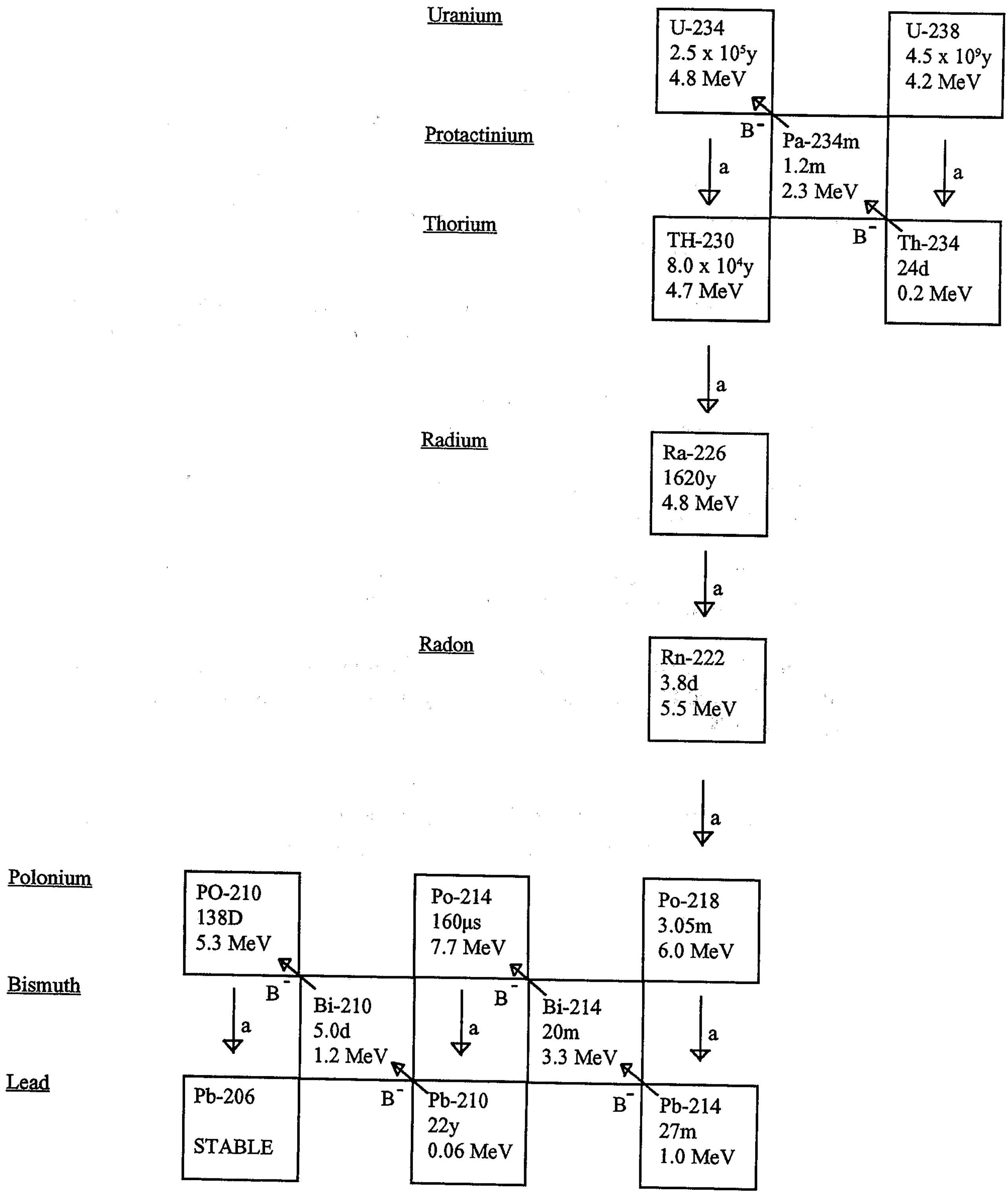

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FIG.1

PRINCIPAL DECAY SCHEME OF URANIUM - 235

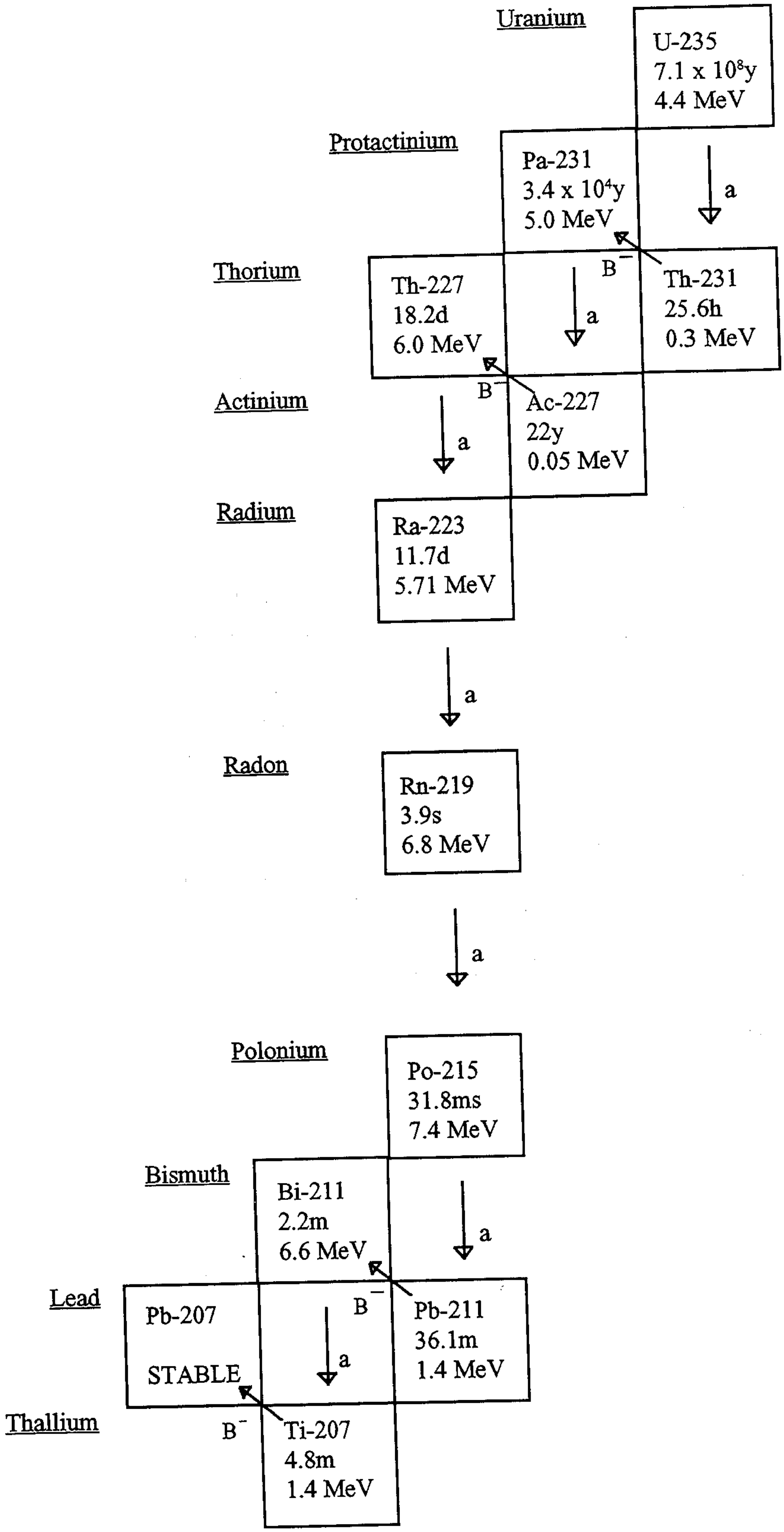

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FIG. 2

PRINCIPAL DECAY SCHEME OF THORIUM - 232

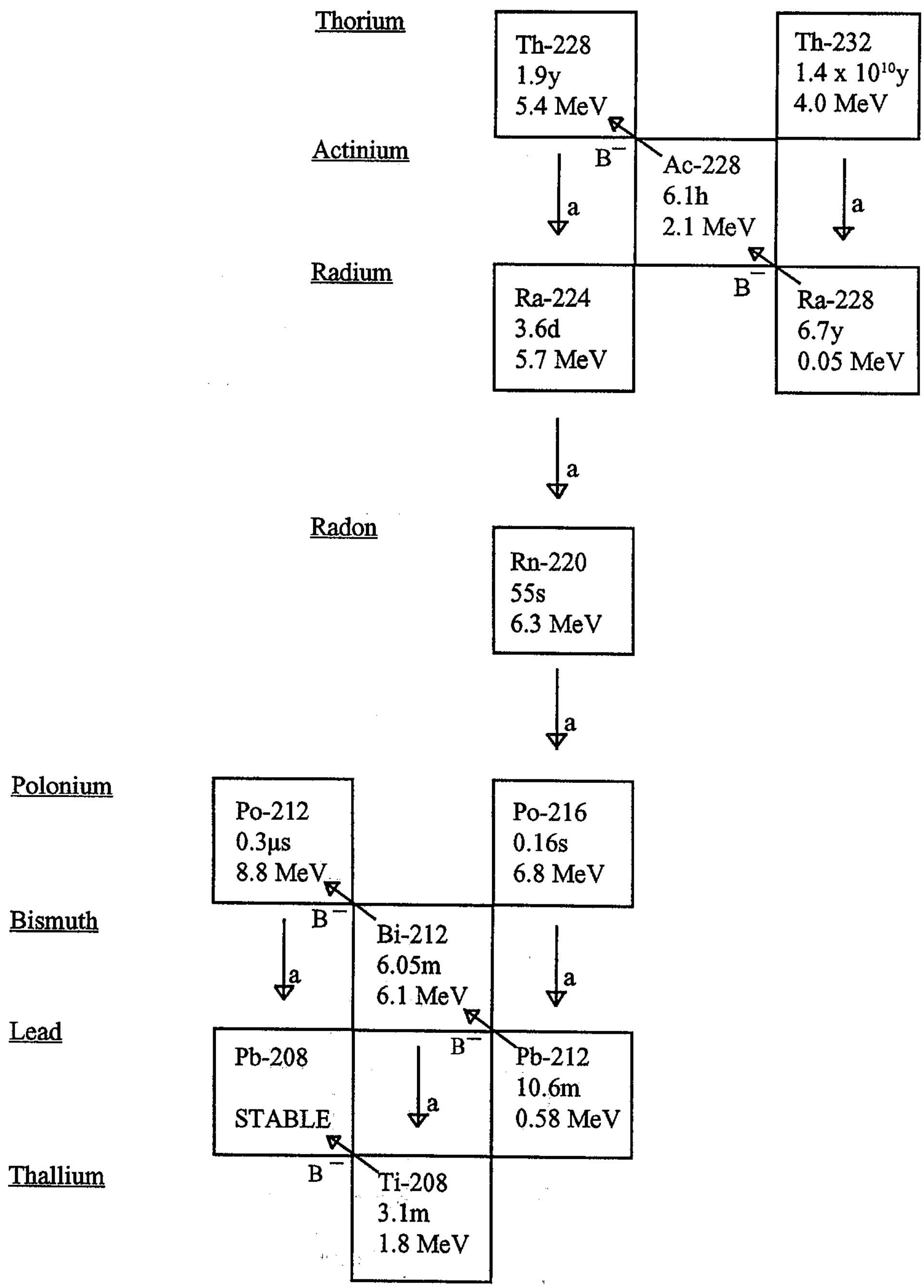

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FIG. 3

<u>**TABLE 1**</u>

NORM SCALE DEPOSTION[6]

TYPICAL LOCATIONS AND RANGES OF THICKNESS, ACTIVITY AND DOSE RATES FOUND IN A NUMBER OF PRODUCTIVE TRAINS

	Thickness mm	Activity Bq/g nCi/q	Dose Rate** u Sv/h (m/rem/h)
1. Downhole Tubing, Safety Valves, etc.	0.5-6	37-15170 (1-410)	120 300 INT (12) (30)
2. Wellheads	1 - 2	48-222 (1.3 - 6)	0.1 - 0.2 (0.01-0.02)
3. Production Manifolds	10 - 50	148-222 (4 - 6)	0.1 - 0.2 (0.01-0.02)
4. Line Before 1st Stage Separator	1 - 5	222-296 (6 - 8)	0.3 - 0.5 (0.03-0.05)
5. Water Outlet from 1st Stage Separator	1 - 2	74-111 (2 - 3)	
6. Line Before 2nd Stage Separator			2.4-4
7. Loose Sludge in Separators to Level of Weirs		3.7 - 70 (0.1-1.9)	0.2-0.5 (0.02-0.05)
8. Scale in Separators	Variable	2368	10 100-150 INT
9. Dehydrator	Sludge	22-28 (0.6-0.75)	
10. Water Outlet from Dehydrator	2 - 2.5	63-89 (1.7-2.4)	0.5 (0.05)
11. Flotation Cell Internals	5 - 75	185-518	
12. Flotation Cell Water Outlet	50	185-370 (5 - 10)	0.5 (0.05)
13. Oil Shipping Pump Impeller	0.5 - 1	277-370 (7.5-10)	
14. Metering Package	0.5 - 1	370-592 (10-16)	370-592 (10-16)
15. Seawater and Produced Water Overboard Dump	50	185-518 (5-14)	185-518 (5-14)

* Activity of actual scale.
** Usually reading taken externally through wall of pipe vessel

TABLE 2

RADON CONCENTRATIONS IN NATURAL GAS AT THE WELLHEAD*[7]

Location of well	Radon concentration pCi/L
Borneo	1 - 3
Canada	
Alberta	10 - 205
British Columbia	390 - 540
Ontario	4 - 800
Federal Republic of Germany	1 - 10
The Netherlands	1 - 45
Nigeria	1 - 3
North Sea	2 - 4
United States	
Colorado, New Mexico	1 - 160
Texas, Kansas, Oklahoma	5 - 1,450
Texas Panhandle	10 - 520
Colorado	11 - 45
California	1 - 100

* From Radon Concentrations in Natural Gas at the Well, United Nations Scientific Committee on the Effects of Atomic Radiation, Sources and Effects of Ionizing Radiation, United Nations, 1977

TABLE 3

NORM CONTAMINATION OF GAS AND NGL PLANTS[7]

NGL Facilities
- De-ethanizers
- Stills
- Fractionators
- Product condensers
- Flash tanks
- Pumps in liquid service
- Piping in liquid service
- NGL storage tanks
- Truck terminals
- Filter separators and other assemblies
- Desiccants
- Waste pits

Piplines
- Filters
- Pig receivers

Machine shops
- In-house
- Contract

TABLE 4

PERSONAL RADIATION DOSES RECORDED BY TLD[8]

Personnel	UK Doses m/Remy-1	mSvy-1	US Doses mRemy1	mSvy-1
Offshore Safety Personnel	0 - 20 (3)	0-0.2 (0.03)	0 - 20 (3)	0 - 0.2 (0.03)
Offshore Cleaning Operators	0 - 80 (23)	0 - 0.8 (0.23)	0 - 60 (20)	0 - 0.6 (0.23)
Onshore Cleaning Operators	0 - 130 (27)	0 - 1.3 (0.27)	0 - 80 (32)	0 - 0.8 (0.32)

( ) Indicates mean dose over group surveyed

TABLE 5

NORM CLEANING TECHNOLOGIES

SCALED EQUIPMENT

METHOD	PROBLEMS	BENEFITS
1. Hand cleaning, brushing scraping.	Direct contamination (DC) Containment (C) Ingestion (IG) Inhalation (IH)	Cheap Universal
2. Power hand tools electric brushing, grinding	D.C.+; C; IG+; IH+ Components only	Faster than (1)
3. Air Driven Tools Rattlers, Needle Gun	DC++, C. IG++ IH++ Difficulty with ueven surfaces & odd shapes	Special Application tools
4. Chemical Cleaning	Chemical Hazard Fumes Chemical Reaction Mixed Waste Disposal	Can recover costly complex items without damage
5. Water Jetting	Higher Capital Cost Water recycle Filter costs	No dust Manageable aerosol Fast/Efficient NORM eflfuent manageable with immediate disposal Great flexibility in cleaning uneven surfaces and complex forms

SLUDGE REMOVAL VESSELS TANKS PONDS

METHOD	PROBLEMS	BENEFITS
1. Pumped Sludge	Heavy soldis residual left with no liquids requireing mechanical removal. Oil water solids phase separation and further processing for disposal required.	Low Costs
2. Hand shoveled tank vessel sludge	Same as (1) Personnel Exposure	Low cost, very flexible
3. High Pressure Jetting and pumping/vacuuming	Breaks up solids into slurry permitting pumping separation easier provided water/oil do not emulsify.	Emulsified suspension easier to pump. transfer, and process

TABLE 6

THREE NORM FACILITIES COMPARED

FEATURE	US/LOUISIANA(1989)	UK(1982 - 83)	US/ALASKA(1992 - 93)
DISPOSAL	BURIAL IN DRUMS	DIFFUSE SUSPENSION TO THE SEA	CLASS II WELL INJECTION
BUILDING	ROOFED FOR RAIN HEAT PROTECTION	OPEN TO RAIN TO PROMOTE WASH DOWN	ROOFED FOR COLD PROTECTION
CONTAINMENT	CONCRETE PADS PLASTIC SHEET TAPE BARRIER CHAIN LINK	TOTAL CONCRETE COVER OF ENTIRE NORM FACILITY 6' CONCRETE BARRIER TO ACTIVE AREAS	DOUBLE/TRIPLE CONTAINMENT 110% SECONDARY IN PROCESS MODULES FULL MEMBRANE PROTECTION CONTROLLED BUILDING ACCESS
PERSONNEL	THREE (3) STAGE DECONTAMINATION	THREE (3) STAGE DECONTAMINATION	THREE (3) STAGE DECONTAMINATION
SURVEYS CONTAMINATION	ALL EQUIPMENT PRIOR RECEIPT + WIPES	ALL EQUIPMENT PRIOR TO RECEIPT - NO WIPES	ALL EQUIPMENT PRIOR TO AND AFTER CLEANING
DOSE RATE	ALL EQUIPMENT PRIOR TO AND AFTER CLEANING	ALL EQUIPMENT PRIOR TO AND AFTER CLEANING	ALL EQUIPMENT PRIOR TO AND AFTER CLEANING FULL LENGTH DECON RECORD BY TUBOSCOPE
WEATHER LOUISIANA	HURRICANES INCHES OF RAIN	GALES, STORMS RARE REGULAR LIGHT RAIN	LIGHT SNOW, WINTER LIGHT RAIN SUMMER
REGULATORY DECISION	50 MICRO REM/H	2X BACKGROUND READING	50 MICRO REM/H
ACTUAL WORKER ANNUAL EXPOSURE	150 MREM	130 MREM	NOT YET KNOWN
RAINFALL	ROOFED PROTECTION OF ALL CLEANING EQUIPMENT 3-4 INCHES PER DAY POSSIBLE	OPEN FACILITY TO DIRECT RAINFALL 0-1 INCHES TYPICAL	SEMI ARID SUMMER LIGHT RAIN WINTER LIGHT SNOW
TEMPERATURE	ROOFED TO PROTECT NORM CLEANING WORKER SUMMER 100° F+	OPEN ALLOWING DIRECT HEATING OR COOLING. WORKERS NEED TO DRESS TO SUIT SEASONS SUMMER 60°F WINTER 30° TO 40° F	COVERED HEATED SUMMER 40° TO 60° F WINTER -25° TO -65° F
WIND	HURRICANE RATING ON ALL STRUCTURES.	POSSIBLE GALE TO STORM STRENGTH WINDS. NO SPECIAL PRECAUTIONS	HIGH WINDS + EXTREME COLD WIND CHILL BELOW -100° F
FLOODING	TIDAL AND BAYOU FLOODING REQUIRE CONTINGENCY PLANNING SITES 5-10' ABOVE SEA LEVEL	NO FLOODING UNLESS A GROUND DRAIN GETS BLOCKED DURING HEAVY RAIN. 10 - 30' AND ABOVE SEA LEVEL	NO FLOODING MUDDY SOFT ROAD SEASON DURING SNOW MELT
DUST	CONTINUOUS WIND	RAINFALL & CONCRETE MINIMIZE ANY DUST AT ALL	DUST DURING SUMMER DRY PERIODS FREEZING ICE CRYSTALS IN WINTER

FIGURE 4

NORM FACILITY ABERDEEN, SCOTLAND

1983

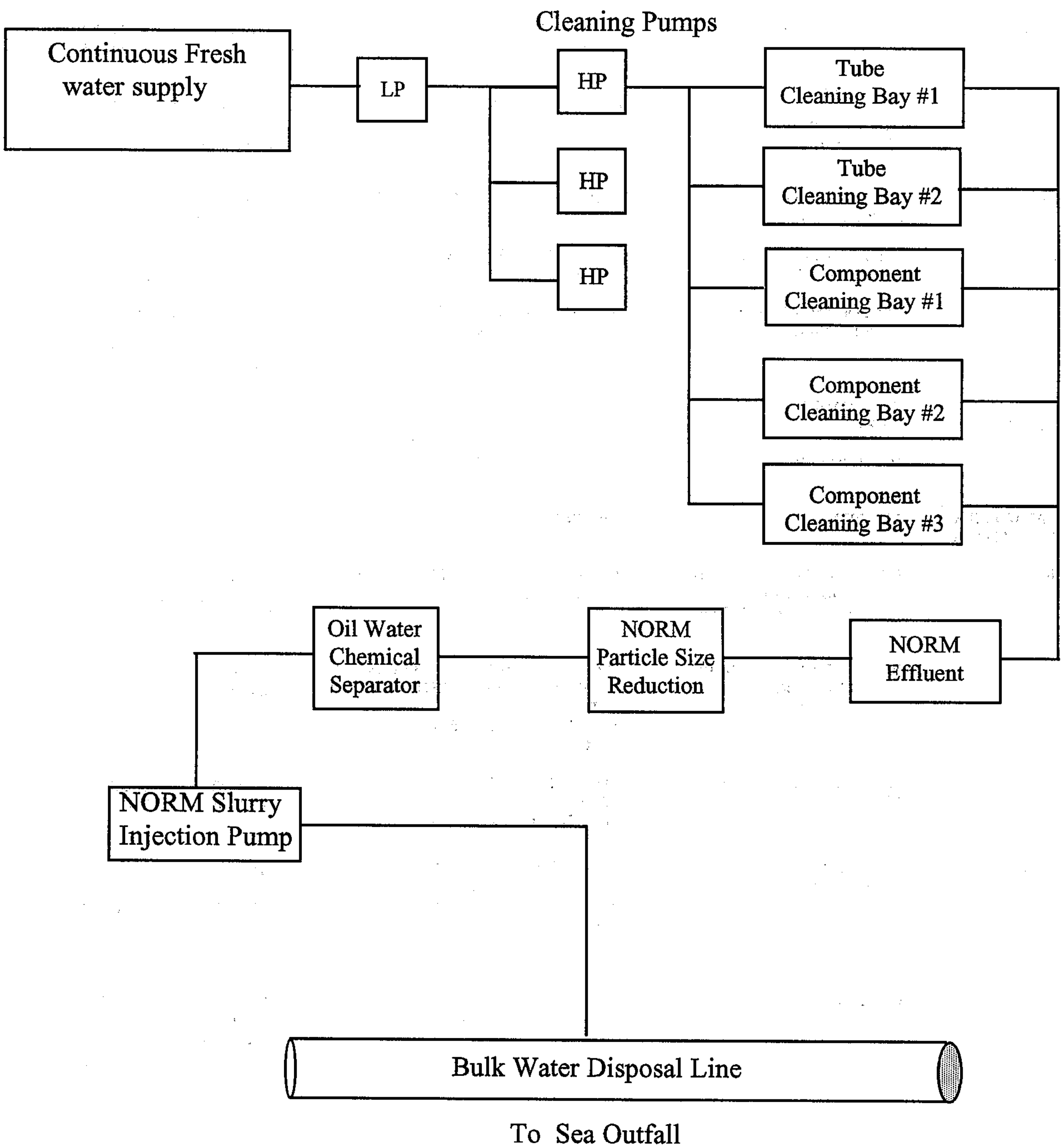


FIGURE 5

NORM FACILITY AMELIA, LOUISIANA

1989

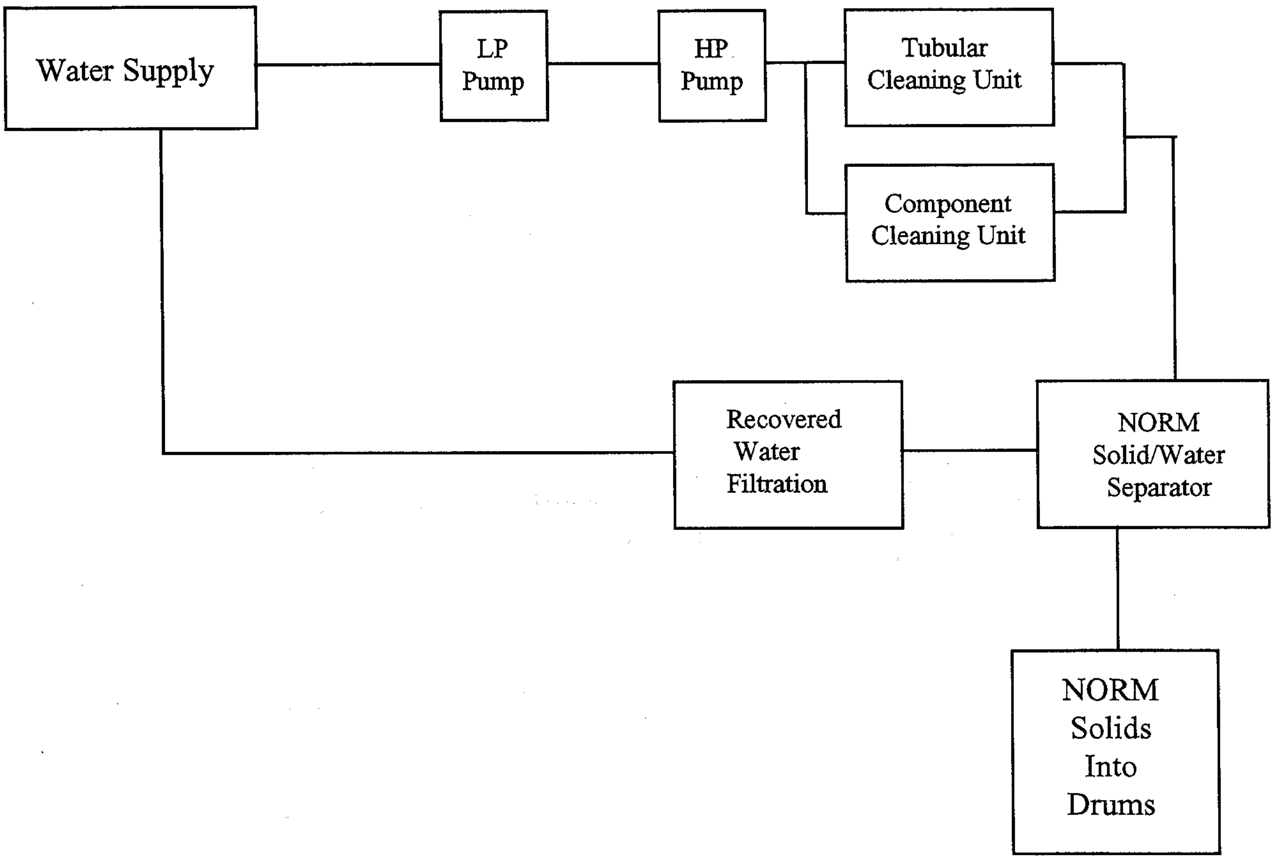
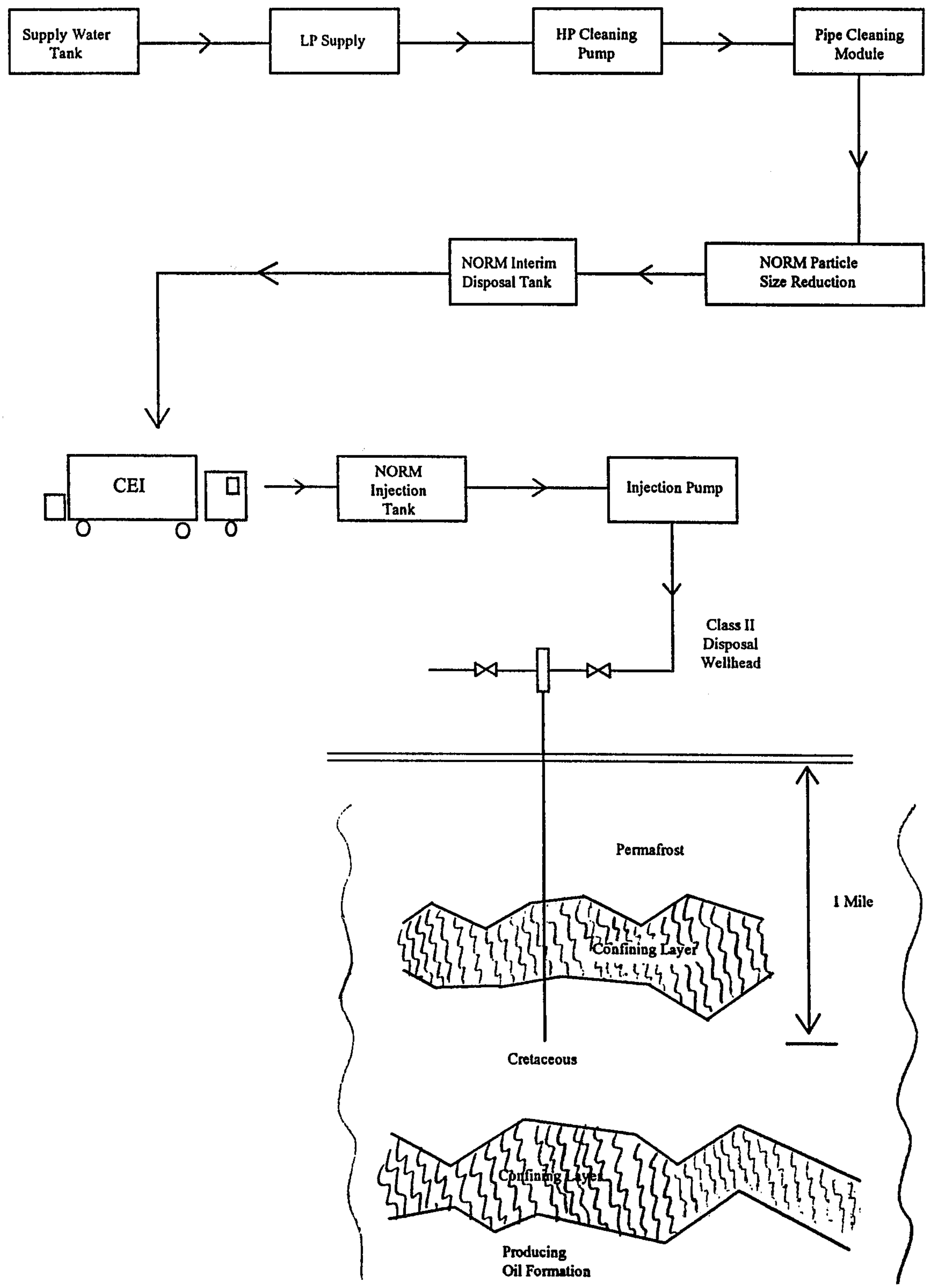


FIGURE 6

NORM FACILITY - DEADHORSE, ALASKA

1993



7th American Water Jet Conference
August 28-31, 1993: Seattle, Washington

Paper 54

NUCLEAR REACTOR REPAIR

BY HIGH PRESSURE HYDROABRASIVE JET

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ABSTRACT

In mid 1991, during a routine inspection, several cracks were detected on the french nuclear reactor BUGEY III. These cracks were situated at the lower end of INCONEL 600 tubes.

The tubes, called adaptors are used as guiding sleeves for the control rods. They had been installed through the boiler's cover and welded to it.

This paper presents the use of the hydroabrasive jet to perform the repairs.

These repair operations were successfully conducted on three different boilers and are certainly one of the major industrial water jet application performed inside a nuclear core.

1.0 INTRODUCTION

On August 1991, the French nuclear power plant Bugey III, PWR, 900 MW is stopped for a routine inspection, this nuclear installation (a 10 years old system) is operated by EDF, the government owned electricity company. During two months, the Engineers and technicians will test and check all the vital components of the system.

On September 23rd, all the tests are completed and it is decided to make the legal pressure proof on the primary circuit before restarting the nuclear power plant.

The test is conducted at a pressure of 21 MPa, a pressure higher than the normal operating pressure of 15 MPa. For the first time on such a system, the technician of EDF will detect some small leaks on the cover of the boiler, it is immediatly decided to stop the pressure proof and find out the origin of the leaks.

FRAMATOME, the french company, general designer and manufacturer of the boiler is contacted and charged to find a remedy to the problem.

2.0 TECHNICAL PROBLEM

EDF and FRAMATOME will work in close relation to rapidly find the causes of problem. Just 24 hours after the leaks were discovered, a defect is found around the welding of one of the 65 adaptors. The adaptors are cylindral shape sleeves used to guide the control rods. The adaptors made of INCONEL 600 alloy are installed through the cover and welded to it.

To find precisely the origin of the problem, the cover (a part of Diameter 4 meter and a weigh of 40 metric tons) is dismounted and set aside from the boiler. Ultra sonic tests are then conducted in the inside diameter of the adaptor. These tests will show that longitudinal cracks, a few centimeters long, are present in the tube and are responsible for the leaks.

After this diagnosis, the french nuclear safety board will ask for additional tests and metallurgical inspection of the adaptors. A complete repair of the defective adaptors is mandatory before any restart of the nuclear installation might be considered.

A vast experimental procedure is launched by EDF and FRAMATOME. It is found that the cracks are initiated by a stress corrosion occuring on the adaptor at the level of the welding junction with the cover.

Additional checks are performed simultaneously on other nuclear power plants ; In fifty per cent of the cases, the same types of cracks are discovered.

Shortly after, it will be revealed that the problem is not limited to French installations, but is a worldwide problem. Sooner or later all the nuclear power plants with be affected.

The French nuclear power plants are operated, for efficiency consideration, at a temperature of 315°C, compared to operating temperature of 290°C in most of the other nuclear countries. It appears that a discrepancy of 25°C in the operating temperature can increase the development of stress corrosion by a factor of 5.

3.0 USE OF WATERJET

In order to do metallurgical analysises on the defective material, it was decided to take a sample of the adaptor. To do so, the extremity of the adaptor had to be cut at the base of its welding. Several cutting processes were analysed, the hydroabrasive waterjet cutting was the only process allowing to cut from the inside diameter of the adaptor a complicated contour following the shape of the welding, without producing any thermically affected zone on the material being cut.

This technology was selected and AQUARESE INDUSTRIES choosen by FRAMATOME to be its partner responsible for the design, manufacturing, and field operation of the waterjet equipment.

4.0 DESIGN OF THE COMPLETE SYSTEM

The complete system is made of three basic groups of equipment.

4.1 High pressure pump

The high pressure pump selected for this application was able to operate at 410 MPa with a flow rate of 6 Lpm. However, the operating pressure was limited to 350 MPa to allow the use of flexible hoses.

The pump was mounted on a metallic skid easy to be carried in a nuclear building.

The inside of the pump was protected against nuclear contamination by a flow of pressurized air introduced through its covers. Several sensors were installed on the pump and connected to the CNC of the machine.

4.2 CNC cutting machine

A specially designed CNC cutting machine was developped to allow programmed abrasive cutting head's displacement. Basically, two motions are given to the nozzle :

- Angular horizontal rotation.
- vertical linear displacement. The combination of these two movements gives the nozzle's trajectory. This trajectory programmed on a CAD system and transfered to the CNC is a complex 3 dimensional curve following the lign determined by the intersection of the adaptor and its welding.

The trajectory differs from adaptor to adaptor and has to be programmed for every cut.

The cutting machine is installed on the upper extremity of the adaptor, the cutting nozzle is mounted on an rigid 9/16" HP tubing connected to the CNC machine. The nozzle goes through the ID of the adaptor (75 mm) and cuts the 15 mm thick inconel material.

4.3 Catcher

A catcher has been designed to collect the jet after the cut, dissipate its remaining energy, and protect the inside surface of the boiler's cover. This catcher has an elliptic shape which fits with geometry of the cover in contact with the catcher.

One of the major role of the catcher is to carefully protect the cover and prevent damages, which could be produced by a direct contact or rebound of the jet. It was also very important to collect 100 % of the highly contaminated waste (contamination level 10 REM).

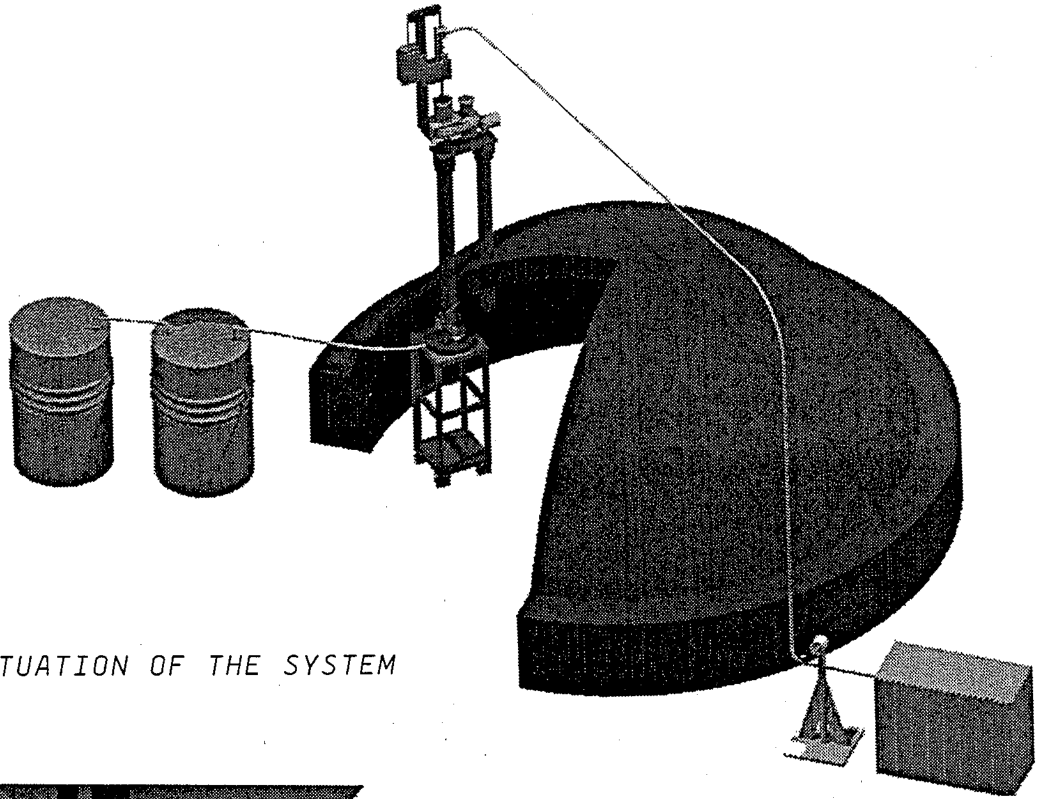
5.0 QUALIFICATION OF THE PROCESS - 1st CUT

A scale one to one mock-up of the boiler's cover was built and used to test the cutting system. All the cutting parameters had to be released and recorded in an operating procedure book. Only two and half months after the decision to use a water jet for the cut, the system was finished and sent to Bugey nuclear installation for the first cut.

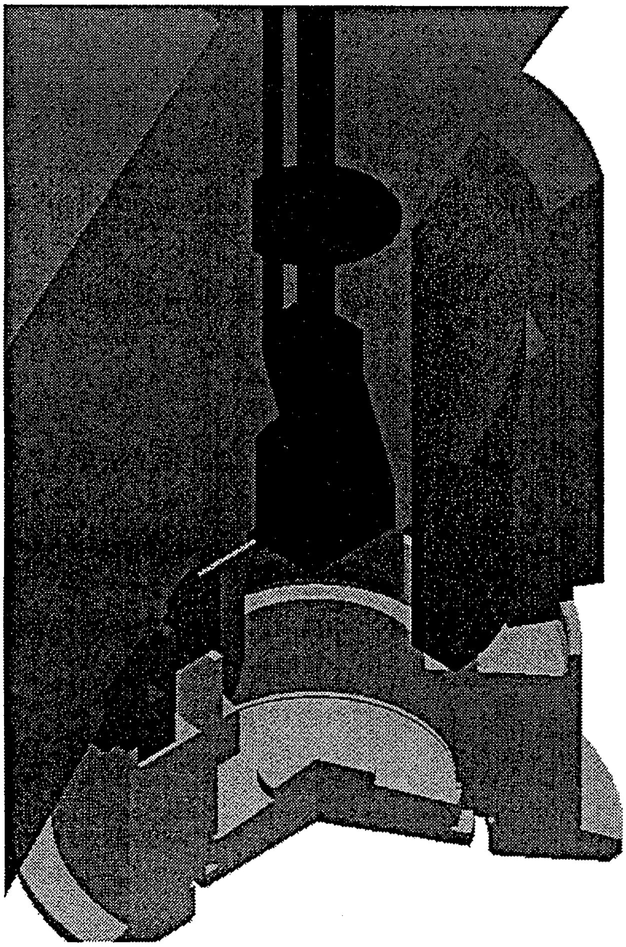
Installation on site and start-up procedure took another two days. The first cut was conducted by 3 engineers and 6 technicians.

Within 20 minutes, the extremity of the adaptors was detached from the cover.

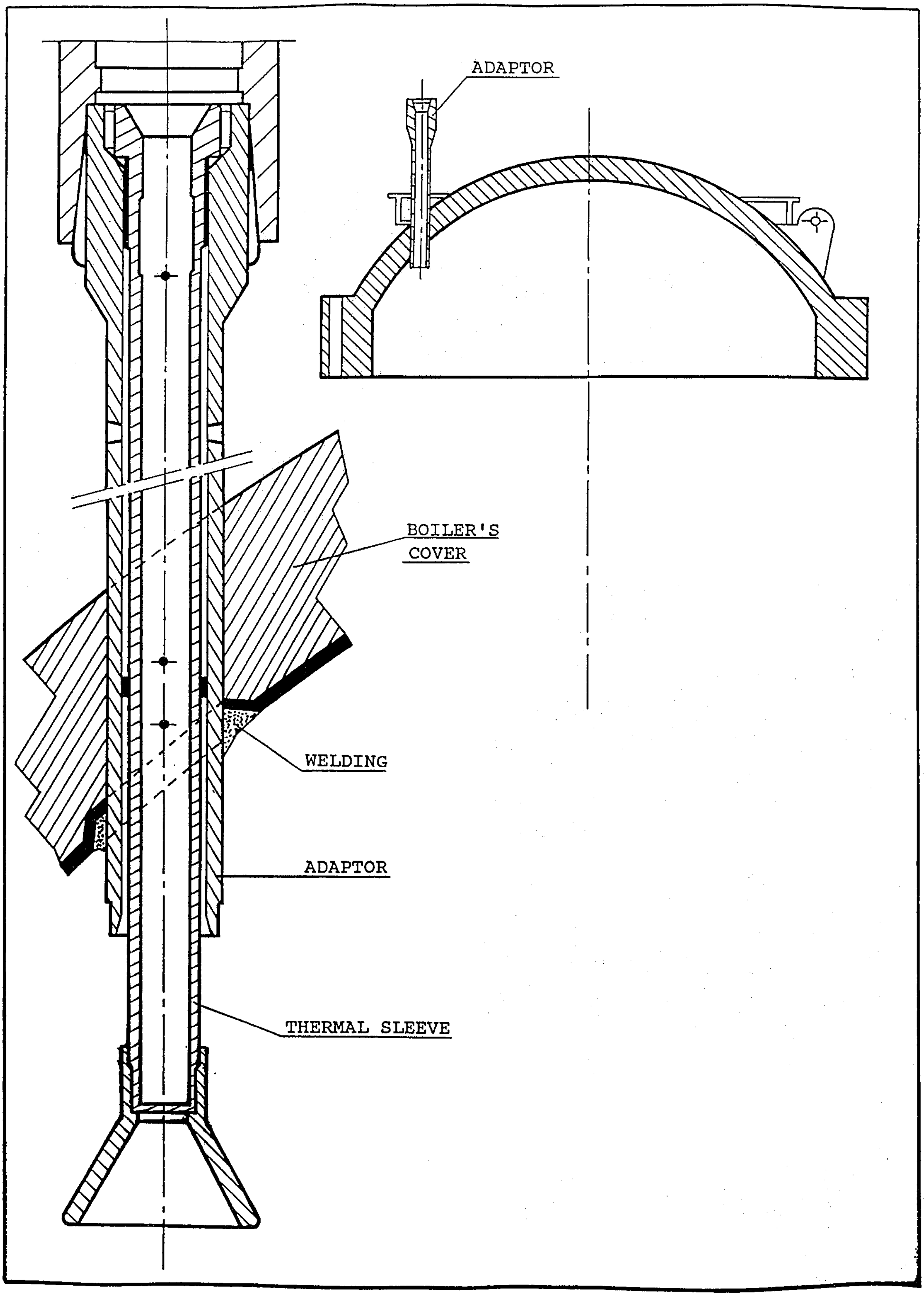
The operation was a success and repeated on two others nuclear power plants.



GENERAL SITUATION OF THE SYSTEM



NOZZLE CUTTING THE TUBE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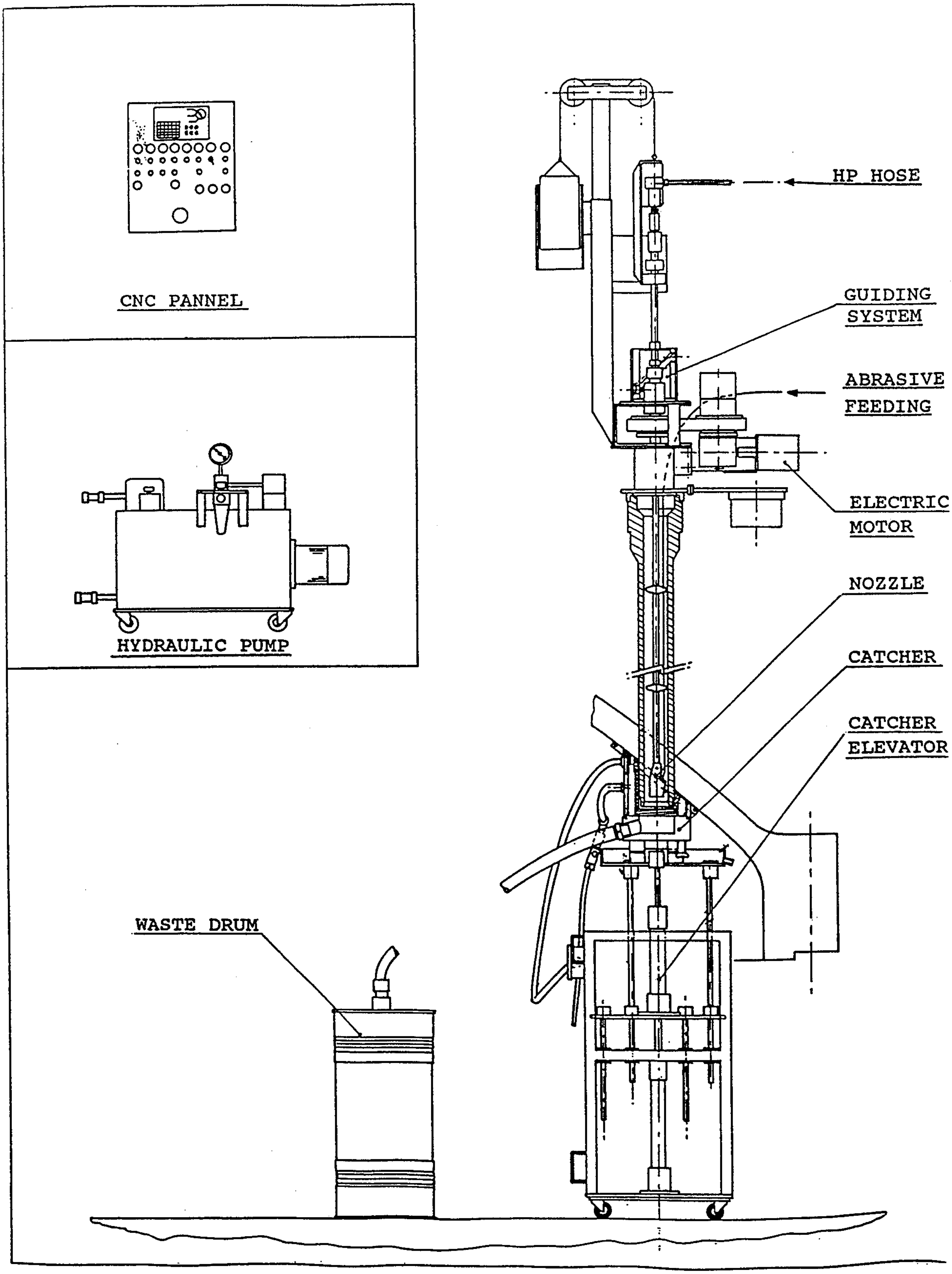
BOILER'S
COVER
WELDING
ADAPTOR
THERMAL SLEEVE


CNC PANNEL
HYDRAULIC PUMP
WASTE DRUM
HP HOSE
GUIDING SYSTEM
ABRASIVE FEEDING
ELECTRIC MOTOR
NOZZLE
CATCHER
CATCHER ELEVATOR

7th American Water Jet Conference
August 28-31, 1993: Seattle, Washington
Paper 55

DEVELOPING A SCARIFIER TO RETRIEVE RADIOACTIVE WASTE FROM HANFORD SINGLE-SHELL TANKS

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ABSTRACT

Radioactive waste is stored in 149 3785 m^3 (million gal) single-shell tanks on the US Department of Energy's Hanford Reservation in eastern Washington. To minimize leakage as the tanks age, the free liquid has been pumped out, leaving concentrated solidified salt cake and sludge deposits. Now methods to dislodge and remove this waste are being developed so that the waste can be retrieved and processed for permanent storage.

This paper presents research and development on ultrahigh-pressure water-jet technology to fracture and dislodge the wastes in these tanks. A water-based prototype scarifier with an integral conveyance system is being developed, and its performance demonstrated in a coupled analytical and experimental investigation. This paper describes experimental objectives and approach and results of the single jet experiments. Previous testing indicates that the method can be readily applied to salt cake waste forms; retrieval and conveyance of sludge and viscous fluid waste forms may present additional challenges.

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1. INTRODUCTION

Radioactive waste is stored in 149 3785 m^3 (million gal) single-shell tanks on the Hanford Reservation in eastern Washington. The free liquid has been pumped from these tanks leaving concentrated solidified salt cake and sludge deposits. The Underground Storage Tank Integrated Demonstration supports the U.S. Department of Energy (DOE) effort to develop methods to retrieve these solidified wastes. Several types of hydraulic waste dislodging tools and retrieval methods are under evaluation: dislodging tools include high-pressure low-flow-rate scarifiers and low-pressure high-flow-rate miners; retrieval systems include pneumatic conveyance using air as the transport fluid and jet pumping using water. Initially, pneumatic conveyance will be evaluated with the scarifier and jet pumping will be evaluated with the low pressure miner. This paper describes the development of the scarifier portion of a scarifier/pneumatic conveyance waste dislodging system.

2. BACKGROUND

Scarifiers erode solid material with high pressure water jets and are currently used to remove concrete from bridge decks without injury to imbedded reinforcing bars or deck supports. Special-purpose scarifiers to decontaminate metal and concrete surfaces have been designed and manufactured by Quest Integrated, Inc. (Pezzimenti, Vlad, and Landau 1989, Tundo, Gessner, and Lawrence 1988); these scarifiers include integral systems for water and waste stream retrieval. This technology is being adapted to remove wastes contained in underground storage tanks across the DOE complex. The technology is hydraulic; however, systems have been designed to minimize water accumulation by applying suction concurrently to remove dislodged material and the water working fluid. The eroded material and water are then conveyed pneumatically away from the surface.

Proof-of-principle tests to evaluate the performance of an existing water jet scarifier prototype to erode salt cake and sludge simulant were performed by Quest (1990); the results indicated that scarifiers would successfully erode salt cake or soft sludge. However, difficulties were encountered when eroded soft sludges were conveyed pneumatically. No attempts were made to optimize the scarifier or the conveyance system during this proof-of-principle test. Based on a review of existing theories and past experiments conducted under similar conditions, a strategy (Bamberger et al 1993) has been formulated for a coupled analytical/experimental approach to develop a multi-functional scarifier coupled with a pneumatic conveyance system. Based on this analysis

- Salt cake is anticipated to be the easiest waste form to retrieve. A theoretical model of hydraulic rock fracture can be applied to estimate jet performance in fracturing the salt cake, and gas-solids transport correlations can be used to predict pneumatic transport of dry solids.

- Deformable sludge is anticipated to be the most difficult to retrieve. No theories, correlations, or data exist to predict performance in this case.

- Viscous fluid is anticipated to be of intermediate retrieval difficulty. Analogies to classical two phase gas-liquid flow can be justified.

Pacific Northwest Laboratory and Quest Integrated, Inc. are collaborating in a joint effort to optimize the scarifier/conveyance system design to dislodge and retrieve tank wastes.

3. OBJECTIVE

The primary objective of this joint effort is to develop a light-weight scarifier dislodging tool with an integral pneumatic conveyance system to dislodge and convey salt cake, sludge, viscous fluids, and scarifier cutting fluid from radioactive waste stored in tanks at Hanford and other sites.

Existing scarifier and pneumatic conveyance technology will be integrated and adapted to

- operate efficiently to remove a variety of waste forms including salt cake, sludge and viscous fluids
- minimize total water accumulation in tanks by incorporating an integral removal/conveyance system
- maximize working fluid retrieval efficiency to achieve >98% fluid retrieval in a single pass
- minimize water use by using high-energy, high-pressure water jets
- decrease the volume of the scarifier unit to 0.3 m (12 in.) cube
- decrease the mass of the scarifier to between 45 and 90 kg (100 and 200 lbm) to ease its placement on robotic manipulators
- determine maximum continuous waste retrieval rates
- maximize the solid loading permitted in the conveyance system
- optimize the size of solid aggregates cut by the scarifier for transport by the conveyance system
- characterize vertical lift capability for a conveyance system; 15 m (50 ft) is required for tank deployment
- operate and survive in the high radiation tank environment
- resist plugging of the conveyance system
- reduce potential entanglement with in-tank hardware by replacing scarifier rotating jet nozzles with linear motion jet nozzles.

4. APPROACH

Modifications to the scarifier to allow it to operate in a tank environment require testing to determine the operating parameters most suited to retrieval and conveyance of the various waste forms contained in tanks. To identify the optimum parameters separate effects experiments to evaluate varying design parameters separately over a broad range are underway. Integrated effects experiments to study interactions between scarifier and conveyance components will follow. Components for testing in the integrated effects experiments will be designed on the basis of the separate effects experimental results. These prototypes will be extensively tested over a narrower range of operational parameters.

The experiments will be conducted in four phases with each phase investigating the dislodging and retrieval of increasingly complex simulants as follows: 1) homogeneous simulants with no surface contour, 2) homogeneous simulants with free surface contours and heterogeneous simulants that include veins of other waste types (for example, salt cake with inclusions of sludge or viscous fluid), 3) simulants that model in-tank debris (for example tapes and pipes), and edge effects (such as the proximity of a tank wall or large component), and 4) integrated system experiments to characterize performance during potential failure modes (such as power outages or system plugging), to determine the ability of the system to recover from upset conditions.

4.1 Scarifier Separate Effects Experiments

The objective of the scarifier separate effects scaled experiments is to provide a scarifier design that will dislodge the waste forms into discrete particulate that can be mobilized and transported pneumatically. The evaluation criteria is to produce particulate in a size distribution that allows continuous transport of salt cake, sludge, and viscous liquids at solids loadings adequate to remove approximately 0.028 m^3/min (1 ft^3/min) or more of waste. The maximum particulate size is estimated to be <0.5 cm (0.2 in.) diameter but preferably <0.25 cm (0.1 in.) diameter. Key parameters that must be determined are the optimum jet (shape, pressure, number, configuration, and translation rate) for the multiple waste forms and an initial containment shroud configuration.

Scarifier separate effects experiments are divided into three types:

- Single jet experiments: to investigate jet parameters that affect the size of particulate.
- Multiple jet experiments: to investigate the effects of jet interaction.
- Shroud development: to investigate shroud configuration necessary to mobilize the dislodged material.

The three waste forms -- salt cake, sludge, and viscous liquid -- will be used to conduct each of these investigations. Results from the single jet tests will be evaluated to determine which configurations should be investigated during multiple jet tests. Results from the multiple jet tests will be evaluated to determine whether they meet the criteria of particle size necessary for pneumatic transport. This criteria will be developed during conveyance separate effects tests.

Mobilization in the shroud will be investigated to determine an initial shroud configuration and whether additional jets of air or water may be required to assist in mobilization of the dislodged material. Shroud optimization is expected to be accomplished via experimental investigations with qualitative results. It is anticipated that shroud development will continue during the integrated effects experiments.

Based on the results of these scarifier separate effects experiments, a scarifier head will be developed for use in the integrated effects experiments.

4.2 Single Jet Test Matrix

The objective of the single jet tests is to determine what regime of jet operation will work best to dislodge and mobilize the salt cake and sludge waste forms. We expect that this global optimum will be a compromise among the individual optimal designs.

The single jet tests were constructed to evaluate six parameters affecting the design of a scarifier head, using a 1/4 replicate of a $2^6 = 64$ factorial experiment. A 1/4 replicate experiment ensures that the six main effects are free of any two-way interactions. Descriptions of the test parameters follow.

Simulant. Simulants represent "typical" waste that the scarifier will encounter. Homogeneous waste forms representing salt cake and sludge, each with uniform surface contour, were evaluated. The simulant was configured to have a flat surface. A potassium magnesium fertilizer simulates the salt cake waste form, and a kaolin clay simulates the sludge waste form.

Jet Shape. Two jet shapes, shown in Figure 1, a round jet and a fan jet, were investigated. Solids are usually cut with a round jet because a high force per unit area is required for most solids. However, waste types such as sludges and viscous liquids may benefit from a fan-shaped jet, which distributes the jet force over a larger area. Both shapes were evaluated to determine which is more effective in mobilizing the simulants.

Jet Size. Jet size (orifice diameter) affects the depth of cut into the simulant, and the depth of cut is proportional to the simulant removal rate. Two diameters, 0.38 and 0.64 mm (0.015 and 0.025 in.), were evaluated. Depth of cut was measured to determine that the size of particulate dislodged is adequate for transport by the retrieval system.

Incidence Angle. A theory of hydraulic rock fracture shows that the incidence angle from the vertical can be optimized (Crow 1973). This theory applies to hard rock. A 0 degree incidence angle referenced from vertical would be expected to cut a deep slot into the simulant. Angles 60 degrees or greater would produce thinner sections of material that may fracture more readily than those cut at a 0 degree angle. Two incidence angles between 0 and 90 deg were evaluated to determine the effect of incidence angle on cutting the simulants into uniformly sized chunks.

Traverse Velocity. Hydraulic rock cutting theory predicts an intrinsic speed for rock cutting, based on the properties of the rock (Crow 1973). Salt cake simulants should reproduce this limiting case. Traverse velocities of 1.3 and 13 m/min (500 and 5000 in./min) were evaluated.

Pressure. Pressure affects the flow rate of the jet and its intensity. Two pressures, 40 and 50 kpsi, were be evaluated. The lower pressure jet is preferable because requires less water addition and a lower pressure intensifier system.

4.3 Multiple Jet Test Matrix

The single jet test results will be used to design the multiple jet scarifier configuration and test matrix. The single jet tests will determine the parameter values that produce the best dislodgement of the waste forms. Tests with multiple jets will determine whether the number of jets affects the rate of waste fracture and dislodging and particle diameter of the eroded waste.

5. EXPERIMENTAL RESULTS

The single jet test assembly consists of a computer-controlled traverse system coupled to a rotary test bed, as shown in Figure 2. Both the salt cake and sludge simulant experiments were conducted in this fixture. The simulants react differently to the round and fan jets.

In the salt cake experiments (Figure 3), the round jet cut a clean, narrow, kerf into the simulant, as shown in Figure 3; while the fan jet eroded a coarse, wide swath across the simulant. Erosion mechanisms are apparent with both jet shapes.

In the sludge experiments, the round jet "sliced through cleanly," not leaving much of a kerf below about 5 cm (2 in.) from the surface; while the fan jet seems to "push" or "dish" a wide trench through the sludge, as shown in Figure 4. In sludge, larger scale displacement in response to the localized jet pressure seems to be a more dominant mechanism than smaller scale "erosion."

The data is being evaluated to rank the effectiveness of each type of jet dislodging the waste form simulants.

6. CONCLUSIONS

Water jets provide a continuous method to fracture and dislodge radioactive wastes stored in underground storage tanks. Research and development is ongoing to develop scarifiers for this purpose and results to date show that the technology can be successfully developed.

7. ACKNOWLEDGMENTS

This research, conducted by Pacific Northwest Laboratory (operated for the U.S. Department of Energy by Battelle Memorial Institute), was supported by the U. S. Department of Energy under contract DE-AC06-76RLO. The work is a part of the U.S. Department of Energy Underground Storage Tank Integrated Demonstration Program lead by Westinghouse Hanford Company. Scarifier development is conducted in conjunction with Quest Integrated, Inc., under the direction of William J. Coleman.

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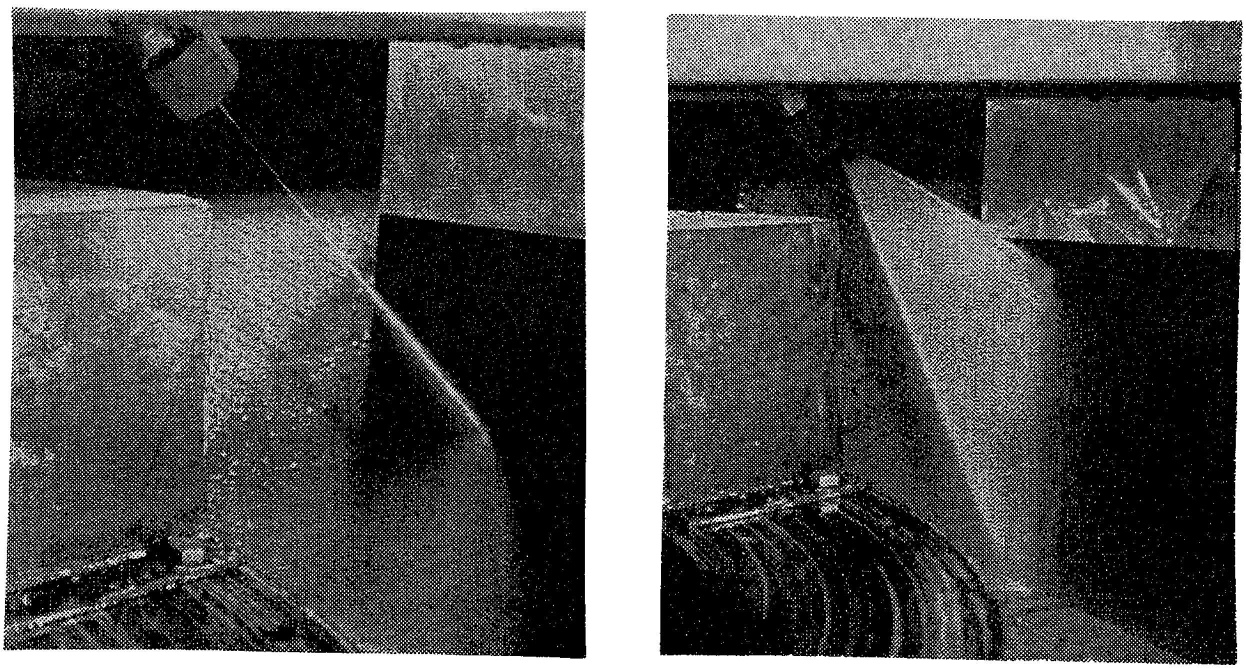

Figure 1. Round and Fan Jet Profiles

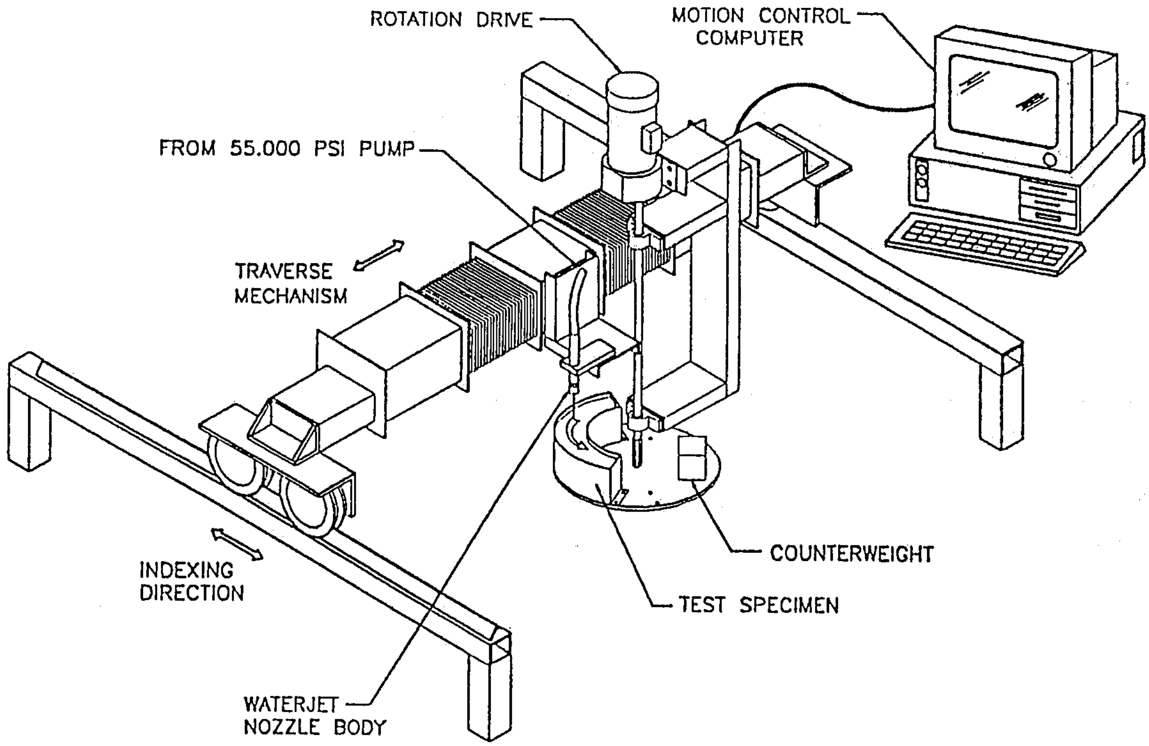

Figure 2. Scarifier Separate Effects Experiment Test Fixture

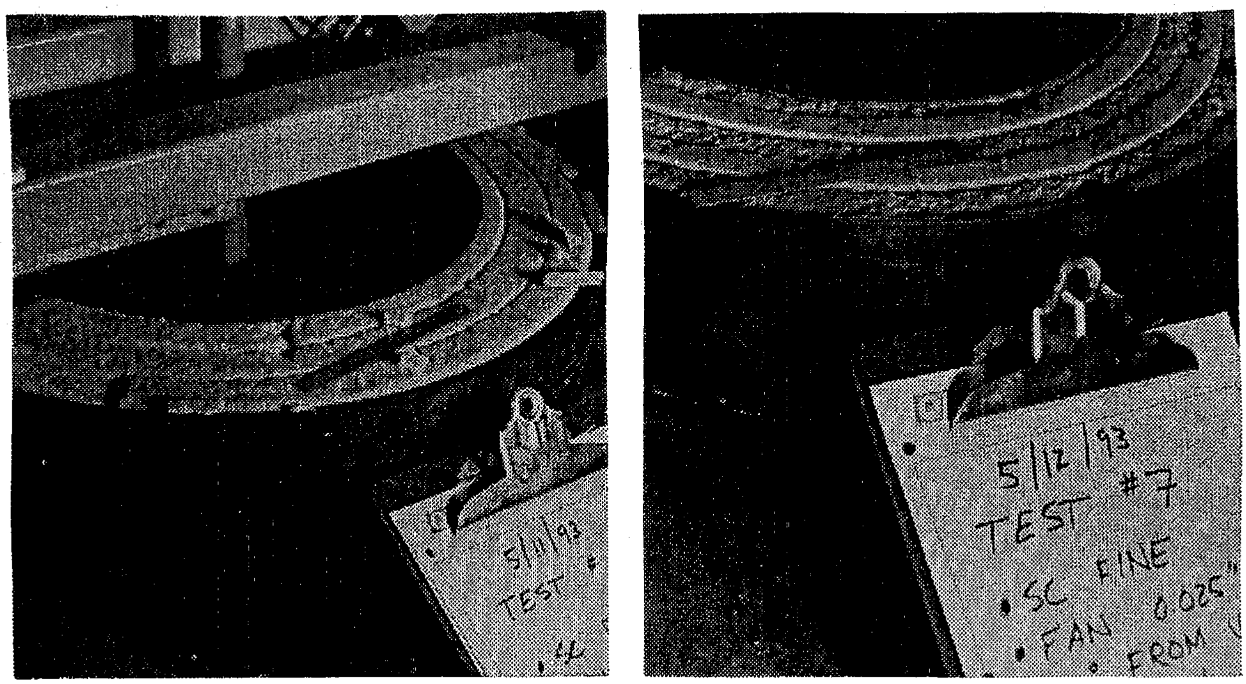

Figure 3. Examples of Round and Fan Jet Cuts through Salt Cake Simulant

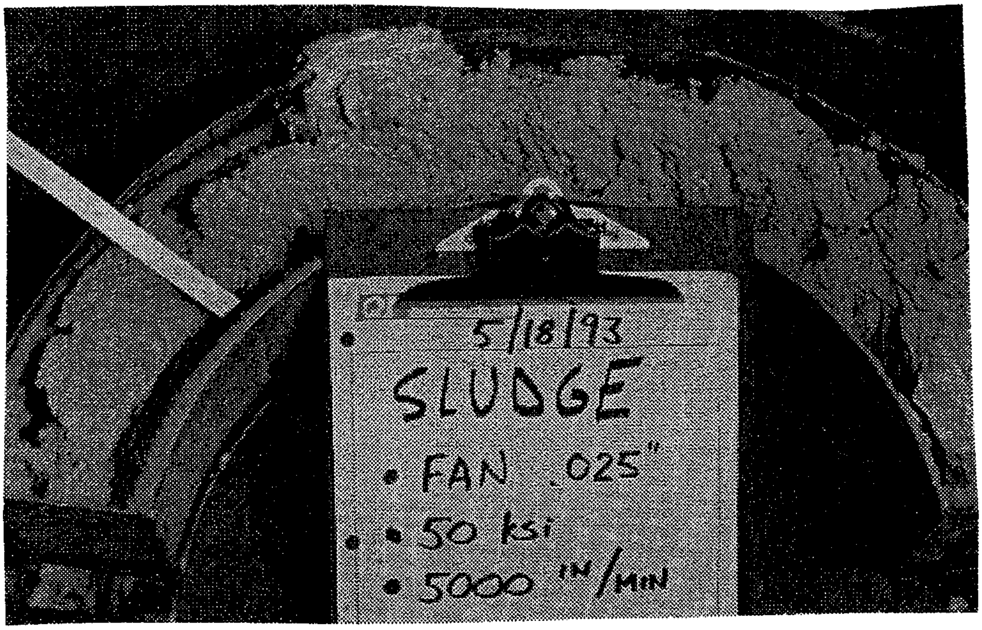

Figure 4. Example of Fan Jet Cut through Sludge Simulant

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Paper 56

AIR JET CUTTING TECHNOLOGY FOR REPAIRING CLAY COVER AT RADIOACTIVE WASTE STORAGE SITES

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ABSTRACT

Air jet nozzles which mix bentonite particles into the air jet have been developed for repairing clay cover at radioactive waste storage sites. With these nozzles, clay consisting of 15% bentonite and 85% sand has been satisfactorily excavated to a depth of 120 cm.

The motivation behind the development of the air jet technology is to avoid the diffusion of radioactive waste from nuclear energy power plants, which is stored in concrete pits and covered with clay.

Cutting efficiency was evaluated using a Laval nozzle and a spiral jet nozzle. A Laval nozzle consists of a reducer and a diffuser in front of a cylinder. Pressurized air is supplied from the rear of the reducer and then flows through a narrow throat, after which it passes through a diffuser and along a cylindrical passage. This flow generates a supersonic jet due to the structure of the diffuser. The jet's low static pressure causes bentonite particles to be drawn into the nozzle through a passage located just downstream of the diffuser.

The spiral jet nozzle has an annular slit connected to a conical cylinder. Pressurized air is forced through the side of the nozzle into a buffer area, and this annular flow creates suction to draw bentonite particles through an inlet port. The spiral jet captures the bentonite particles and accelerates them, concentrating the particles along the jet's axis.

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1 INTRODUCTION

The motivation behind the development of this technology is to avoid the diffusion of radioactive materials at a radioactive waste storage site. The objective of the study is to develop an air jet nozzle which efficiently mixes bentonite particles in an air jet and accelerates the particles.

In some cases, low-level radioactive waste from nuclear energy power plants is stored in a concrete pits. The pits are covered with clay containing bentonite and sand, because bentonite can prevent water from entering a pit.

In these cases, low-level waste is packed firmly in such a concrete pit so radioactive materials will not diffuse. However, if diffusion of radioactive materials should be detected in an emergency, technology for repairing the pit would be needed. This technology must make it possible to quickly excavate the clay around the pit to repair it. It must also be possible to operate the repair system at a distance from the location of the repair. Normal mechanical repair methods, such as using back-hoes, cannot be employed because workers could be exposed to radioactivity.

Assuming the above, the water jet nozzle technology which is used for excavation might appear be useful for making such repairs. However, water jets cannot be employed because bentonite will swell in the presence of water. Swelled bentonite loses valuable inherent properties such as its ability to create a strong aquiclude and high structural intensity. Under these circumstances, particles mixed with an air jet and moving at high velocities could be useful to excavate the clay containing bentonite which covers the concrete storage pits.

Air jets incorporating abrasives have mainly been used for blasting, as discussed by Skibniewski and Hendrickson (1988), so few studies of using air jets for excavation have been previously reported. The air jet technology described in this report possesses high excavation efficiency due its ability to accelerate bentonite particles. This is achieved by increasing air jet velocity as much as possible while concentrating the bentonite particles in the center of the air jet to effectively obtain fluid force.

2 CONCEPT OF NOZZLE DESIGN APPROACH

Two types air jet nozzles capable of mixing bentonite particles with high-pressure air have been developed: the Laval nozzle and the spiral jet nozzle. Each takes advantage of a different mechanism to accelerate the bentonite particles.

2.1 Structure of Laval Nozzle

As discussed by Kobayashi (1990), a Laval nozzle for excavating the clay covering a concrete pit consists of a reducer and a diffuser in front of a cylinder, as shown in Figure 1. Pressurized air is supplied from the rear of the reducer and then passes through a narrow cylindrical throat. Kobayashi (1990) comments that this generates a compact high speed jet due to the structure of the diffuser, because the static pressure of the jet can be nearly the same as atmospheric pressure. Actually, this Laval nozzle was designed so that a jet issuing from the diffuser will expand a little excessively so that particles can be drawn in from a passage just downstream of the diffuser by the low static pressure of the jet. The particles can be accelerated to high speeds due to the fluid force of the high-speed jet created by the nozzle.

2.2 Structure of Spiral Jet Nozzle

Spiral jet nozzles have been used for passing optical cords through pipelines with many bends, as discussed by Horii (1990). The performance of the spiral jet makes it possible to pass these cords very effectively because choking is prevented. However, previous industrial applications of the spiral jet nozzle have been limited to low-pressure conditions (3–6 kgf/cm^2).

A high-pressure spiral jet nozzle for excavating the clay cover of concrete storage pits was designed. The nozzle has an annular slit connected to a conical cylinder, as shown in Figure 2. Pressurized air is forced through the side of the nozzle into the buffer area and then through the angled annular slit. This annular flow creates suction force which draws additional air and particles through an inlet port. Due to the Coanda effect of the annular jet flow adhering to the nozzle walls, the downstream flow in the nozzle develops into a spiral jet. At a given mass flow rate, a spiral jet issued from a spiral jet nozzle is much more compact than a typical turbulent jet. This orderly spiral jet captures bentonite particles and accelerates them while concentrating the particles along the jet's axis.

3 EXPERIMENTS

Clay in a tank was excavated using these two types of nozzles to evaluate the excavation performance of the nozzles.

3.1 Experiment Apparatus

3.1.1. Clay and Bentonite Particles

The clay in the tank consisted of 15% bentonite and 85% sand. Water content was 17%, resembling that of clay covering a concrete pit at a radioactive waste storage site. The clay in the tank was compacted to a dry density of 1.7 g/cm^3, had a coefficient of permeability of 2.50x10^{-9} cm/sec, and had a swelling pressure of 0.33 kgf/cm^2. The angle of internal friction of the clay in the tank was 29.4° and internal cohesion force was 0.18 kgf/cm^2 when measured using the CU three-axis compression test.

Bentonite particles were used for excavating the clay because an aquiclude forms as they accumulate while excavation is in progress. The particles were pulverized rough bentonite stone between 1 mm and 5 mm in diameter. The coefficient of swelling was less than 10^{-3} cm/sec under natural accumulation conditions.

3.1.2 Nozzles

Both nozzles had the same exhaust port diameter (d_e). Dimensions of the Laval nozzle were: throat diameter (d_n) 7 mm, angle of reducer (θ_1) 20°, angle of diffuser (θ_2) 10°, diameter of exhaust port (d_e) 15 mm, length of exhaust port (L) 150 mm. Throat diameter was set to accelerate the flow in the throat to the speed of sound, based on the ability of the air-supply compressor. After θ_1 and θ_2 were set to maximize excavating efficiency, d_n was determined such that the air jet would expand to 1.45 times the appropriate expansion as discussed by Kobayashi (1990). L was set so as to avoid generating shock waves caused by friction between the pipe wall and the jet.

The specifications of the spiral jet nozzle were: angle of annular slit (θ)17.5°, area of annular slit (AA) 31.4 mm^2, and diameter of exhaust port (d_e) 15 mm. The velocity and concentration of the jet issued from the spiral jet nozzle depend on θ and AA. Large values for θ and AA result in the occurrence of back flow caused by exfoliation at the inner wall near the annular slit. After θ was fixed at the small angle of 17.5° to prevent exfoliation, d_e was set appropriately to obtain maximum air volume. Suction flow and volume of supply air for various values of annular slit area are shown in Figure 3. Suction forces fluctuated over time due to backflow when AA was larger 31.4 mm^2. The diameter of the exhaust port was set according to the value for AA which would provide the highest excavation performance.

3.2 Experiment Conditions

Air pressure was 1.62x10^6 Pa (16.5 kgf/cm^2). Air supply volume was 5.08 m^3/min for the Laval nozzle and 4.18 m^3/min for the spiral jet nozzle. With the spiral jet nozzle, increasing the width of the annular slit would allow the volume of air supply to be increased but over the critical width the flow would be choked. A spiral jet nozzle air supply volume of 4.18 m^3/min was the greatest possible without generating back flow.

The amounts of bentonite particles supplied were 1.5 kg/min to the Laval nozzle and 2.4 kg/min to the spiral jet nozzle. The difference between these amounts is due to the nozzles' rates of suction flow. Traverse velocity was 50 cm/min, and the number of traverses was 10.

3.3 Results

The state of excavation after using a Laval nozzle is shown in Figure 4, and depth of excavation for both nozzles is shown in Figure 5. As can be seen in Figure 5, after the first traverse the depth of excavation obtained with the Laval nozzle was 12 cm and that obtained with spiral jet nozzle was 13 cm. As the number of traverses increased, so did the depth of excavation. After the tenth traverse both nozzles had excavated to a depth of 27 cm.

4 DISCUSSION

The experiment results show that an identical final depth of excavation was achieved with each nozzle. However, the mechanisms of particle acceleration were different because the internal configurations of the two nozzles were different. High excavating efficiency requires larger volumes of air and concentration of the jet along its axis.

4.1 Concentration of Jet

The jets were made visible by flowing 820 cc/min of water into the particle inlet ports to serve as a tracer so particle concentration could be observed.

Photos of the resulting jets are shown in Figure 6. Though the jet issued from Laval nozzle was not dispersed, the jet issued from the spiral jet nozzle was much tighter close to the nozzle. Downstream from the nozzle, the spiral jet dispersed somewhat.

4.2 Particle Velocity

Since depth of excavation is related to particle velocity, the velocities of particles in the jets issued from Laval nozzle and the spiral jet nozzle were observed by an optical method outlined in Figure 7. Two multi-flash lights (red and blue) were triggered by a controller. The flashes were separated by a specified time delay interval. Simultaneously with each set of flashes, a CCD camera obtained one video frame. Particle velocity was then calculated from the distance between red and blue particles in the images and the delay interval.

Particles were made of spherical Styrofoam (mean diameter: 2.8 mm; density: 0.43 g/cm^3) instead of bentonite particles, because the spherical Styrofoam particles were of uniform diameter and density. This made it possible to accurately measure velocity.

Sample video frames are shown in Figure 8. Mean velocity was calculated from frame 20 to show particles just as they left the nozzle at the center of the axis. Velocity was estimated to be 320 m/sec from the Laval nozzle and 250 m/sec from the spiral jet nozzle.

4.3 Scaled-Up Laval Nozzle

Only the Laval nozzle was scaled up to examine critical excavating depth. Throat diameter (d_n) was 13 mm, angle of reducer (θ_1) was 20°, angle of diffuser (θ_2) was 10°, exhaust port diameter (d_e) was 28 mm, and length of exhaust port (L) was 280 mm.

Clay in a tank was excavated with a traverse velocity of 5 cm/min and a particle supply of 10.1 kg/min. Five traverses were performed, and the results are shown in Figure 9. Maximum depth of excavation was 120 cm. In the future, experiments will be conducted with scaled-up spiral jet nozzles also.

5 CONCLUSION

Two types of air jet nozzles for repairing the clay covering radioactive waste storage pits were developed. With these nozzles, clay consisting of 15% bentonite and 85% sand was excavated to the satisfactory depth of 120 cm.

One nozzle was a Laval nozzle consisting of a reducer and a diffuser, between which is a narrow throat. The other nozzle was a spiral jet nozzle with an annular slit connected to a conical cylinder. The nozzles take advantage of different mechanisms to incorporate and accelerate particles in the jet flow.

Adequate results were obtained with each jet, but better results might be produced by pre-mixing bentonite particles and pressurized air for both nozzles, and by employing two-step acceleration in the spiral jet nozzle. Two-step acceleration can be achieved by attaching a second spiral jet nozzle at the particle inlet port to prevent exfoliation.

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NOMENCLATURE

Laval Nozzle

d_n throat diameter

θ_1 angle of reducer

θ_2 angle of diffuser

d_e diameter of exhaust port

L length of exhaust port

Spiral Nozzle

θ angle of annular slit

AA area of annular slit

d_e diameter of exhaust port

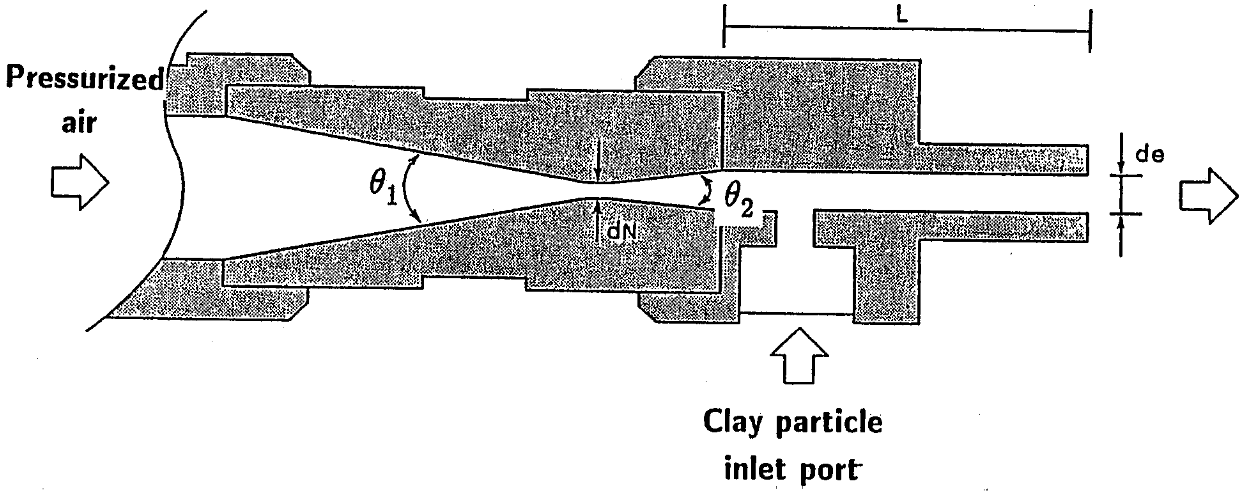


Figure 1. Laval nozzle

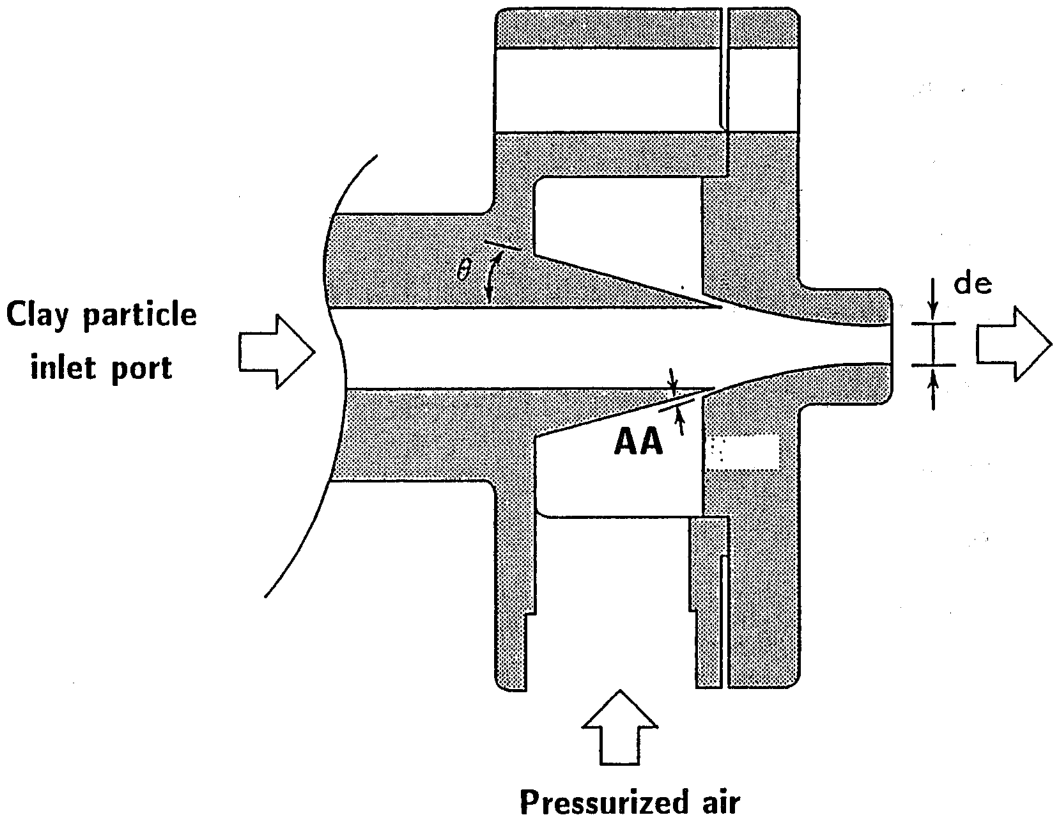


Figure 2. Spiral jet nozzle

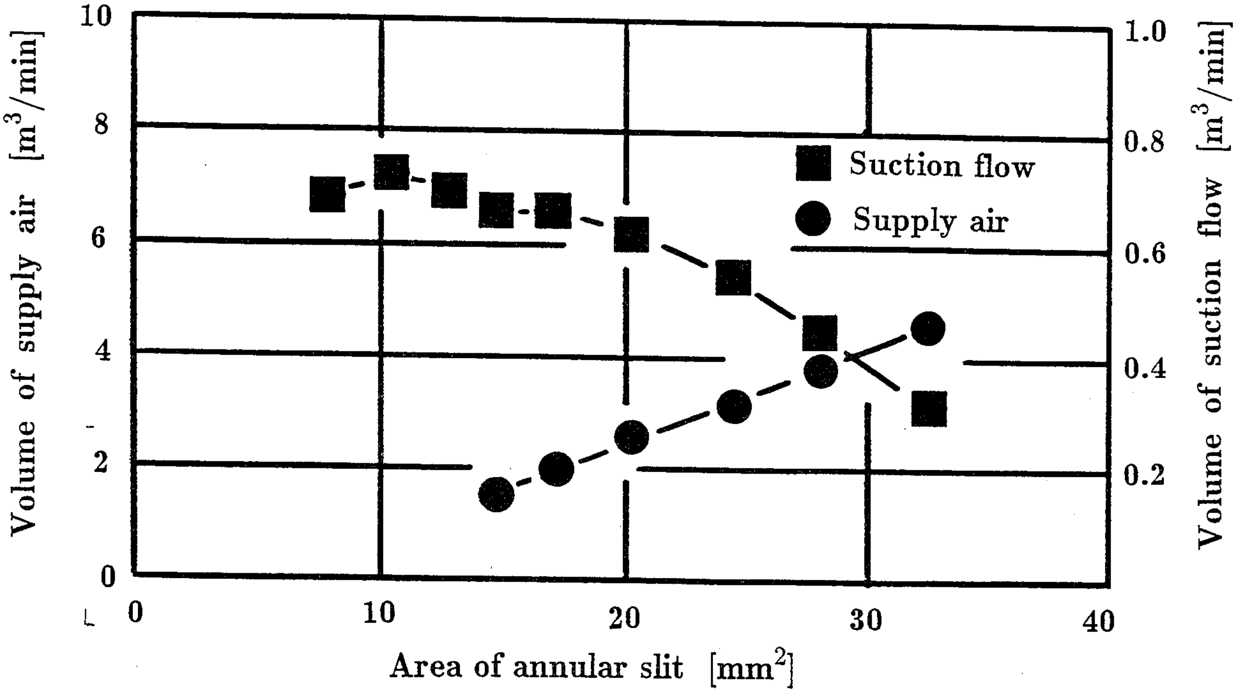


Figure 3. Volume of suction flow and supply air

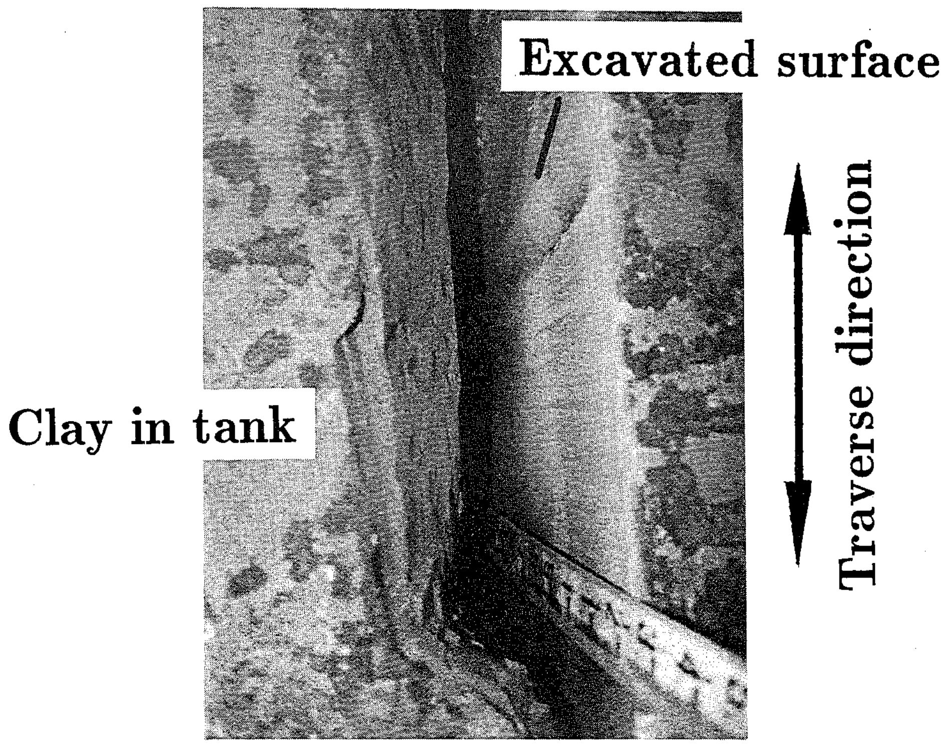


Figure 4. State of excavation

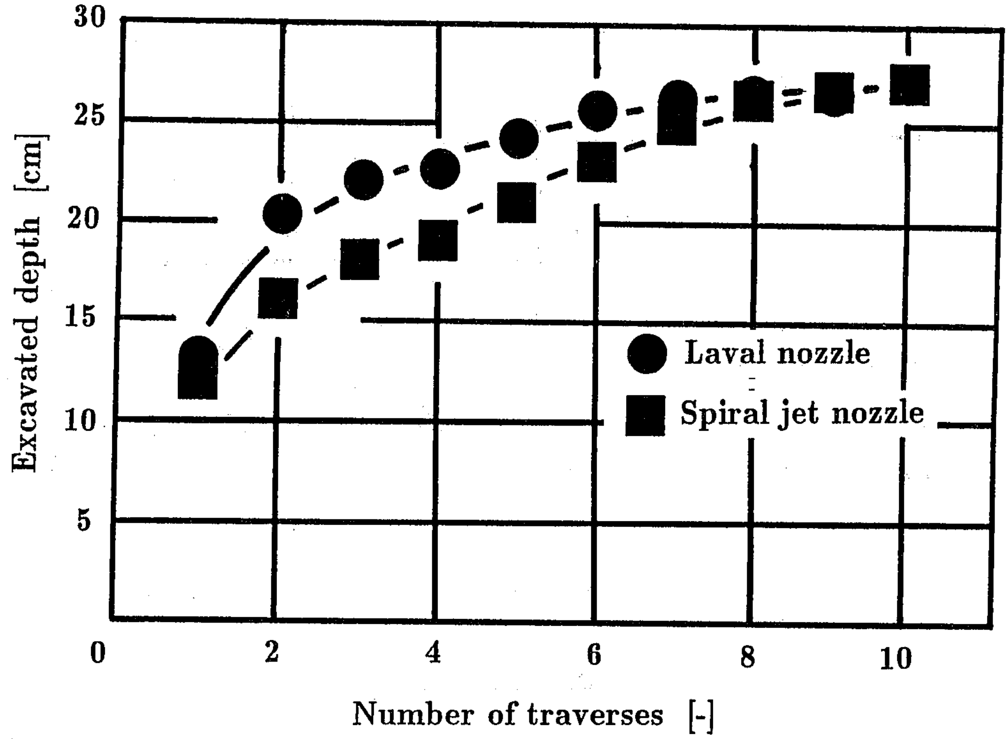
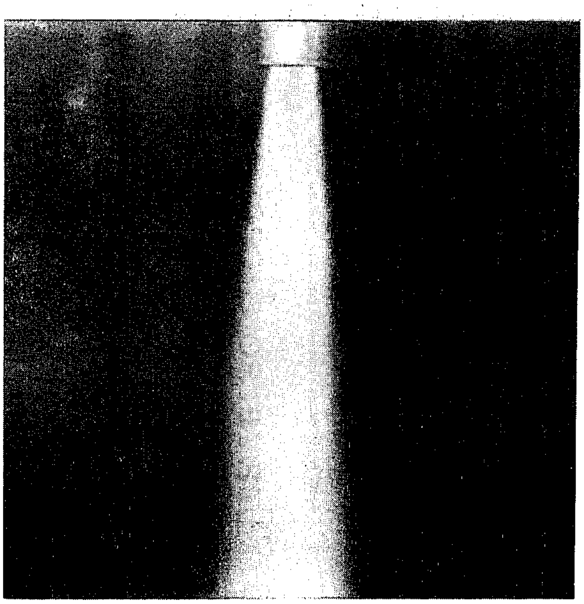
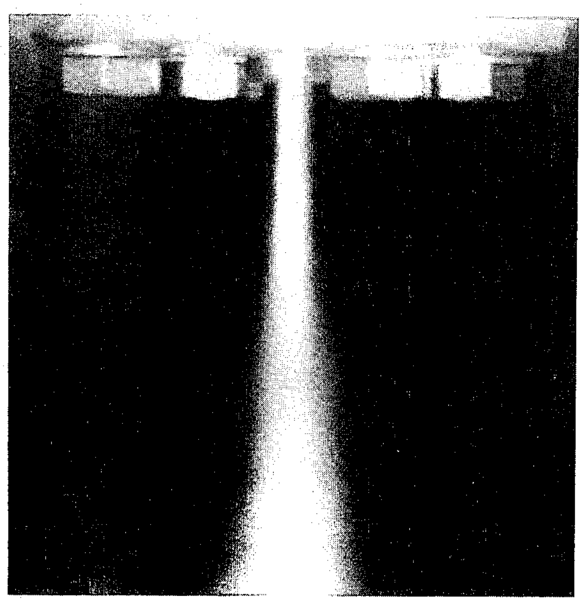


Figure 5. Excavation depth



Laval nozzle



Spiral jet nozzle

Figure 6. Visualization of jets

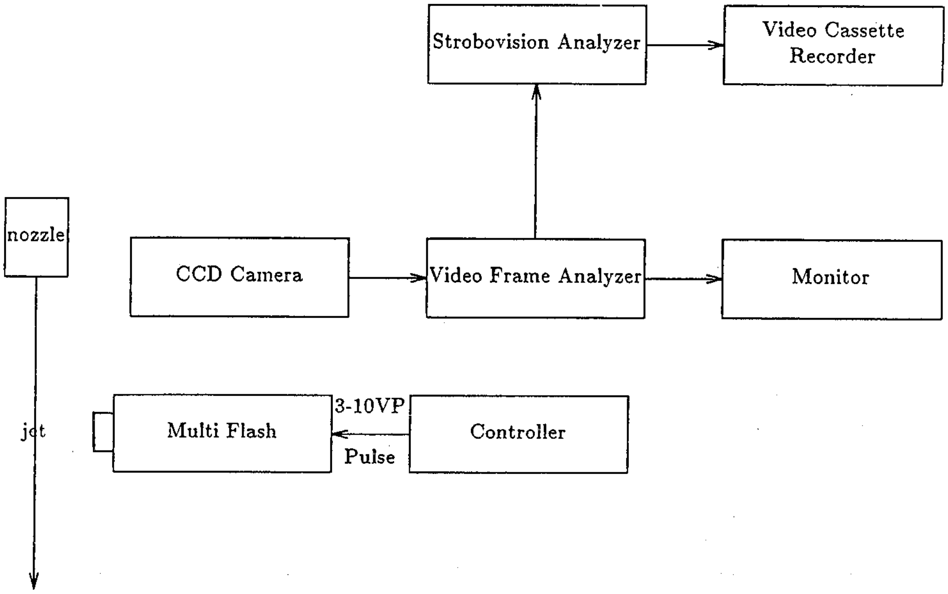


Figure 7. Velocity measurement system

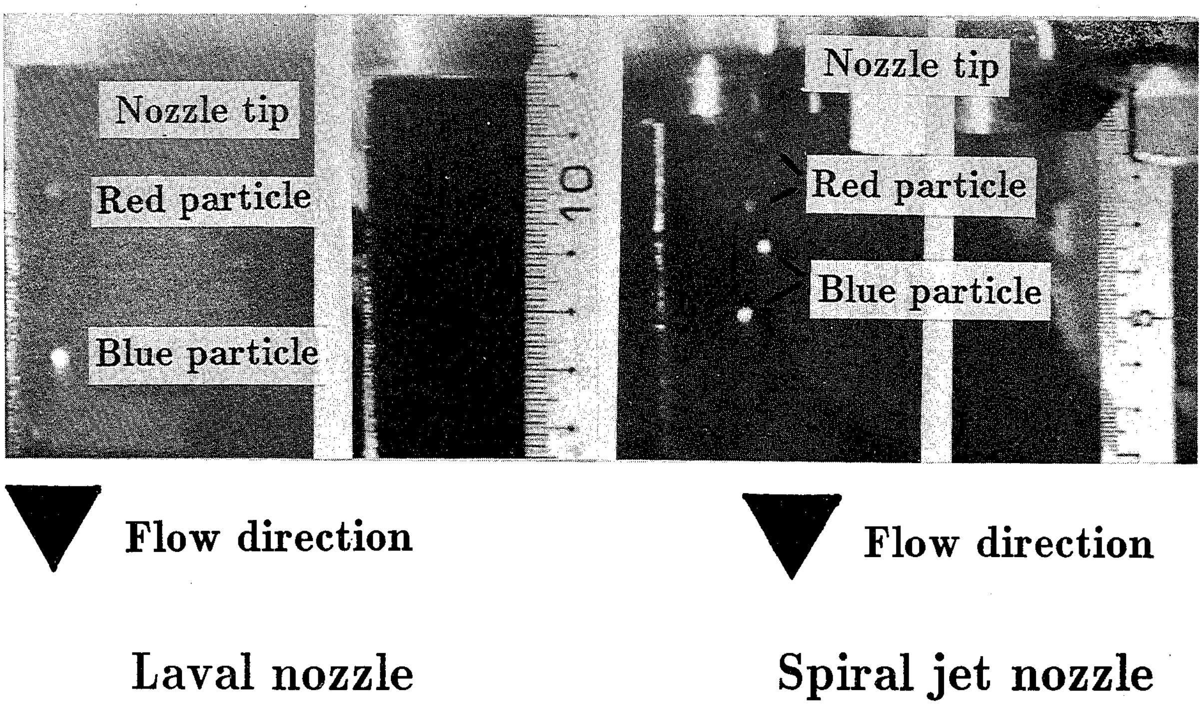


Figure 8. Distance between two particles

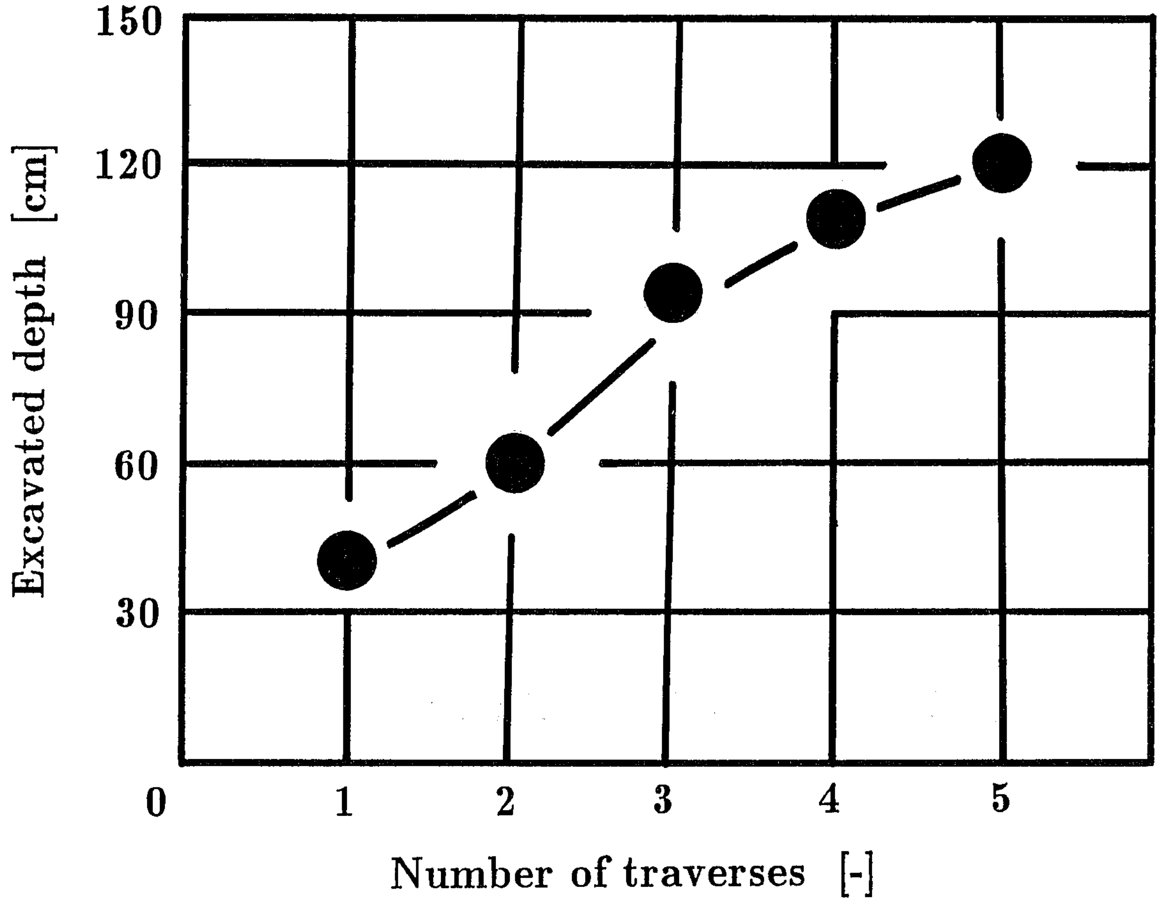


Figure 9. Excavation depth using scaled-up nozzle

7th American Water Jet Conference
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Paper 57

SAFE WATER ABRASIVE CUTTING OF AMMUNITION

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ABSTRACT

With 350 bar water abrasive jet system, safe separation, cutting and flushing of ammunition, missiles and other bodies filled with explosives.

The system has been widely tested and it has been used in both NATO and WARSAW PACT applications. The system has received relevant certifications and applied for patents.

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1.0 INTRODUCTION

The radical political changes in the recent past in Europe and in the balance of military forces have led to huge quantities of ammunition which have to be disposed of. The methods used in the past such as firing, dumping and scattering at sea, for example, can no longer be used under today's ecological points of view.

Ecologically justifiable methods of disposal of the component parts of ammunition first of all necessitate their dismantling. In the case of found ammunition but also in the case of other ammunition, especially that of the former Warsaw Pact, this is often not possible without cutting methods.

When cutting explosive substances there is always the problem of keeping the pressure and the introduction of heat to values below the explosion limits given for the respective explosive.

Abrasive water-jet cutting, water torching, thus offers favorable preconditions here, since water as the carrier medium for the abrasive agent simultaneously removes the heat from that part of the ammunition generated as a consequence of the cutting action, such that the ignition energy is never reached.

This knowledge led to the idea of applying abrasive water torching to cutting open the bodies of ammunition prior to disposal of ammunition from the former Warsaw Pact states.

Joint execution of a series of trials for testing the application of the water torching method for cutting ammunition from the Warsaw Pact was therefore agreed between a subsidiary of the Diehl Group Germany and the firm Genflo Engineering.

The following aims were pursued here:

- Exploring the reaction of different explosives and quantities and different kinds of typical ammunition combinations on applying this procedure.
- Testing the method in small-scale technical trials with a wide range of different ammunition from the Warsaw Pact states for large-scale implementation of the method.
- Conducting the cutting trials with process water recycled in a circulation system.
- Determination of performance parameters for the purpose of calculations for applying the method.
- Optimization of the machines and equipment used for this procedure.
- Determination of the safety criteria for the application of this procedure.

2.0 DESCRIPTION OF THE PROCESS

Abrasive water-jet cutting was implemented by Messrs. Genflo as the cutting method. (Fig. 1: Genflo process diagram)

A water pressure of up to 350 bar in the pressure vessels is generated by a plunger pump driven by a diesel engine. Two pressure vessels are operated alternately. The pressure vessels are filled with approximately 150 kg abrasive agent and closed.

A bypass line going off from the main pressure line agitates the abrasive agents in the pressure vessel in operation to such a degree that the abrasive agents are sucked out of the vessel by the main pressure line. A relatively homogeneous abrasive-water suspension is formed in the main pressure line in the flow profile on the way to the nozzle. Due to the velocity distribution in the flow profile, the greater part of the solid particles are conveyed in the center of the flow such that wear in the pressure lines is kept to a minimum.

The suspension is accelerated on passing through the tungsten carbide nozzle and impinges onto the ammunition to be cut. The material particles torn off as result of the grinding and cutting effect are picked up by the suspension and conveyed away.

In the tests carried out, the jet velocity lay between 200 and 240 m/s.

It was necessary to run the water in a recycling circuit due to contamination of the process water with environmentally hazardous constituents from the explosives during the cutting procedure.

3.0 TEST FACILITY

3.1 General

The following aims had in the main to be performed by the facility:

- Remote control of the facility from a dispatch center located behind a wall approximately 100 m from the cutting equipment.
- An as wide a range as possible of achievable nozzle feed rates, with special consideration given to low rates.
- Process water recycling to ensure operation of the high-pressure pump.
- Acquisition of all important process parameter data.
- Monitor observation and recording of the cutting procedure.
- Capability for performing longitudinal, transverse and tangential cutting.
- Safe and reliable clamping of the ammunition during cutting.

These aims were implemented in the facility parts

- cutter
- water circulation
- hydraulic control
- process control, data acquisition, remote control.

3.2 Cutter

The heart of the cutter is the high-pressure plunger pump driven by a diesel engine with two pressure vessels for generating the cutting suspension. This facility is completely accommodated in a 10" container (Fig. 2). This was installed behind the protection wall. The water was supplied from a local hydrant.

As described above, the cutting suspension is fed to the cutting nozzle via a pressure hose. As it is being conveyed along the pipe, the suspension is homogenized by the turbulence in the pipe flow.

The cutting table (Fig. 3) fulfills the following functions:

- Guiding the cutting nozzle.
- Holding the ammunition.

- Absorbing and braking the cutting jet.
- Converting the motion of the piston movement of the hydraulic cylinder into a longitudinal motion of the carriage with cutting nozzle attached to it and into a rotational motion of the ammunition.

The movement of the piston in the hydraulic cylinder is transferred to a toothed belt. A clamping device on the cutting carriage transmits this movement. This movement can be transformed into a rotational movement of the continuous shaft of the ammunition support shafts by means of a coupling. The Vullkolan guide rollers attached to this shaft transfer the rotational movement to the ammunition by frictional contact.

One shaft of the ammunition support is split in order to permit tangential cutting without destroying the body of the shaft.

Corrosion-neutral steel was extensively used for making the cutting table in order to obviate conservation of the parts. Thus, the share of materials not directly connected with the cutting process is extensively reduced in order not to influence the results of the chemical analysis of the process water.

The nozzle holder is fixed in a guide hole by a clamping device.

The used cutting suspension can be pumped off through an opening in the bottom of the cutting container. An overflow controls the level in the cutting container.

3.3 Water Circulation

After the cutting suspension has been emitted from the nozzle, the jet is braked by the water in the cutting container and by steel plates on the bottom of the container.

The water level in the cutting container is maintained by an overflow. The water-grit mixture is pumped from the lowest point of the container bottom, which is fitted at an angle, into the grit tank which functions as a settling tank (Fig. 4/5). The water flows back into the cutting container via an overflow.

The water coming out of the overflow of the cutting container gathers in the pump sump of the cutting area. The cutting area was lined up to a height of 0.5 m with foil and subsequently protected against mechanical loading with a coat of plaster in order to prevent water escaping into the surrounding area.

The contaminated water is pumped out of the sump into the top tank of a total of 6 tanks in cascade, each with a volume of approximately 0.8 m^3 (Fig. 6).

After running through the cascade, in which the greater part of the solid particles settles, the water is pumped through a filter column (Fig. 7) into the high-level reservoir. The filter column consists of two screen filters with 20 μm and 100 μm and a fabric filter with 5 μm pass width. According to manufacturer's detail, the water filtered in this way can be used for operation with the high-pressure pump without any restrictions.

After a certain water level has been reached, the water flows back into tank 6 of the cascade. This thus prevents overflowing and holds an as large a quantity of water as possible available for supplying the high-pressure pump.

The water is pumped out of the high-level reservoir by another pump through an approximately 100 m long water pipe into the reservoir of the machine container from which the high-pressure pump is fed.

3.4 Hydraulic Control

A hydraulic system with hydraulic motor and drive piston was selected as the drive for the moving elements in order to prevent equipment explosions. The hydraulic circulation is driven by a hydraulic motor. Two hydraulic valves moved by electrical rotating actuators are installed in the circuit (Fig. 8). The flow of hydraulic oil in both directions of flow is steered by a 3 - 4 directional valve controlled by solenoid switches.

On opening the valve, hydraulic oil is conveyed into a hydraulic cylinder and the piston thus moves upward. The hydraulic oil located above the piston is pressed into an accumulator prepressurized with 10 bar. This causes the pressure in the accumulator to increase to approximately 130 bar with the piston fully run out. As a consequence of this pressure, the piston moves back to its starting position after changeover of the 3 - 4 directional valve.

The pressure in the hydraulic accumulator is measured with a pressure transducer and serves as a measure of the distance moved by the nozzle.

3.5 Process Control, Data Acquisition And Remote Control

The entire system is controlled from a dispatcher room, which is blastwave protected, located at a distance of about 100 m from the cutting facility (Fig. 9). The following values are measured:

- Water pressure after the high-pressure pump.
- Water pressure in the bypass line into the pressure vessel for agitating the abrasive particles.
- Pressure in the hydraulic accumulator for measuring the nozzle travel.
- Water temperature in the reservoir of the machine container.

These measured values are displayed and recorded.

The water pressures are used for controlling the machine parameters, the wear status of the valves for the pressure vessels and the jet nozzle.

The pressure in the hydraulic accumulator is as described above an equivalent for the nozzle advance.

Visual monitoring of the cutting process is performed with a video camera. A rotating acrylic disk is provided in front of the camera as splash protection.

The picture is displayed on a monitor in the vicinity of the cutting area and on a monitor in the dispatcher room. The former is used for checking the clamping of the ammunition. The cutting process is controlled by means of the picture on the monitor in the dispatcher room. The entire cutting procedure is documented with a video recorder.

A control desk for switching the 4 water pumps and the hydraulic pump complete the control room. In addition, the emergency stop for the diesel engine is within easy reach so as to be able to abort the test at any time by interrupting the cutting process.

It was possible to take water samples from all cascade tanks, from the grit vessel and from the high-level reservoir by means of valves.

4.0 RESULTS

The test results are to be first of all clarified by means of a few figures. In the first figure (Fig. 10) you see the longitudinal cut of a No. 8 detonating cap. The cut runs through the priming composition out of the secondary charge nitropenta and the priming charge fulminate of mercury. In spite of the explosive nature a detonation did not take place.

Even the propelling charge igniter (Fig. 11) with explosive components fulminate of mercury and black powder was cut without any problems.

Other explosives were cut, such as:

- A-IX-2 hexogen with aluminum powder in the pressed explosive of a 100 mm armor-piercing shell (Fig. 12),
- TNT antipersonnel H.E. shell 100 mm (Fig. 13). The grain of the pressed explosive can be clearly seen,
- Trinitrotoloul-hexogen mixture in armor hand grenade RKG-3M (Fig. 14),
- A-IX-1 hexogen in the warhead of the anti-tank guided missile 9M14M (Fig. 15),
- TGAG 5 trinitrotoloul-hexogen-aluminum powder in the antipersonnel H.E. shell M 21 (Fig. 16),
- TD-50 trinitrotoloul-dinitronaphthalene (Fig. 17).

The performance of the cutting process is evidently demonstrated by the figure of the cross-section through a 100 mm armor-piercing shell (Fig. 18). The hardened steel permits a cutting speed of 8 mm/min. Explosive washout is low.

A grinding sand with the trade name Garnet with a relatively homogeneous grain size from 0.5 to 0.59 mm was selected as the abrasive agent.

Preliminary tests had shown that the highest cutting rates could be obtained with this material. Multiple use of the abrasive was not envisaged. This variant is to be included for industrial application in order to reduce costs.

The pure cutting time during the trials was a little less than 6 hours. The concentration of explosive in the circulating water of 10.7 mg TNT and 6.8 mg hexogen per litre reached here is not an operationally hazardous concentration. It was more critical to keep the concentration of solid particles in the cutting water to a particle size and concentration permissible for the pump. The pH value of the water changed during the trials from neutral (pH value 7) to acid reaction (pH value under 6). Further components in the water could not be demonstrated with the analysis technique available or they lay below the limit of proof.

Proof of applicability of the abrasive water-jet cutting was demonstrated by the tests conducted. As a result of the trials, a patent procedure was introduced for the method of jet penetration during cutting.

5.0 CONCLUSIONS

The trials produced the proof that in comparison with other methods in use abrasive water-jet cutting is a relatively safe method for cutting ammunition and parts of ammunition.

No detonations occurred during the trials, which indicate technical safety performance limits of the process. Before final implementation of a machine in a disposal operation it is necessary to investigate critical pressures and cutting jet advancing speeds. A further increase in jet pressure was not possible with the machine used.

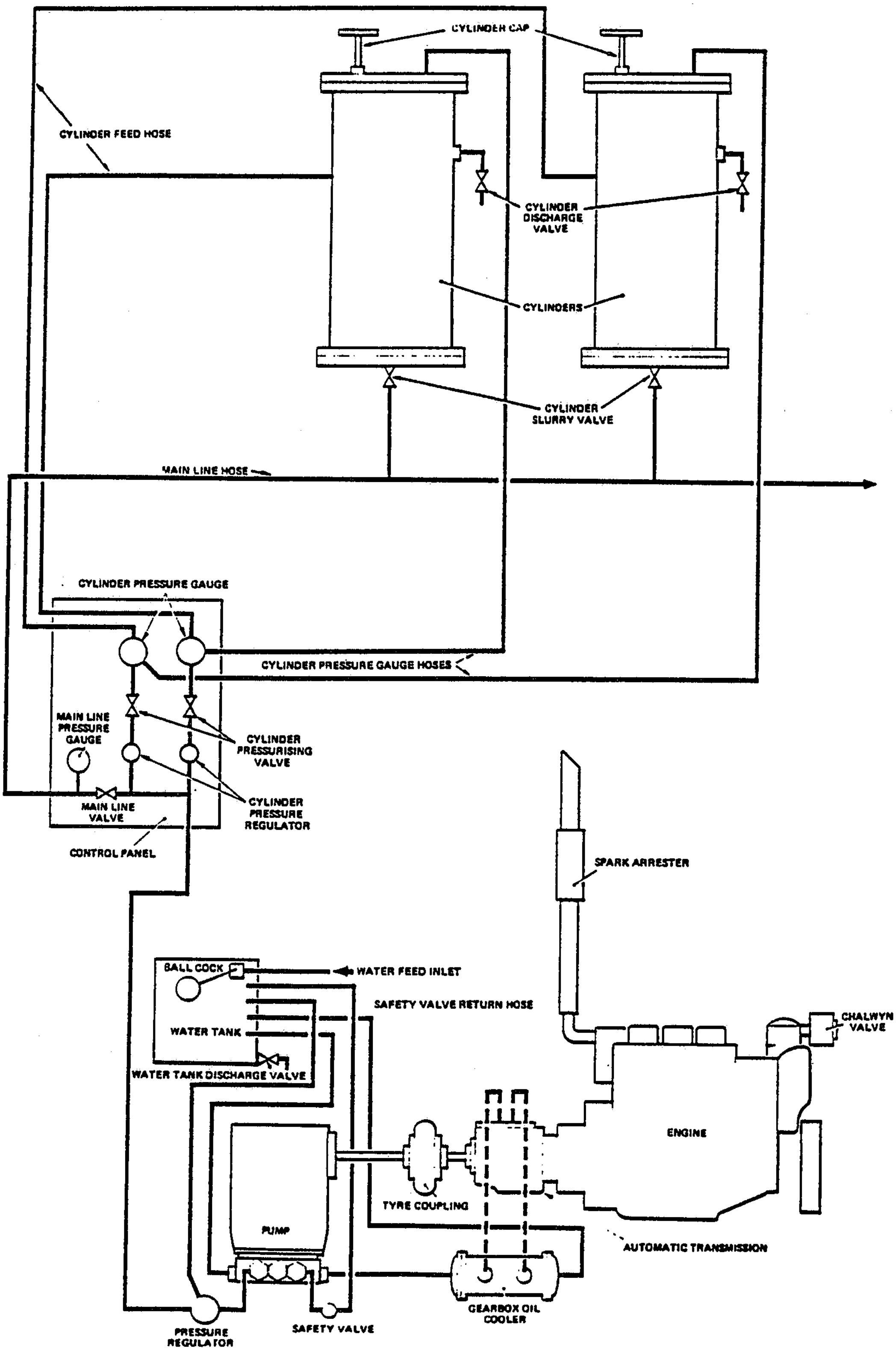
It should also be examined how a reduction in the process water arising can be achieved with smaller jets and smaller grain diameters of the abrasive agent.

It must also be clarified which minimum amount of water is necessary to remove the heat generated as a result of cutting in order to remain below critical limits.

Reuse of the abrasive should be provided for by the installation of screening and drying facilities into the system. A safety risk is not seen here.

This first series of trials has further pushed ahead the process of gathering knowledge for the application of abrasive water torching in the disposal of ammunition. Further series of tests will have to follow.

Application of this procedure for disarming bombs with sensitive fuses is also envisaged.



COLD CUTTING SYSTEM (SCHEMATIC DIAGRAM)

COLD CUTTING SYSTEM

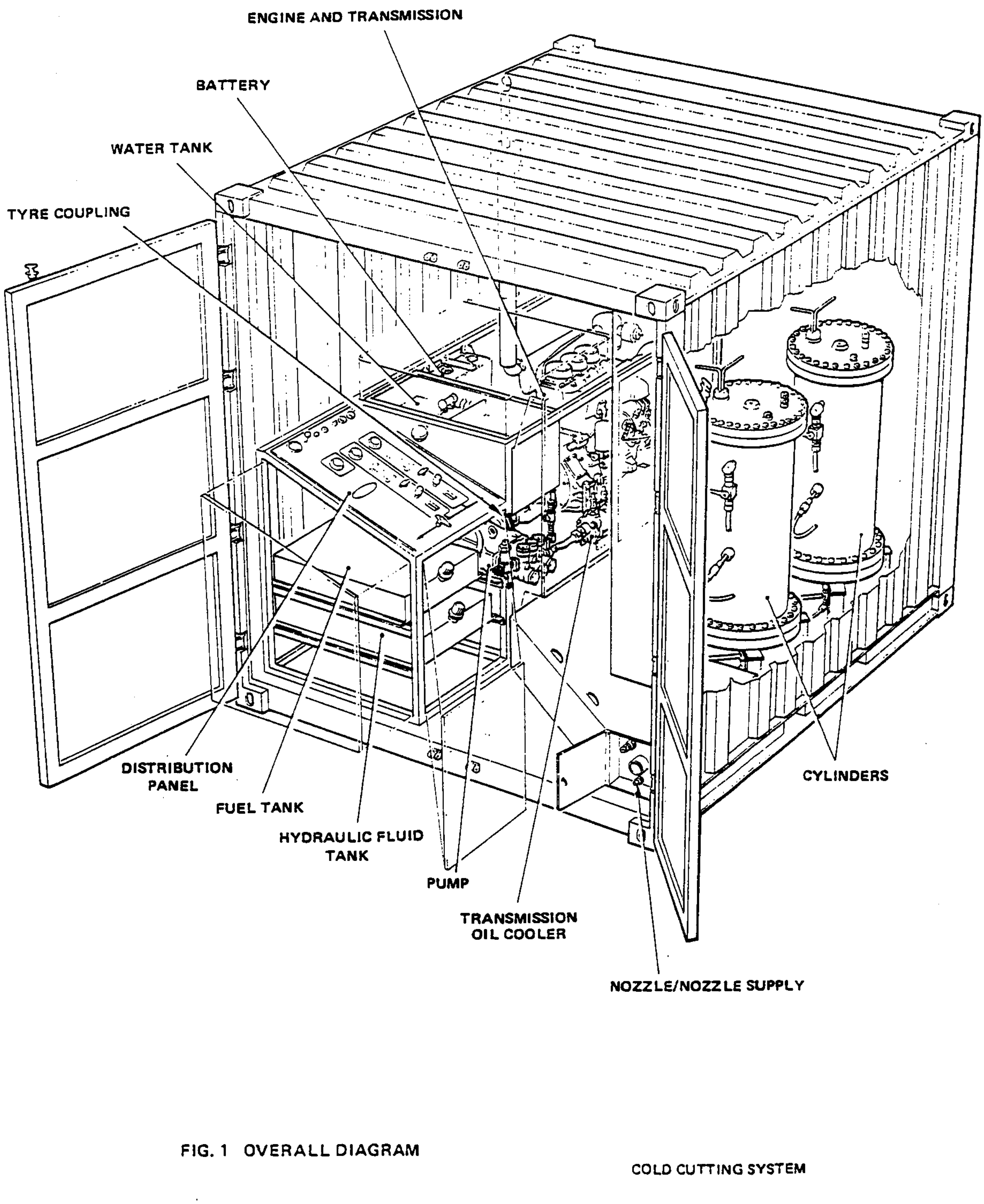
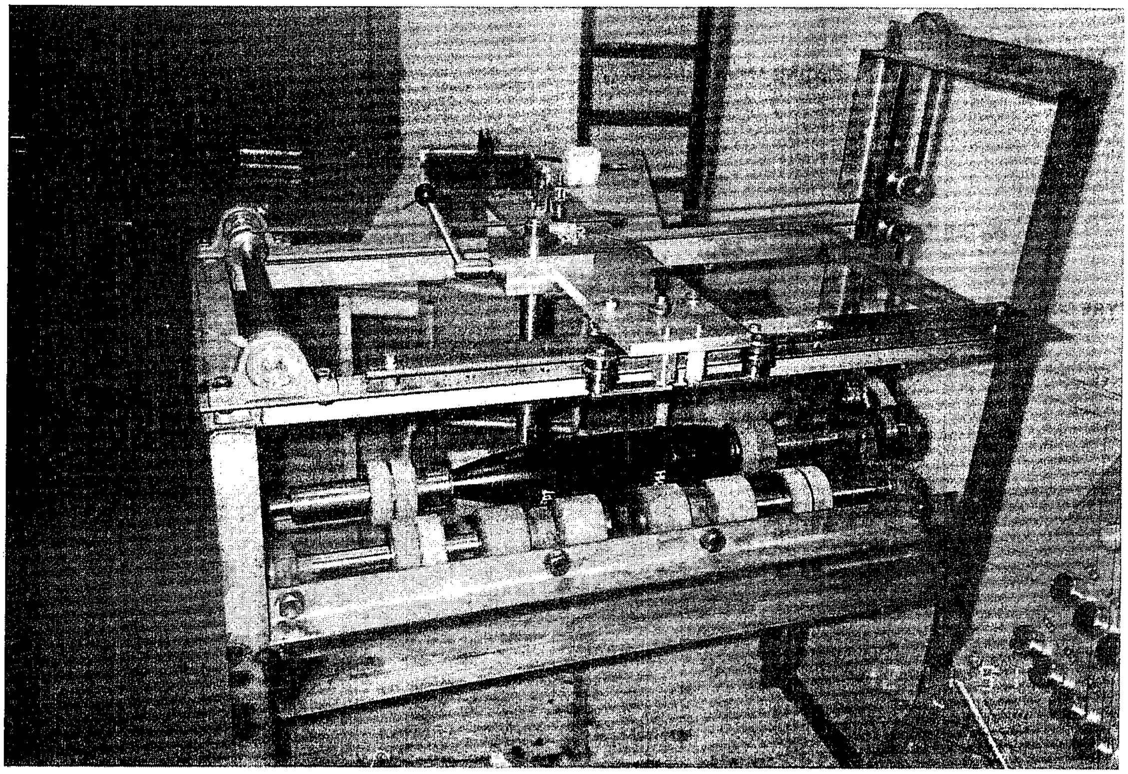
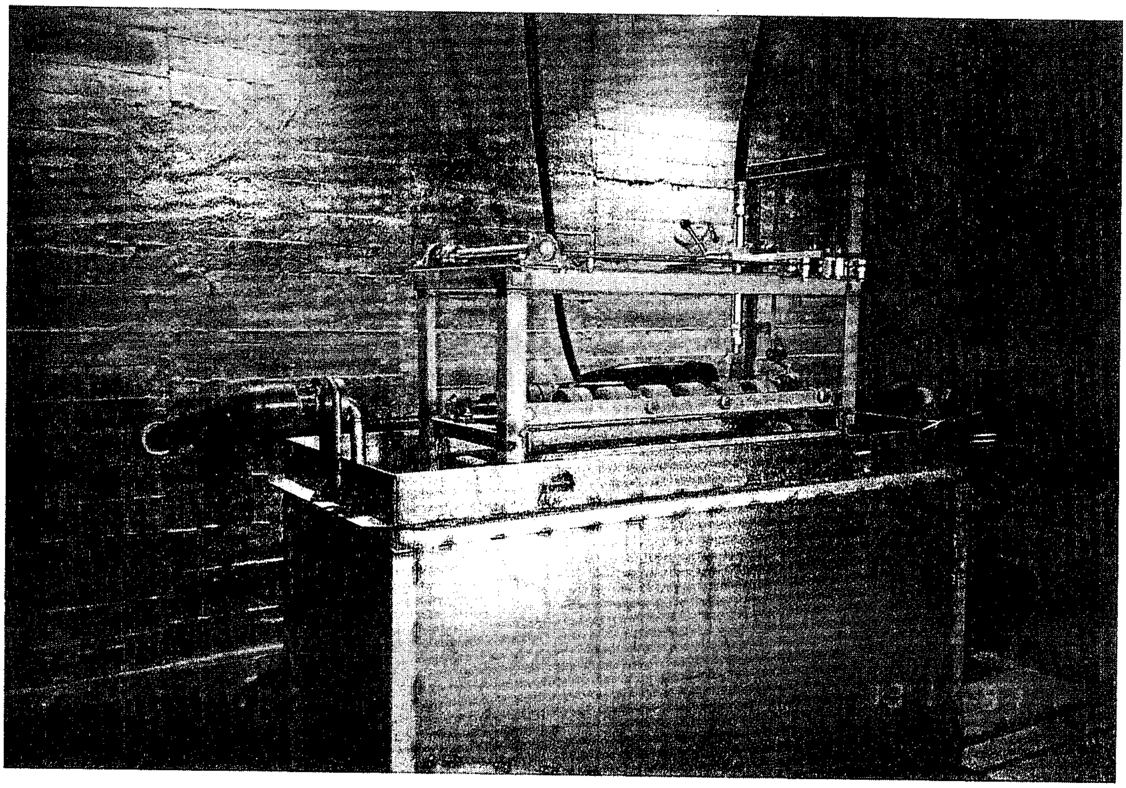


FIG. 1 OVERALL DIAGRAM

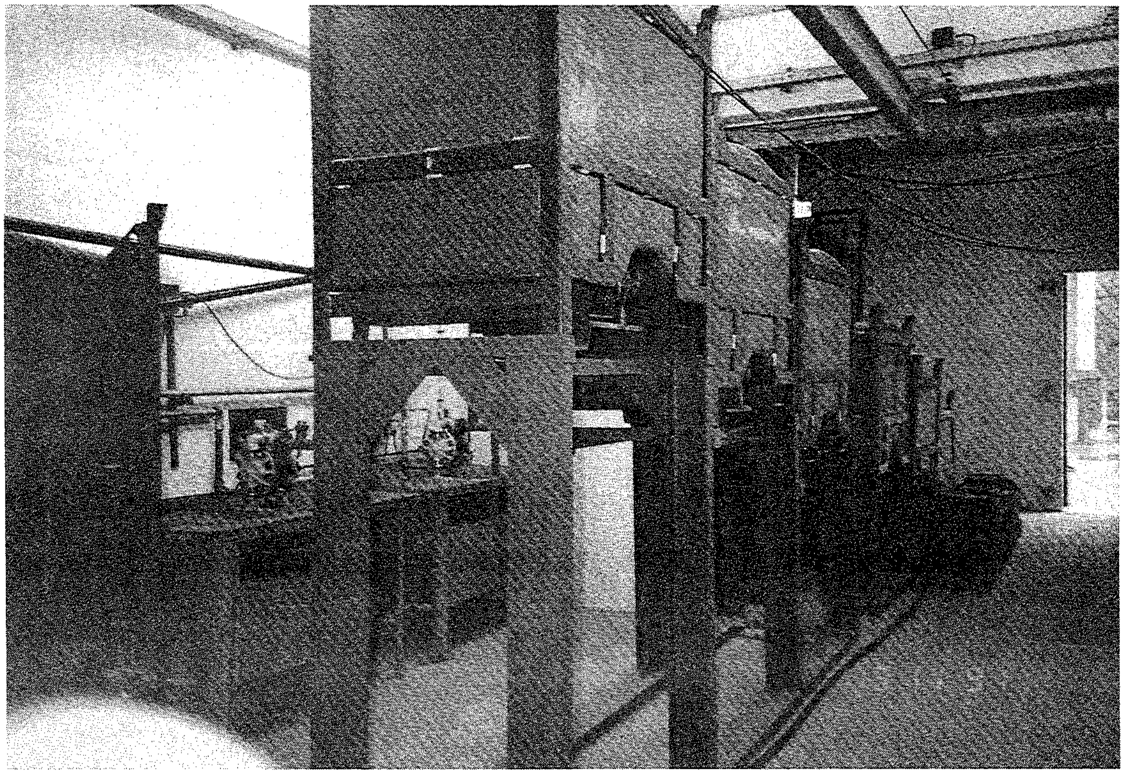
COLD CUTTING SYSTEM

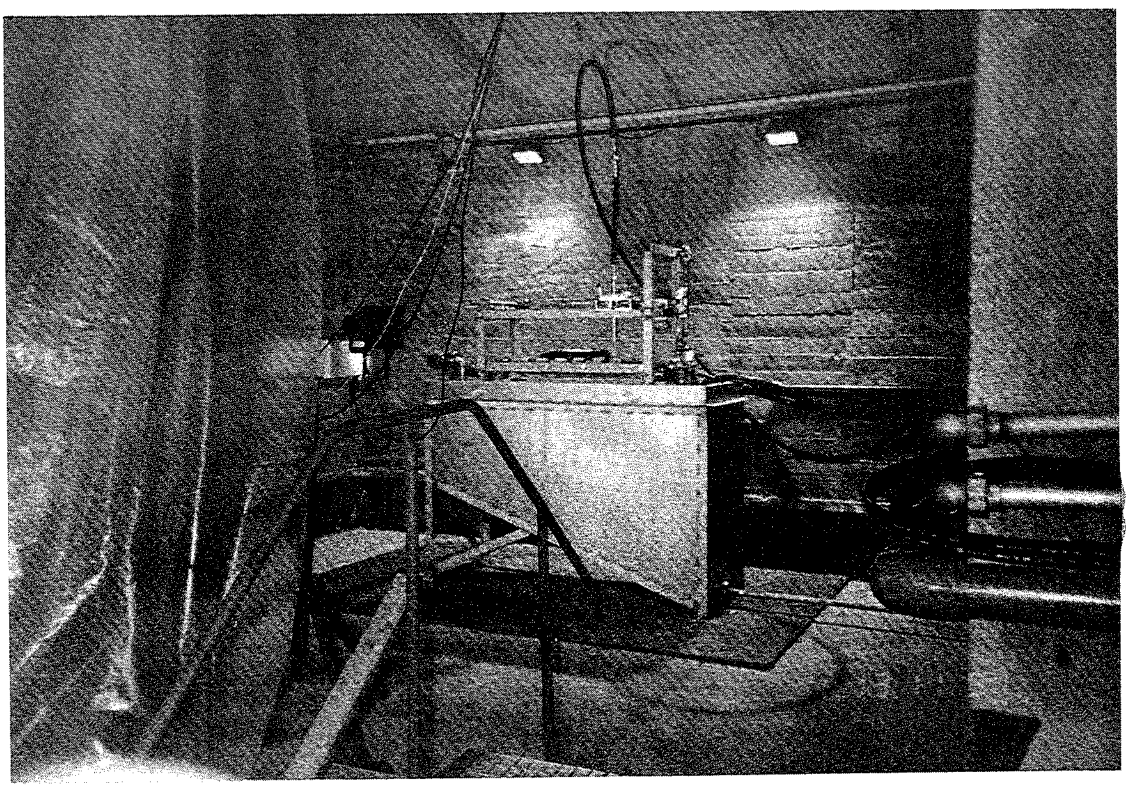
PICTURE 3 CUTTING TABLE WITH CATCHER



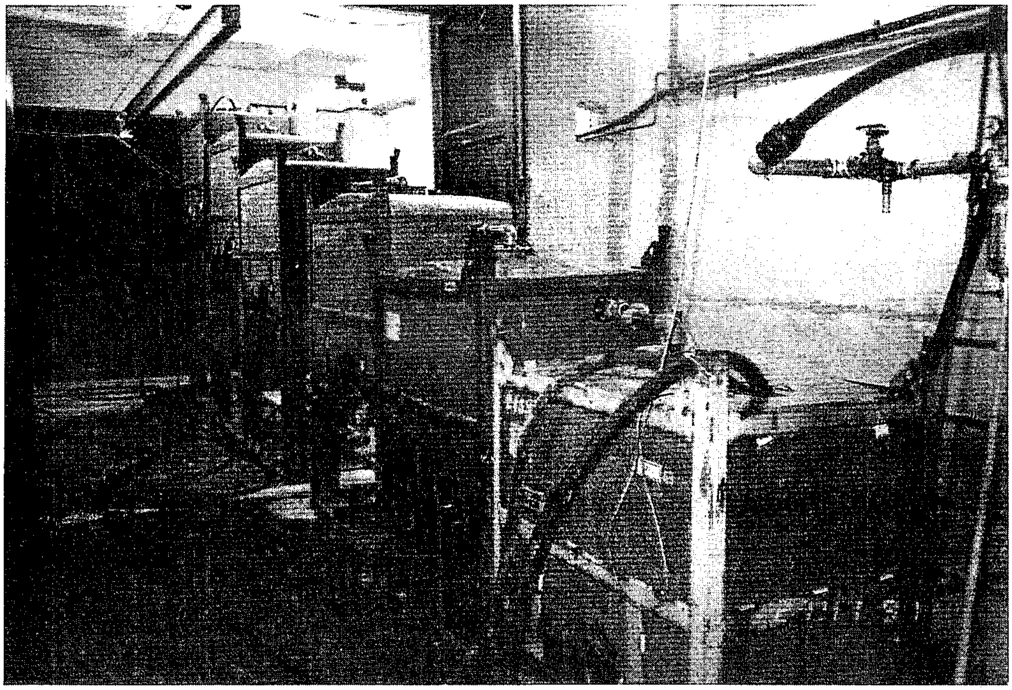


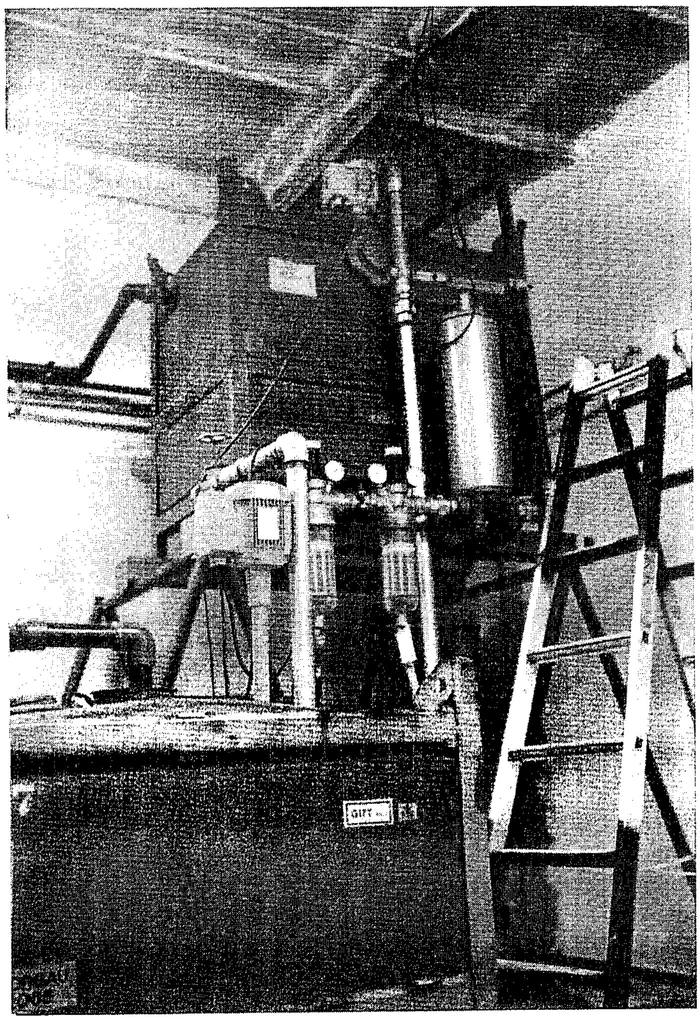
PICTURE 4 + 5



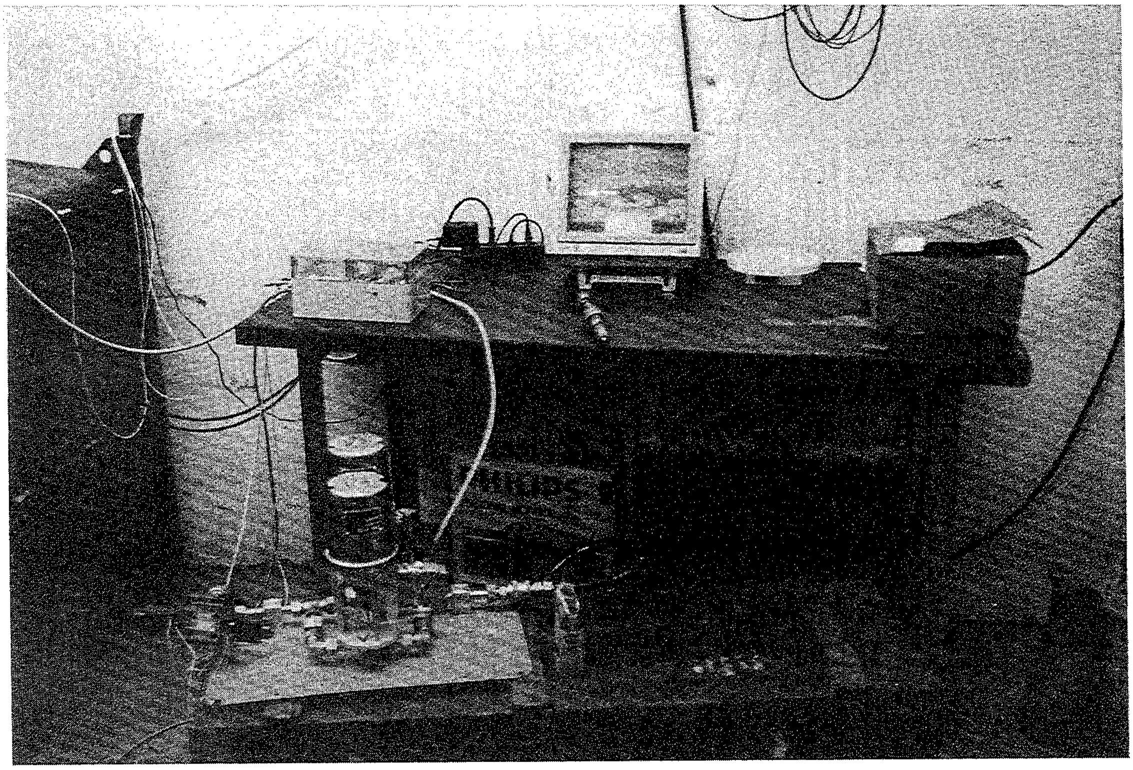


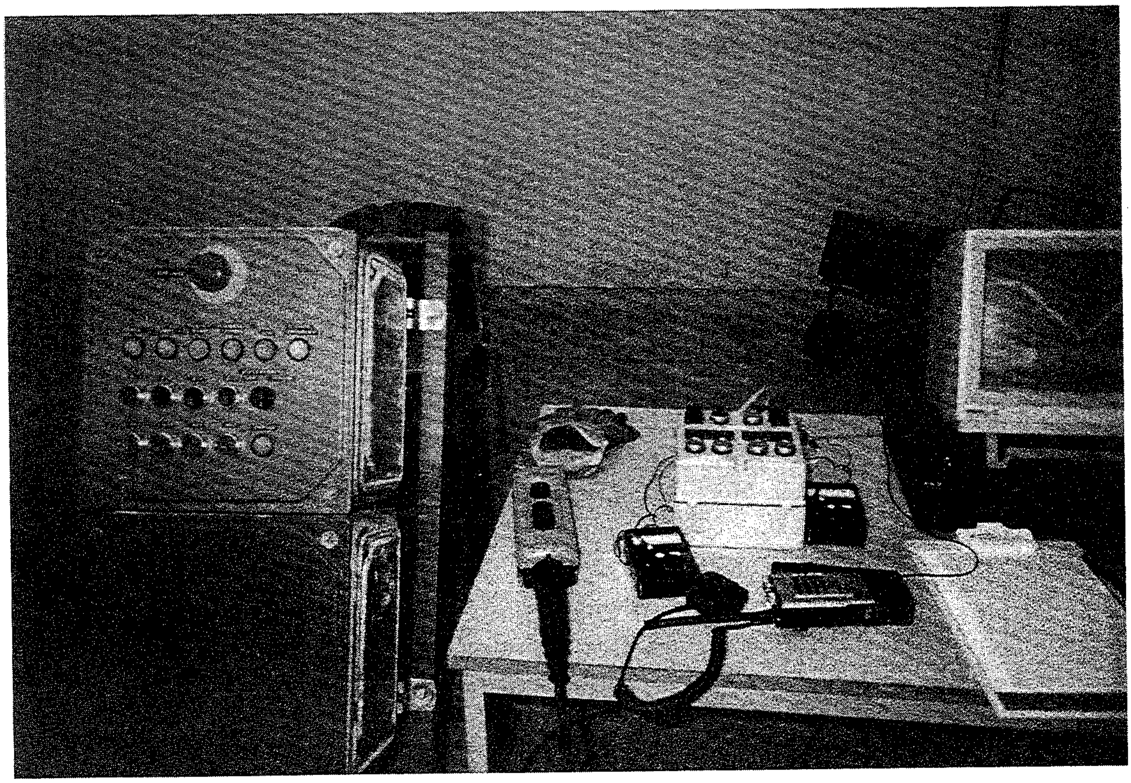
PICTURE 6 + 7



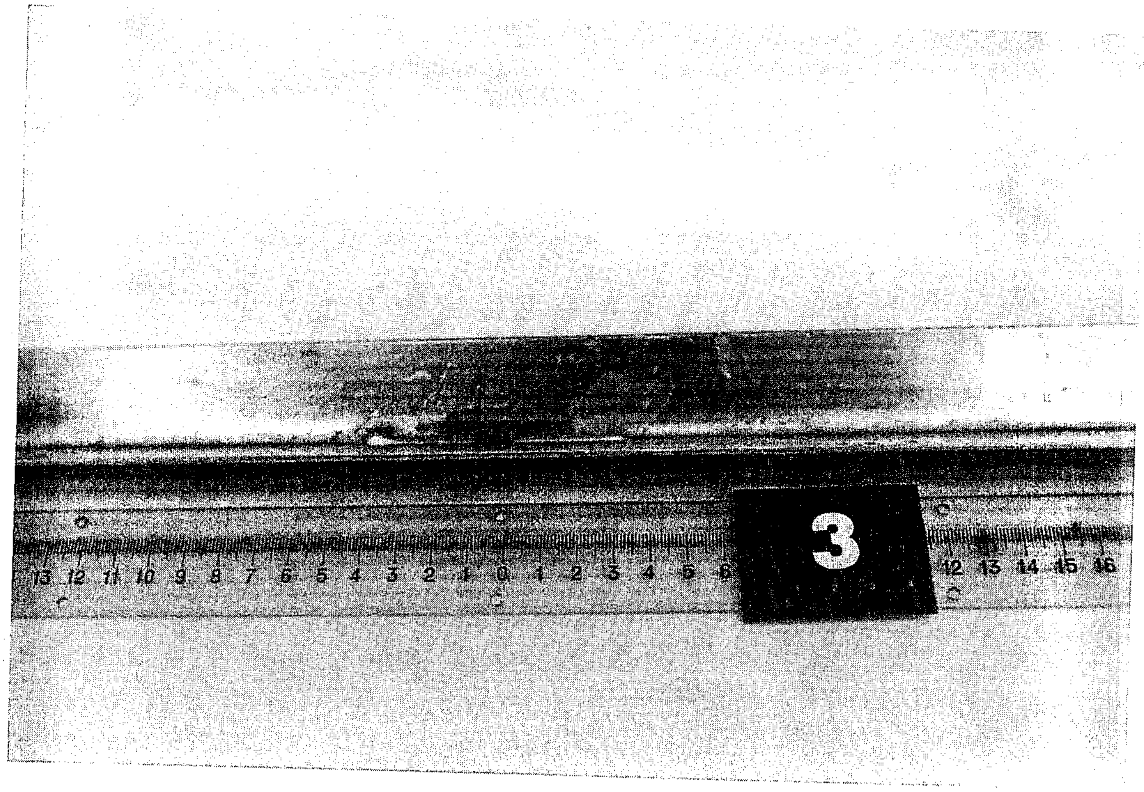


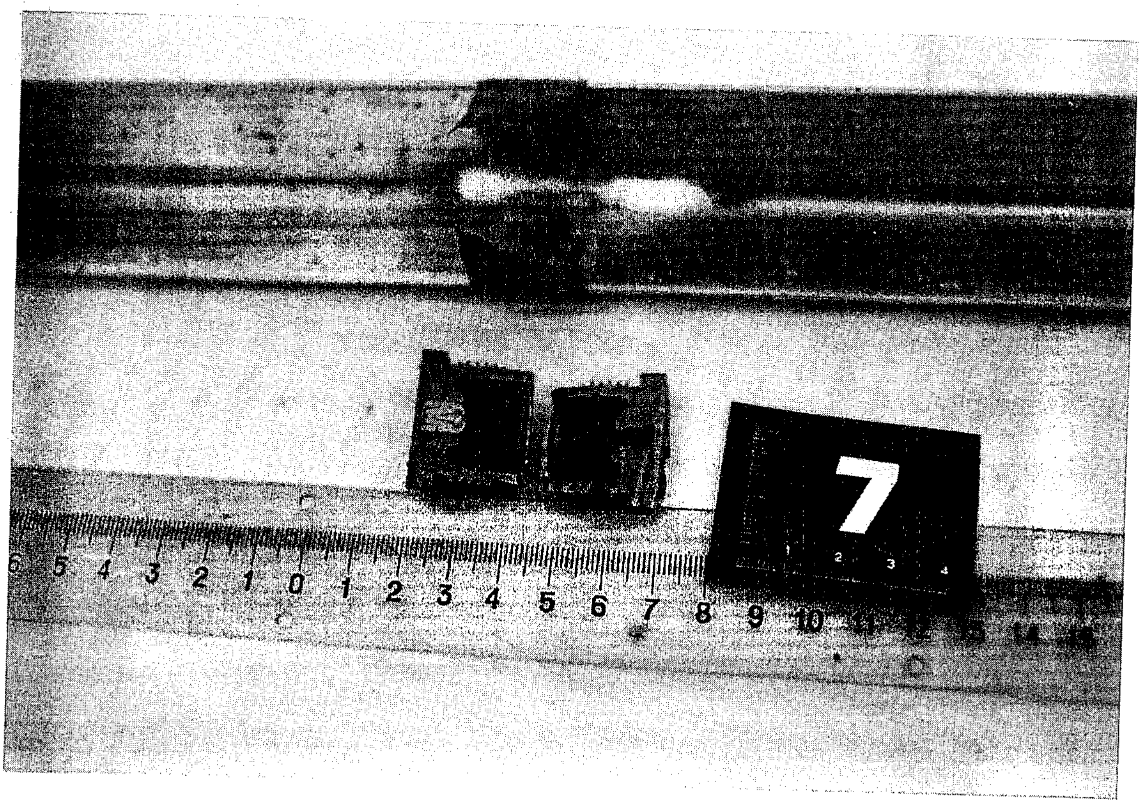
PICTURE 8 + 9



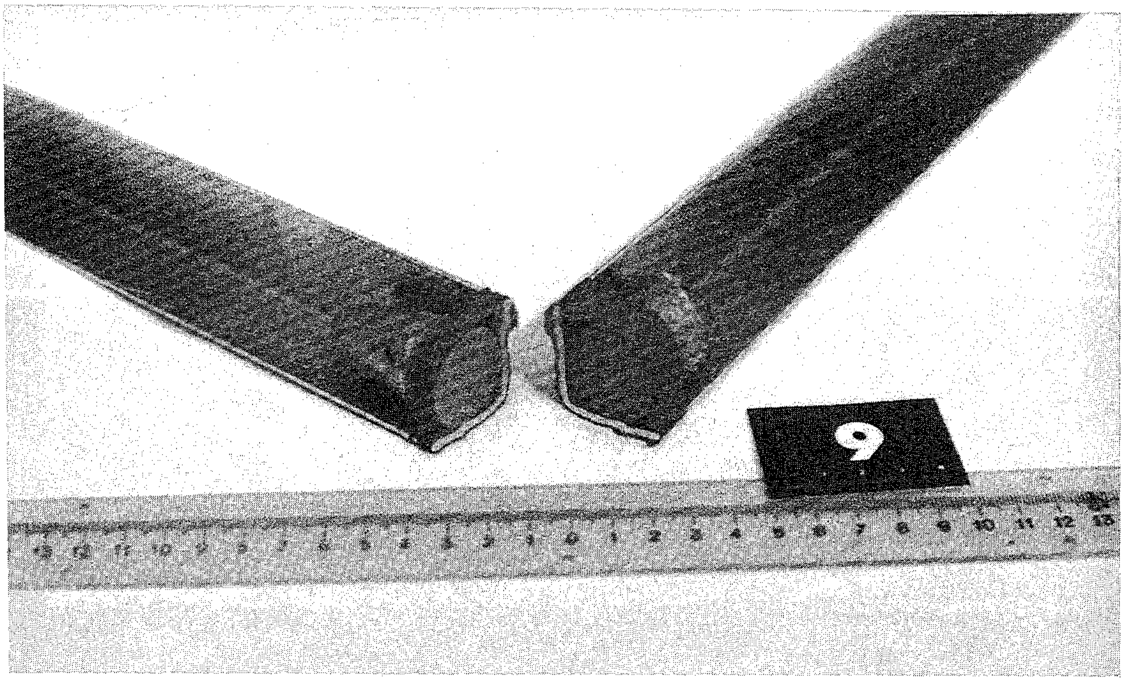


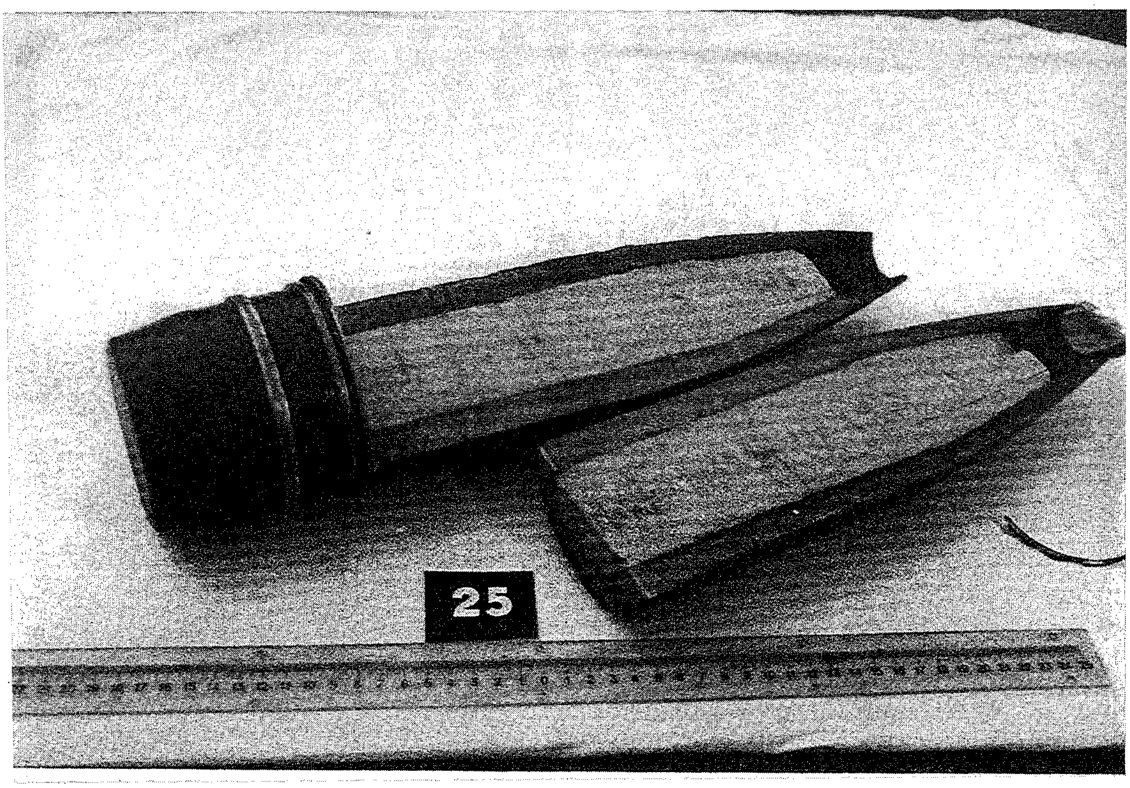
PICTURE 10 + 11



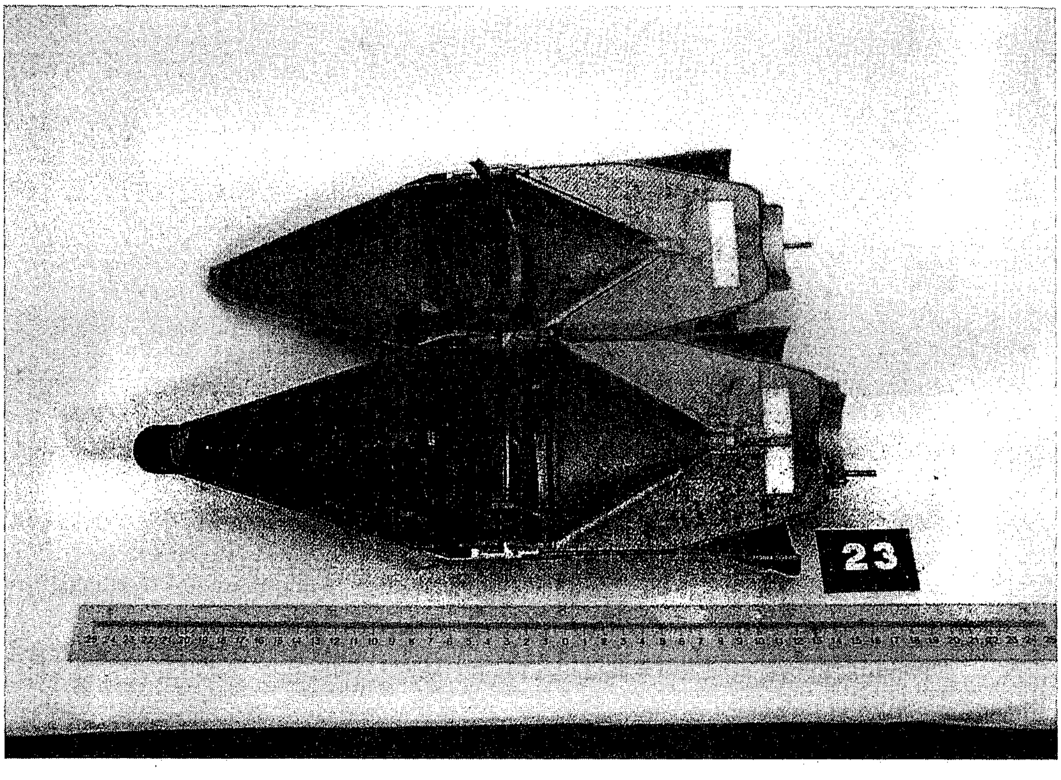


PICTURE 12 + 13

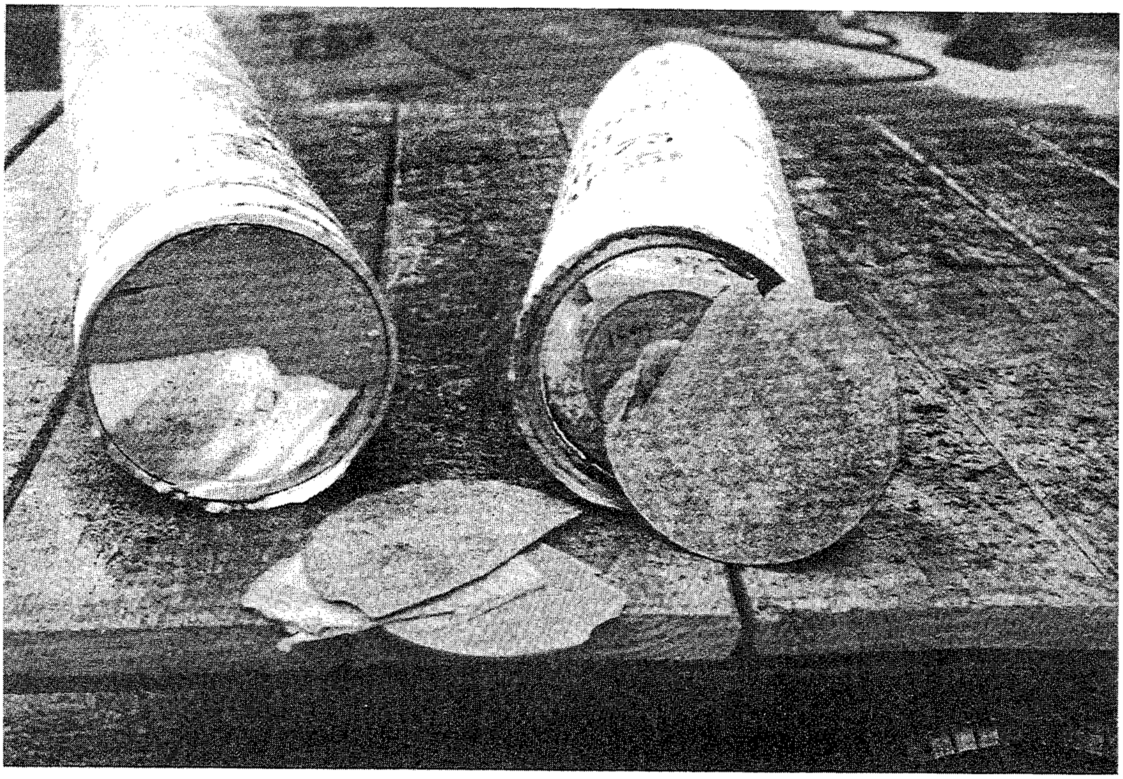


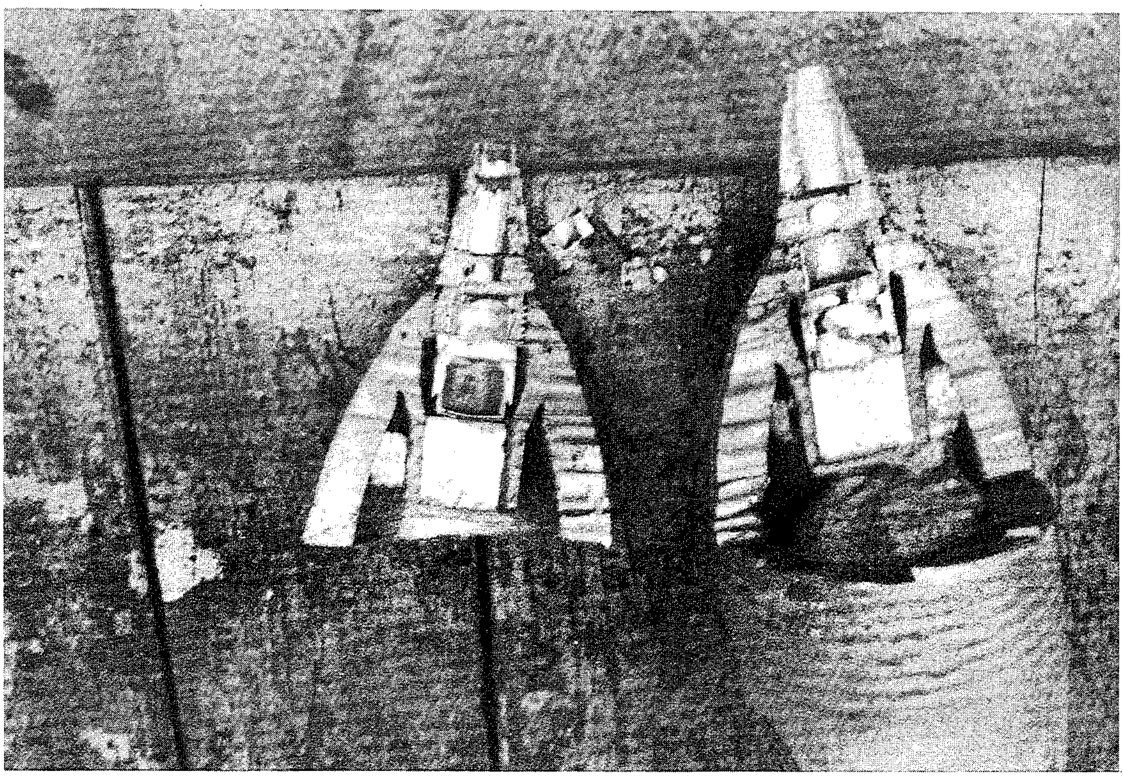


PICTURE 14 + 15

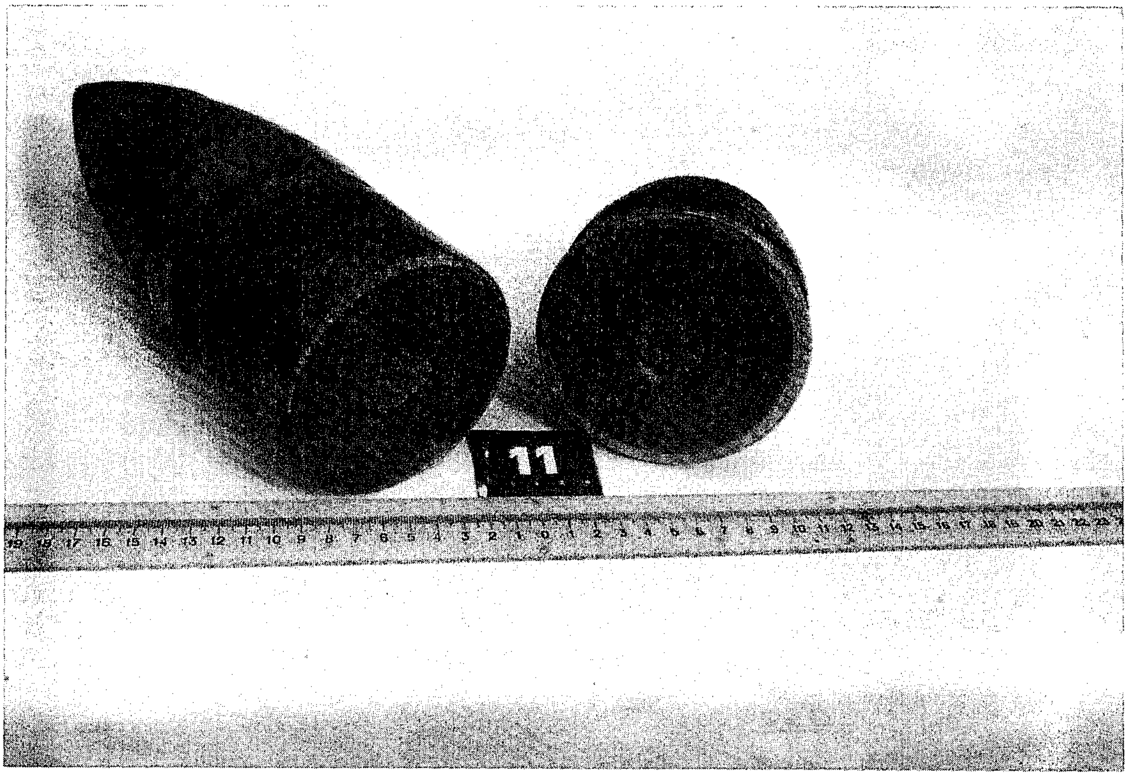


PICTURE 16 + 17





PICTURE 18



7th American Water Jet Conference
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Paper 58

ABRASIVE WATERJET MILLING: AN EXPERIMENTAL INVESTIGATION

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ABSTRACT

The use of abrasive waterjets for cutting applications is a well-known, although not fully understood, technology. As in the case of laser cutting, a natural "next step" is the *implementation of the abrasive waterjet as a milling tool.* Such a tool, utilizing the unique features of the abrasive jet cutting process, would help solve problems in materials processing of modern hard-to-cut materials, permitting a wider spectrum of applications.

This paper is based on an experimental investigation of the use of abrasive waterjets as a three-dimensional controlled erosion process. The work was focused on the quality of the exposed bottom surface. Factors influencing the depth of cut, variations in depth, and bottom surface texture for materials of different characteristics have been tested and discussed. In analyzing the produced bottom surface, an evaluation of accuracy and repeatability of the machining process was made. Problems inherent to the process are discussed.

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1. INTRODUCTION

The abrasive waterjet technology successfully has been applied to cut a wide variety of materials, and seems to be especially compatible with hard-to-cut materials, due to its typical features. These include low thermal stress by an essentially cold and well localized cut, exerting low force, and capable of cutting the matrix material between reinforcements in a composite material by means of the microscopic cutting edges of each grain.

The abrasive waterjet (AWJ) is formed by introducing abrasives into a chamber embracing a high velocity waterjet. This waterjet passes a focusing nozzle creating a venturi effect drawing the abrasives into the jet, where mixing takes place. In the mixing process, the jet atomizes while entraining the abrasive particles. Drops of water, abrasive particles and air rush at high speed into the focusing/mixing nozzle, where they recollimate into a three-phase abrasive waterjet. On impact, the kinetic energy of the particles allows them to exert local pressures on the target material, sufficient to disintegrate the material by means of several mechanisms.

As in the case of laser technology, where at present 5-axis milling machines are commercially available, the waterjet technology now has reached a phase where development of a milling process is the natural evolution.

A precision control of the abrasive waterjet's penetration would yield a milling operation. In a paper, Hashish (1987) presents a study stating the feasibility of milling with abrasive waterjets. Since the AWJ cutting operation essentially is based on erosion phenomena, such a milling procedure also could be called a three-dimensional controlled erosion process (TDCE). TDCE is subject to an increasing interest, especially in the area of machining ceramics, where it provides a potential for producing geometries not obtainable directly in hot isostatic pressing, nor in subsequent traditional shaping operations. Studies in this area have been performed by Freist et al. (1989), and Zeng and Kim (1991).

The depth of penetration of the abrasive waterjet is a result of jet/material interaction, controlled by many parameters. A discussion of the importance of some parameters for the desired milling results is included in this paper. Optimizing them is a complex problem, not within the scope of this study.

2. EXPERIMENT

The experiment was three-fold: an introductory investigation using a factorial design, a conventional *"ceteris paribus"*[1] parametric test, and concluding with an endeavor to optimize the process in respect to a desired outcome. The intention of the introductory investigation was to make a quantitative comparative estimate of the effects of a selected set of parameters. The statistical method of factorial design was employed here. The objective of part two of the test was to illuminate the nature of the process and its relation to some of the parameters. Part three was based on the experience from part one, and serves as a complement, since no functions were derived directly from part one.

[1] "all other things being equal"

2.1 Experimental Setup

For the experiment, a high pressure intensifier was used. Water was used as cutting fluid and, besides abrasives, no further additives were employed. Throughout the tests, the jet was formed by a 0.25 mm sapphire orifice. Abrasives were supplied by a vibrating feeder and gravity-fed into a mixing chamber of single side-port injection type. Two mixing nozzle types were used: tungsten carbide WC (short length), and composite carbide ceramic MoC-WC (long length, the so-called long-life nozzle). They have slightly different geometries. The cutting head setup was arranged to allow stand-off and angle adjustments and was mounted on an XY table. The arrangement is shown in figure 1. In the analysis, dial gauges and a stylus instrument were used for measuring cutting results.

Materials used were

in part 1,2 and 3: Steel, alloyed with
0.18% C, 0.43% Si, 1.27% Mn, 0.016% P, 0.018% S, 0.013% Al, 0.022% Nb, 0.006% N

in part 3: Aluminum, alloyed with
1.0% Si, 0.7% Mn, 0.8% Mg

2.2 Introductory Experiment

A factorial approach to experimental design was adopted for this study, mainly because of its facility in describing the relative importance of the various parameters investigated. The two-level factorial design experiment is not adequate for fully exploring the influence of the participating parameters, or factors, but provides a convenient way of discovering major trends. To reduce the number of tests needed, a fractional factorial design was employed. The method used is described in detail by Box et al. (1978).

To establish a process meeting high demands on machining quality, combined with practical functionality, it is of great importance to be familiar with the means available. The performance of the abrasive waterjet according to Hashish (1987) is related to a number of hydraulic, abrasive, mixing nozzle, and cutting parameters. Since the cutting process is a result of interaction between the abrasive jet and the target material, work material properties, such as hardness, flow stress, etc., also become parameters. To investigate the varying potential for controlling them, the following eight parameters were selected for this study as being most interesting from a process control point of wiev:

- Water pressure
- Ratio of orifice / mixing tube diameter
- Length of mixing tube
- Abrasive mass flow
- Abrasive grain size
- Traverse rate
- Angle of attack
- Stand-off distance

These parameters, which are the factors of the experiment, were varied at two levels. It must be emphasized here, that the subjective selection of levels could give lopsided results. Therefore, in a nonanalytical evaluation it is important to consider whether the yielded response could be the result of an improperly high difference between levels chosen for each parameter. Response variables measured during this experiment were

- Depth of cut
- Surface roughness
- Surface waviness

In surface analysis, there are numerous ways to characterize a surface, depending on its intended function. The R_a and W_t parameters are prevalent in industrial use and consequently were selected for reference. They were filtered with a cut-off length of 0.8 mm. The factors and selected levels are shown in table 1. Table 2 shows the design matrix used for the introductory experiment, and the yielded response for each parameter combination.

Effects of each factor and two-factor interaction were calculated in respect to each response variable. In the analysis, it was assumed that higher order interactions than two were negligible. According to Box et al., the problems of subjective aspects in selection of parameter levels could be overcome by using a normal probability plot to indicate the most significant parameters. Inspection of these plots (figures 2, 3, 4) combined with the calculated effects, gives a comparative estimate of the importance of each parameter. It was found that the most important factors in obtaining *depth of cut* were, in order of magnitude: high abrasive mass flow, low traverse rate, high water pressure, and any two-factor interactions of AE, BC, FG, and DH (see factor explanation in table 2). The inability to separate the two-factor interactions due to poor resolution is a drawback inherent to the fractional factorial design.

The analysis for factor importance in order to obtain *low surface roughness* indicated, in order of magnitude: high abrasive mass flow, low angle of attack, small abrasive grain size, and low traverse rates. Most beneficial to *low waviness* were: low abrasive mass flow, small abrasive grain size, and low water pressure. Also influential, albeit on a smaller scale, were a short mixing tube length and any two-factor interactions of AH, DE, BF, and CG. In the following synopsis of the above, signs show whether (+) or (-) level favors the results. Effects are listed here in order of significance for the above three response variables:

Depth of cut:
+ abrasive mass flow
- traverse rate
+ water pressure
a two-factor interaction

Surface roughness:
+ abrasive mass flow
- angle of attack
- abrasive grain size
- traverse rate

Surface waviness:
- abrasive mass flow
- abrasive grain size
- water pressure
- length of mixing tube
plus a two-factor interaction

Since the parameters favoring a low surface roughness do not agree with those propitious to high material removal rate, a milling strategy could be to use a parameter combination in accordance with optimal depth of cut and low waviness for the rough cuts, and for finishing to use a parameter setting propitious to surface finish. However, according to Hashish (1987), a poor tolerance from preceding cuts will not be improved by additional machining. This speaks for a strategy of precautiousness in rough cuts, focusing on low tolerance and waviness. For a finishing cut however, a finer and by shape, density or hardness less aggressive abrasive can be used. The finishing operation should, therefore, essentially only polish the surface.

2.3 Main Experiment

In order to reduce cutting depth tolerance, the strategy employed in experiments made by Hashish (1987) was to maintain a high traverse rate while masking the workpiece. This entails, as will be shown below, a sustained high material removal rate with a narrow tolerance band. *With no masking of the workpiece*, the jet would have to be tightly controlled for momentaneous changes of direction that induce strong acceleration forces. This means high requirements for stability of a machine using a stationary workpiece setup as in most waterjet cutting applications. Another strategy, employing no masking, for narrowing the depth tolerance would be, as shown above, to keep a rather low mass flow of fine abrasives. This is a less efficient way of rapid material removal, but at the same time it simplifies the cutting head manipulator concept (although requiring tighter process control). Potentially, it could contribute to a practical milling technique.

The following tests were conducted to visualize parameter influence on basic AWJ milling performance. Standard parameter settings are provided in table 3.

2.3.1 Lateral Feed Increment

All milling experiments were made with repeated adjacent cuts (figure 5). The lateral increment strongly controls the resulting milling performace, as shown in figure 6. At an increment/jet diameter ratio of more than approximately 0.4, the surface texture clearly showed the jet traverse path. At smaller lateral increments, part of the jet does not reach unmachined material, causing jet interaction with the previosly cut surface to become more pronounced, resulting in an accelerated rate of penetration and a slightly different surface texture, indicating the direction of jet deflection. The strong influence of an increase in stand-off distance from 1 to 5 mm, can be explained by the diversion of the not fully collimated abrasive jet. In regard to material removal rate, an optimum lateral feed rate to tolerance ratio can be observed in figure 7.

2.3.2 Abrasive Mass Flow

An increase of abrasive mass flow significantly increased the depth of cut, as indicated in the introductory experiment. Inspection of the graph in figure 8 points to a linear trend of increasing cutting depths (after a certain range of "hesitancy"). This was accompanied by a strongly increased deterioration of surface smoothness, combined with an augmented material removal rate, as shown in figure 9. According to Hashish (1984), the linearity could be expected to terminate at higher flow rates, as a result of increased interference between particles. In a paper presented by Neusen et al. (1992), a method for measuring abrasive particle velocities was introduced. They found that *particle velocities remain relatively constant even though the rate of adding abrasives was significantly increased.* With this in mind, a linear relationship between depth of cut and number of particles involved in the cutting action seems legitimate.

A noteworthy observation was the enhanced surface finish obtained during the introductory experiment, by increasing the mass flow. An explanation of this phenomenon could be that the greater mass flow results in better coverage in accordance with normal distribution. However, the applicability of this may be somewhat reduced by an associated increase in waviness.

2.3.3 Traverse Rate

The time of exposure to the abrasive jet is directly related to the traverse rate. Hence, this parameter naturally strongly controls the depth of cut. The relationship between depth of cut and traverse rate constitutes a nearly straight line in the double-logarithmic plot shown in figure 10. Figure 11 further shows that material removal rates remain relatively constant, while tolerances are greatly influenced by traverse rate. The irregularities in cutting depth are due to technical variations (stochastic and cyclic) in parameters, such as water pressure, abrasive flow rate etc. As the energy used for disintegrating workpiece material is related to the time of exposure to the jet power, a faster traverse means that less energy will be transferred to any area unit under exposure. Therefore, a variation of say 10% accordingly has less influence on cutting performance, thus producing a more consistent depth of cut.

2.3.4 Water Pressure

Intensified water pressure results in a progressive growth of cutting depth. The hydraulic power varies with the 1.5 power of the pressure ($p^{1.5}$), which in itself yields a progressively increasing power available for particle entrainment. This mainly will control the function shown in figure 12, also describing a narrower tolerance at lower pressures.

2.3.5 Stand-off Distance

The relation between stand-off distance and depth of cut is displayed in figure 13. As the distance between mixing nozzle exit and workpiece increases, the jet becomes wider and more diffuse due to jet diversion. The density of energy transmitted to the target material thereby decreases, resulting in less pronounced surface irregularities. In a paper investigating mass distribution in the abrasive waterjet, Neusen et al. (1991) presents a saddle-shaped distribution of abrasives indicating a maximum particle density at a radial distance of 50-60% of the jet radius. However, as an effect of abrasive particle distribution in the jet, the circumferential region of lower power density also becomes wider, making precise control of regions under jet exposure more difficult. The diffuse jet creates a wider cut with a more diffuse boundary to the uncut material, showing indentions of stray particles. Using a strategy of large stand-offs for narrowing depth tolerances thus would demand some kind of masking.

2.4 Optimization Effort

As an outcome of the experience gained from the preceding tests, a final endeavor in this experiment was an attempt at surface optimization using both on-line controllable variables and fixed settings, here referred to as *invariants*. However, it should be emphasized that this does not necessarily mean that optimum conditions prevail, since unrecognized interaction between parameters may cause different results at other parameter levels.

2.4.1 Discussion of Standard Setting for Remaining Tests

A noteworthy observation was the promising results obtained in test 5 (see table 2) of the introductory designed factorial experiment. This test features a parameter setting yielding one of the best results, both for surface roughness and waviness, in combination with an upper range depth of cut. Parameter settings for test 5 coincide well with the recommendations for surface roughness amelioration, and are in fairly good accordance with those intended to minimize surface waviness, with the exceptions of high abrasive mass flow (see synopsis concluding section 2.2) and, less significant, the length of the mixing tube. A low water pressure was used, conducive to low waviness more than disfavoring surface roughness. Also incorporated with these features was an upper range depth of cut, abetted by a high abrasive mass flow and a long mixing tube.

From "test 5" settings, additional enhancements were made by exchanging the mixing nozzle for a shorter model, decreasing surface waviness while not significantly contributing to surface roughness although tending to make shallower the depth of cut. With this basic constellation, listed in table 4, the remaining part of the experiment was performed, varying only one parameter at a time.

2.4.2 Study of Process Invariants

The last part of surface optimization deals with the process invariants of
- work material influence
- abrasive material influence.

A ductile aluminum alloy and a steel alloy, as described above, were used to study work material effects.

Different abrasives were selected to study their influence on surface generation. The abrasives subjected to testing were

- garnet
- Al_2O_3
- zircon
- glass
- steel

An abrasive grain size of 0.2 mm was used (except for Al_2O_3 where only 0.15 mm grains were available). Each abrasive was used on the two work materials employing the standard settings of table 4, except for using, in some tests, a jet attack angle of 90° (upright). Furthermore, some tests were made with the jet pointing generally backwards toward the already cut area, in a direction 30° from the horizontal in a plane perpendicular to the traverse direction. Depth of cut, bottom surface roughness (featuring λ_c=0.8mm), and depth tolerance were measured. The results, displayed in figures 14, 15 and 16, essentially indicate that, as could be expected, *both surface roughness and tolerances benefit from an inclined jet attack angle*. This causes a "free form macrolapping" operation further smoothing the surface. However, this feature is of less significance. The effect of secondary machining could also be detected as a difference in surface roughness at different locations on the machined area. When machining aluminum, the tests using an inclined jet attack angle showed that significant enhancement of tolerance could be achieved by using glass beads as the abrasive medium. With their relative softness and blunter edges they mount less aggressive attacks on the target material. The direction of jet deflection, when using a lateral inclination, features a partly overlapping machining sequence, where the jet is warped toward the already machined surface and slightly turned in the opposite direction of the traverse. Then, the "washing-off" occurring on the surface tends to act as a polishing operation, resulting in a less rough surface.

2.4.3 Visual Surface Analysis Using Scanning Electron Microscope

To better comprehend the cutting process, a closer examination of the surface was conducted with SEM micrographs.

In his study of erosion phenomena, Bitter (1963) suggests that the particle erosion process consists of two modes of cutting: deformation wear and cutting wear. The deformation wear mode entails strain hardening of the material by multiple particle impact, resulting in fracture. It is the most prevalent one at high impact angles, while the shear-based cutting wear mode dominates at low impact angles. Based on calculations for a spherical particle, he derives a transition angle of approximately 20° between these two modes. A more sharp-edged particle, for example a grain of garnet, would raise the transition angle in favor of the cutting wear mode in the experimental setup, which was restricted to a jet attack angle of 30°.

Figures 18 and 19 show SEM micrographs of steel cut with garnet abrasives at a jet attack angle of 90° respectively 30°. At the perpendicular attack angle an essentially isotropic surface emerges, a pattern typical for surfaces produced by a stochastic process. However, signs of fracture, indicating deformation wear as well as plastic deformation from scratching cutting wear could be detected. Because of collisions between particles in the jet, it is likely that traces of both wear modes will appear in surfaces at different angles, due to the spectrum of directions of rebounding particles. The 30° impingement shows a prevailing cutting deformation mode.

Using glass beads as abrasive media produced a glossy, light-reflecting surface. Studying figure 20, which shows a smooth surface, clearly explains this feature. This should be compared with figure 18, where the broken surface scatters the light reflections, typical for a fracture surface. Using garnet grains, figure 19, and glass beads, figure 21, showed a radically enhanced surface finish with the glass beads. On inspecting these pictures, it should be kept in mind that the scale (400x) makes the grains appear equal to the size of golf balls.

3. DISCUSSION

For successful implementation of abrasive waterjets as a three-dimensional controlled erosion process a great number of parameters need to be precisely controlled. Some of them have been investigated in this paper. The process is greatly influenced by technical disturbances, which are difficult to control, calling for strategies to avoid them. Control of cutting parameters is often restricted by the mechanical design of certain machine elements of the system. Thus, only some parameters can be controlled on-line, such as

- water pressure
- abrasive mass flow
- position in X,Y,Z, pitch and roll, including,
  - stand-off distance
  - attack angle, or angle of cutting
- feed direction
- traverse rate

In section 2.3, experimental relationships are shown as a guidance for the control of those parameters. Other important parameters essentially require an operation shut-down to be adjusted. Referred to as invariants here, they include the

- waterjet orifice diameter
- abrasive mixing nozzle controlling
  - diameter of jet
  - coherency of jet
- abrasive grain size
- abrasive material

The influence of the invariants was discussed in section 2.3.2, showing different material sensitivity for each mode of particle erosion. The soft material was more readily machined using a less dense and blunter abrasive. It was also shown that, by inclination of the jet attack angle, enhancement of certain surface characteristics can be obtained. A more pleasing appearance also can be achieved by using a less aggressive abrasive.

4. CONCLUSIONS

The AWJ milled surfaces are characterized by a variance in depth of cut, partly due to the stochastic nature of the process. It is also sensitive to many disturbances, such as fluctuations in water pressure, abrasive mass flow, and traverse movement, but also to material properties and the different mechanisms for material removal.

Minimizing surface roughness in AWJ milling to some extent appears to be incompatible with surface waviness amelioration. When possible, a compromise featuring the most significant promoters of each effect could produce relatively promising results. A further study should elucidate the two-factor interactions detected in this study.

Abrasive mass flow, angle of jet attack, and abrasive grain size all are important factors in obtaining a smooth surface. Process optimization, when cutting materials of different characteristics, could be attained by varying these factors in combination with the use of different abrasive media.

An AWJ milling system should be developed for insensitivity to variations in water pressure, abrasive mass flow, and traverse rate. Any fluctuations of these important parameters will negatively affect the obtainable surface finish, waviness, and depth tolerance. Components need to be designed accordingly.

A further study is needed on how to overcome unwanted effects of secondary machining induced by the deflected jet, a problem most pronounced when cutting at low attack angles.

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Table1: Factor levels.

Factor	Parameter	level (-)	level (+)
A	diameter ratio (d_n/d_a) [mm]	0.25/0.76	0.25/1.10
B	water pressure [MPa]	250	330
C	abrasive mass flow [g/s]	34	130
D	abrasive grain size [mm][1]	<0.35	>0.5
E	mixing tube length [mm][2]	50.6	69.7
F	traverse rate [mm/s]	15	26
G	attack angle [deg]	30°	90°
H	stand-off distance [mm]	10	20

[1] Variations in grain size, due to manufacturer's quality, made manual sieving necessary to guarantee consistency.
[2] The two mixing tubes (WC[+], MoC-WC[-]) also show a slight difference in entrance geometry.

Table 2: Design matrix of 2_{IV}^{8-4} fractional factorial design experiment.

test no.	A	B	C	D	E	F	G	H	yield h [mm][1]	yield R_a [μm]	yield W_t [μm]
1	-	-	-	-	-	-	-	-	0.45	7.0	41.3
2	+	-	-	-	+	+	+	-	0.20	12.3	41.5
3	-	+	-	-	+	-	+	+	0.54	9.5	66.2
4	+	+	-	-	-	+	-	+	0.32	8.7	50.5
5	-	-	+	-	+	+	-	+	0.70	4.7	48.8
6	+	-	+	-	-	-	+	+	1.24	5.1	69.6
7	-	+	+	-	-	+	+	-	1.09	7.1	86.9
8	+	+	+	-	+	-	-	-	2.16	4.7	87.7
9	-	-	-	+	-	+	+	+	0.14	13.2	46.2
10	+	-	-	+	+	-	-	+	0.34	8.8	82.4
11	-	+	-	+	+	+	-	-	0.18	9.1	67.4
12	+	+	-	+	-	-	+	-	0.30	11.6	56.9
13	-	-	+	+	+	-	+	-	1.30	7.5	107.7
14	+	-	+	+	-	+	-	-	0.94	6.6	66.7
15	-	+	+	+	-	-	-	+	2.49	5.1	102.9
16	+	+	+	+	+	+	+	+	1.51	11.0	137.4

[1] Depth of cut

Table 3: Standard setting for parametric test.

Nozzle combination:	0.25/0.76 mm
Mixing nozzle type:	Long-life
Water pressure:	330 MPa
Abrasive flow:	34 g/min.
Abrasive grain size:	0.35 mm
Traverse rate:	26mm/s
Jet attack angle:	90°
Stand-off:	5 mm
Lateral feed increment:	0.4 mm

Table 4: Basic constellation of last experiment test.

Nozzle combination:	0.25/0.76 mm
Mixing nozzle type:	WC
Water pressure:	250 MPa
Abrasive flow:	130 g/min.
Abrasive grain size:	0.35 mm
Traverse rate:	26 mm/s
Jet attack angle:	30°
Stand-off:	10 mm
Lateral feed increment:	0.4 mm

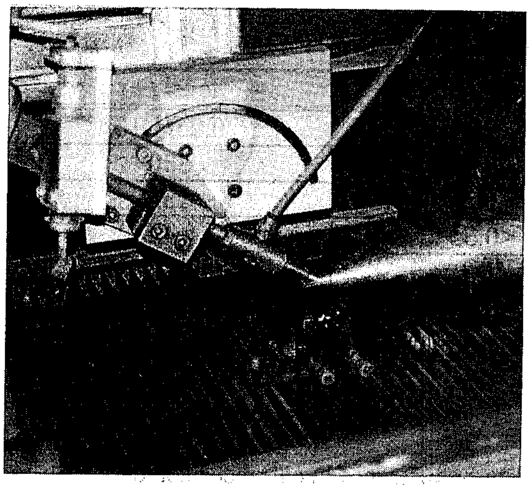

Fig 1: Test set-up.

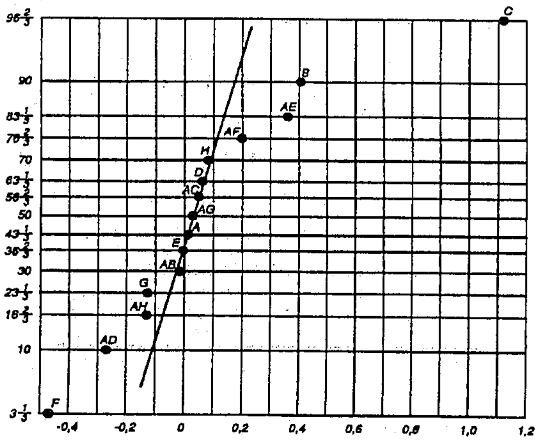

Fig 2: Normal probability plot of depth of cut.

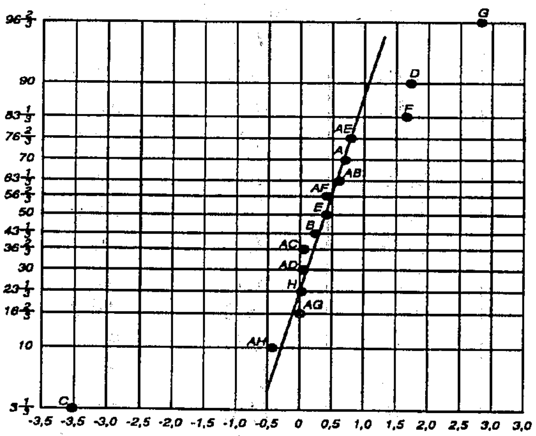

Fig 3: Normal probability plot of surface roughness.

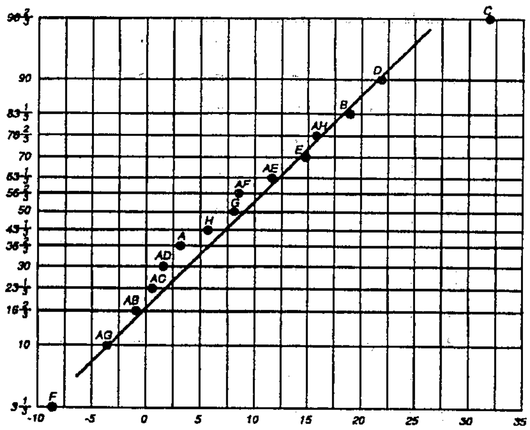

Fig 4: Normal probability plot of surface waviness.

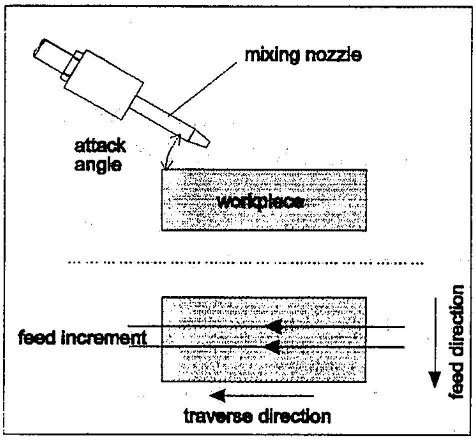

Fig 5: Milling procedure.

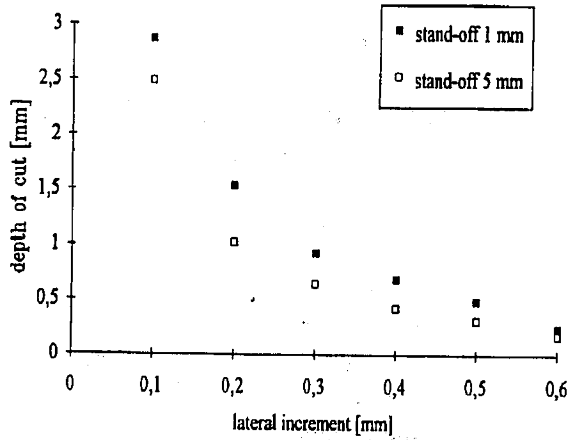

Fig 6: Depth of cut vs. lateral feed increment.

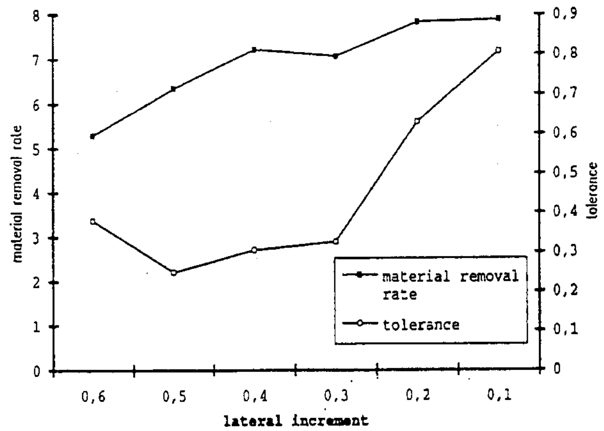

Fig 7: Material removal rate [mm³/s] and tolerance [mm] vs. lateral feed increment [mm]

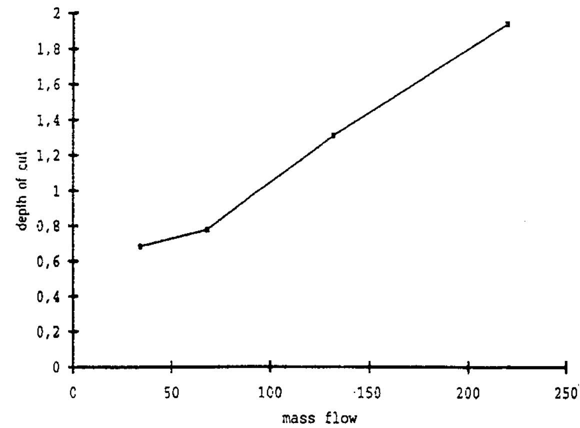

Fig 8:Depth of cut [mm] vs. abrasive mass flow [g/min.]

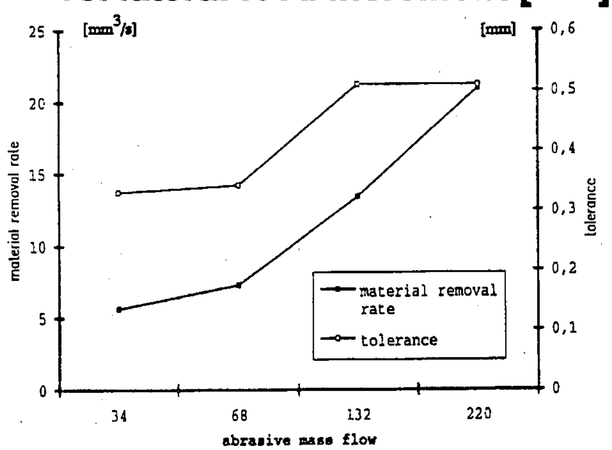

Fig 9: Material removal rate and tolerance vs. abrasive mass flow.

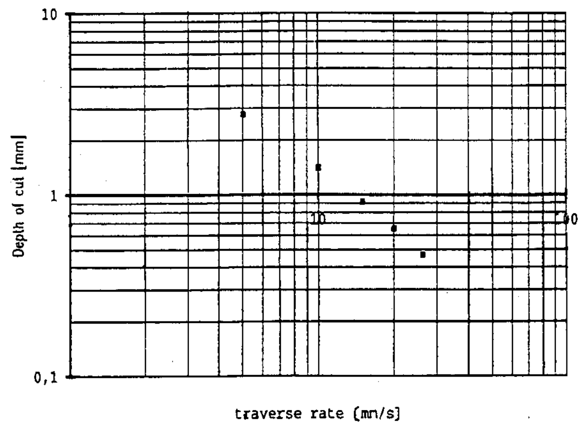

Fig 10: Depth of cut [mm] vs. traverse rate [mm/s].

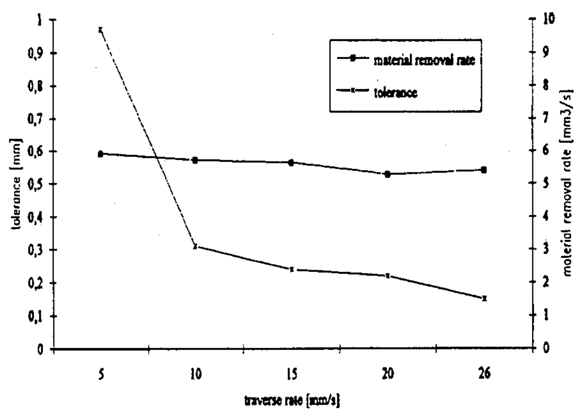

Fig 11: Material removal rate and tolerance [mm] vs. traverse rate [mm/s].

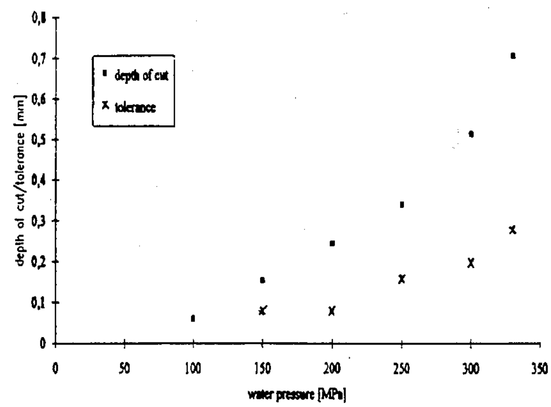

Fig 12: Depth of cut [mm] vs. water pressure [MPa].

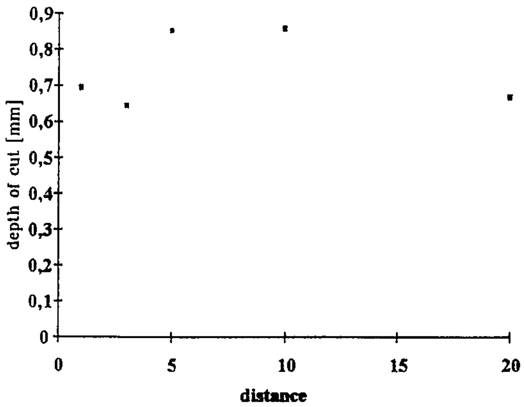

Fig 13: Relation of stand-off distance [mm] and depth of cut [mm].

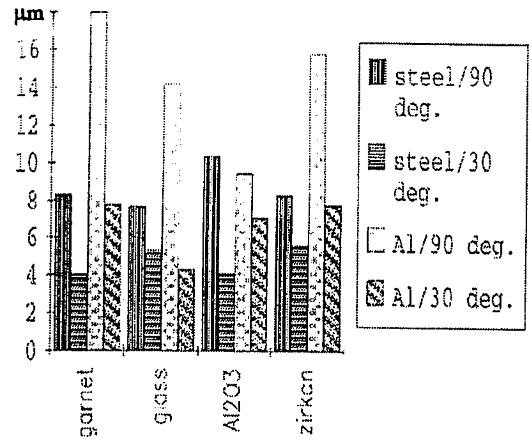

Fig 14: Surface roughness using different abrasives

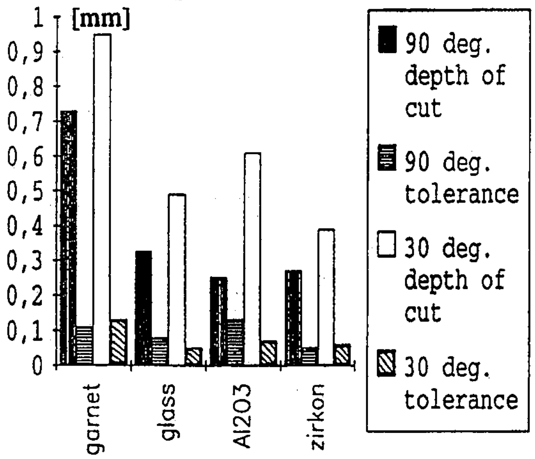

Fig 15: Depth of cut and tolerances when cutting steel at different angles

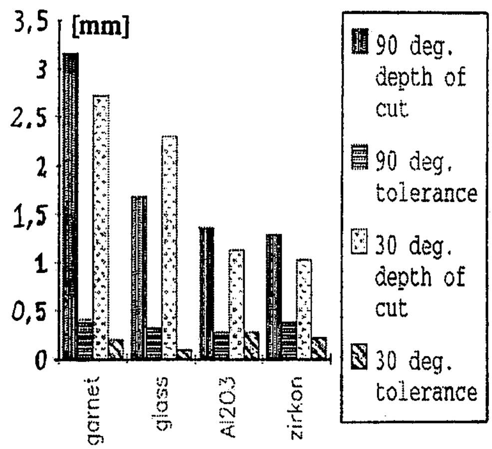

Fig 16:Depth of cut and tolerances when cutting Al at different angles

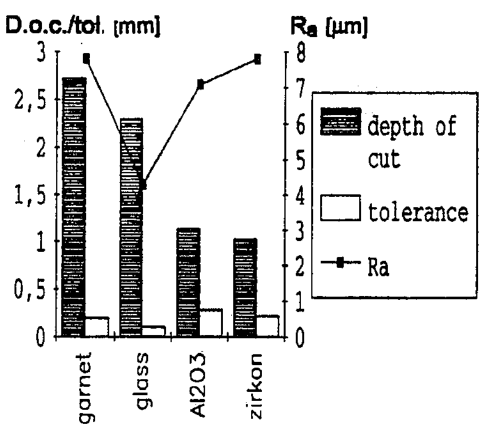

Fig 17: Influence of abrasive material when cutting Al at 30 deg. jet attack angle.

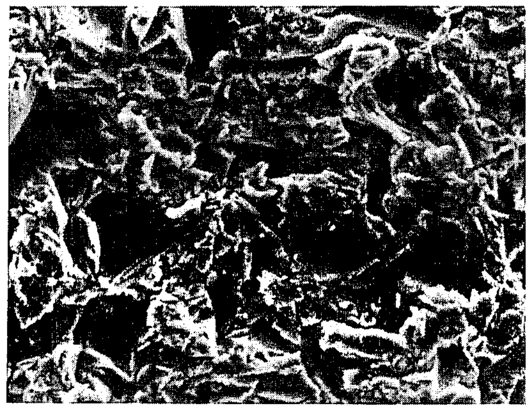

Fig 18: SEM micrograph of Al cut at 90 deg. attack angle using garnet abrasive.

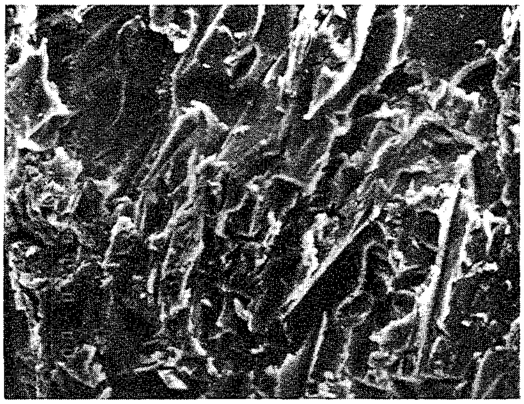

Fig 19: SEM micrograph of Al cut at 30 deg. attack angle using garnet abrasive.

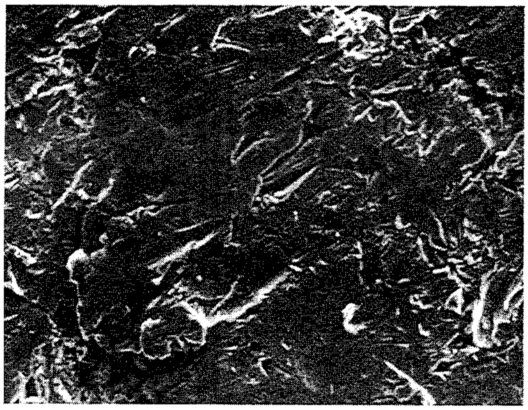

Fig 20: SEM micrograph of steel cut at 90 deg. attack angle using glass beads.

Fig 21: SEM micrograph of Al cut at 30 deg. attack angle using glass beads.

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Paper 59

DIAMOND POLISHING WITH ABRASIVE SUSPENSION JETS

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ABSTRACT

A study was conducted to determine the feasibility of polishing diamond with high-pressure abrasive suspension jets. A nozzle system that produces a high-velocity radial flow with zero or near-zero impact angles was developed and used for limited polishing tests. The relatively high particle flow rates (10 g/s) and velocities (over 150 m/s) result in relatively high polishing rates. The inertial effect of the abrasive particles appears to contribute significantly to the material removal. A diamond film was polished from 3 to 1.3 microns at a rate of 2.7 micron/s/mm^2 using 600-mesh SiC abrasives.

Organized and Sponsored by the Water Jet Technology Association.

1. INTRODUCTION

Abrasive suspension jets (ASJs) have proven to be very successful in many machining applications, including cutting, turning, milling, and drilling. Several significant advantages can be realized with the ASJ as a polishing tool. These potential advantages include high productivity, flexibility and suitability for different part geometries, suitability for a wide range of materials, and versatility for performing other machining operations.

In this paper, diamond polishing techniques will be reviewed first. This will be followed by a description of polishing tests. Conclusions are summarized and recommendations presented in the final section.

2. DIAMOND FILM POLISHING TECHNIQUES

There have been a number of innovative attempts to polish chemical vapor deposition (CVD) diamond films. The use of a reactive-ion (oxygen) beam with the aid of photoresist/titanium silica planarizing film was reported by Tianji et al. (1990). The process is simply to coat the diamond surface with a liquid coating that is then hardened by baking. The ions of the polishing beam impinge on the new surface at an angle that achieves equal etch rates in both the coating and the diamond. The final surface finish will be equal to that of the coating. With this process, diamond films can be polished from 5 microns to 35 angstroms. The process is slow and limited by the characteristics of the coating, however, with polishing rates normally less than 100 Å/min.

The polishing of polycrystalline diamond (PCD) film surfaces by contact with iron in a hydrogen atmosphere at elevated temperatures has been reported in the Japanese literature (Yang et al., 1988). This technique is limited because the high temperatures involved (over 700°C) produce mechanical failure and thermal shocking of the film.

Harker et al. (1990) conducted experiments on the combined use of high-temperature reactive plasma etching and lapping with an iron plate in a hydrogen atmosphere. It was observed that the primary reactive polishing process occurs only at the points of direct contact between the plate and the high points of the faceted film. Local polishing rates of 5 microns/hour have been observed. The major limitations to this technique are due to the stresses and nonuniformities in the initial films themselves.

Thorpe et al. (1990) conducted similar tests and found that the best results are obtained at 850°C and a contact pressure of 4 kPa. Local surface roughnesses of a few hundred angstroms were achieved after 2 hours.

Yoshikawa (1990) used hot metal polishing and found that the polishing rate is highest in a vacuum atmosphere of hydrogen. Hot plate polishing of rough diamond films requires that surface planing first be conducted using a YAG laser. Yoshikawa (1990) reported the optimal conditions for polishing. The procedure requires that a plate of iron be used, and rough polishing occurs at 950°C while final polishing occurs at 750°C.

Hickey et al. (1991) indicated, from preliminary studies, that the hot iron polishing technique depends on the orientation of the diamond crystals.

3. POLISHING TESTS

An ASJ is produced by the direct pumping of an abrasive suspension (Hashish, 1989). The system used in this study utilizes a pressure vessel, which is termed an isolator. A free piston inside the vessel isolates the suspension (or any liquid to be pumped) from the high-pressure water used for pumping. The system has been developed for pressures of up to 345 MPa and abrasive concentrations of up to 50% by weight.

Figure 1 shows the polishing nozzle. A nozzle made out of a soft material such as nylon or copper is used to deliver abrasive suspension to the workpiece. This nozzle is mounted inside a supply chamber such that it can flow axially under the pressure inside the suspension chamber. The nozzle, in fact, acts like a face seal where the leakage flows outward radially as the nozzle wears out by rubbing against the workpiece material. The friction between the nozzle and the wall of the supply tube, in addition to the pressure force under the nozzle, balances the nozzle extrusion force due to the chamber pressure. This establishes a boundary layer under the nozzle in which abrasives flow at a nearly zero degree angle of impact. It is most important that the flow inside the nozzle hole be slow enough not to cause high-velocity impacts at normal angles. Figure 2 shows a picture of the test setup.

This nozzle was used to polish SiC and diamond. The following test conditions were used, and the results of the tests are discussed below:

- Pressure: up to 138 MPa
- Suspension: 20% by weight SiC
- Grit size: from 220 to 600 mesh
- Part rotation: stationary and 2400 rpm
- Nozzle traverse rate: stationary and 0.31 mm/s

The polishing of reaction-bonded silicon carbide indicated that effective polishing can be obtained with metallic nozzles. Only the peaks are affected by the radial flow. Figure 3 shows two pictures at different magnifications of an SiC surface after 5 minutes of exposure to the radial flow jet.

The polishing of PCD (COMPAX) was performed using a metallic (SS 15-5 Ph) nozzle material. A sample supplied by GE Superabrasives was mounted and rotated at 2400 rpm while the nozzle traveled across it at 0.31 mm/s. Figure 4 shows the progression of polishing with 600-mesh SiC abrasives. Observe the continued improvement with time. Note, however, that the polishing rate is significant during the first 5 minutes, then it gradually decreases with time. Finer abrasives need to be used after specific intervals of exposure. This was not done in the present tests. Figure 5 shows the PCD sample after polishing.

A diamond composite material was also tested. The material contained micron-size diamond grit in a metallic binder. The exact composition of the material was not provided to us. A picture of the polished material is shown in Figure 6.

We received a sample of CVD diamond from the Norton Company for use in the polishing tests. The CVD diamond was in the form of a thin wafer with one rough side (several microns) and a smoother side (3 microns). The sample was mounted on a bar using an epoxy adhesive and was left to cure for several hours. The sample was then tested using the same set of parameters as for COMPAX above. Figure 7 shows photographs of the progression of surface finish improvement. Figure 8 shows the polished sample--note the clearly reflected image in the polished zone.

From the data shown on Figure 7, where the film was polished from 3 microns to 1 micron, it can be calculated that the polishing rate is about 2.7 micron/s/mm^2.

4. DISCUSSION

The jet flow of the abrasive suspension under the nozzle is essential to maintaining a high-velocity particle flow at a near-zero angle of impact. The velocity of the particles drops after some radial distance from the center due to conservation of continuity. This is advantageous because, when the abrasives exit from the gap, they do not cause material removal in an uncontrolled environment. The force imposed on the particles should be through the fluid layer and not by contact with the face of the nozzle. In fact, if the face of the nozzle interacts with the loose abrasives, as in three-body wear, the process will be reduced to a small-scale lapping process. In this case, the velocity of the particles is reduced and, consequently, the polishing rate.

From the above description, the polishing system can be regarded as a four-body wear system. This is in contrast to the known three-body lapping or two-body fixed abrasive wear systems. The boundary layer represents the fourth body, which serves to accelerate the abrasives and impose the proper normal force. This normal force is affected by the solid face of the nozzle and other system parameters, such as pressure and dimensions.

The performance of this nozzle concept for grinding and polishing can be greatly enhanced by the use of the proper nozzle material. The structure of the nozzle material and the contact loads must not affect the polishing results if the nozzle were to contact the workpiece; i.e., the hydrodynamic field between the nozzle face and the workpiece must not be affected. A diamond composite material would be useful for diamond polishing to combine both inertia (of loose abrasives) and abrasion effects (of fixed diamond in nozzle matrix).

Based on the above, ASJs may offer substantial advantages as polishing tools for two reasons. The first is that a very large number of abrasive particles, on the order of 10^6 to 10^{10}, can be delivered to the workpiece every second. In fixed abrasive grinding, this requires very high rotational speeds. The second reason is that these particles are moving at high velocities, over 150 m/s. These high velocities cannot be obtained in loose abrasive grinding (30 mm). The challenge in applying the ASJ to a surface for polishing is not to violate the known basic physics for working in the ductile-regime mode. Moreover, to make use of the physio-chemical nature of the polishing process, the depth of engagement should be less than a critical depth (Bifano et al., 1991). This implies that the normal force acting on a particle should not exceed a certain limit. Manipulation of the liquid flow to transmit the proper forces (normal and tangential) to the particles is another challenge. The fluid mechanics of a slurry flow, as well as the solid mechanics of the particle interactions, should be correctly coupled to obtain polishing. The machinery used for the process only needs to control the required kinematics for figure control. This is a major departure from conventional grinding approaches where the machine is required to control both the dynamics of the process and the kinematics of figure control, which leads to extremely stiff, massive, and expensive machines.

5. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations can be made based on the results of this study of diamond film polishing:

- A diamond film was polished to a 1-micron finish at a rate of 2.7 micron/s/mm^2 using 600-mesh SiC abrasives.
- The nozzle geometry and the rheological characteristics of the abrasive suspension need to be optimized. Angstrom level surface finishes are achievable with optimized strategies that need to be developed.

ACKNOWLEDGMENT

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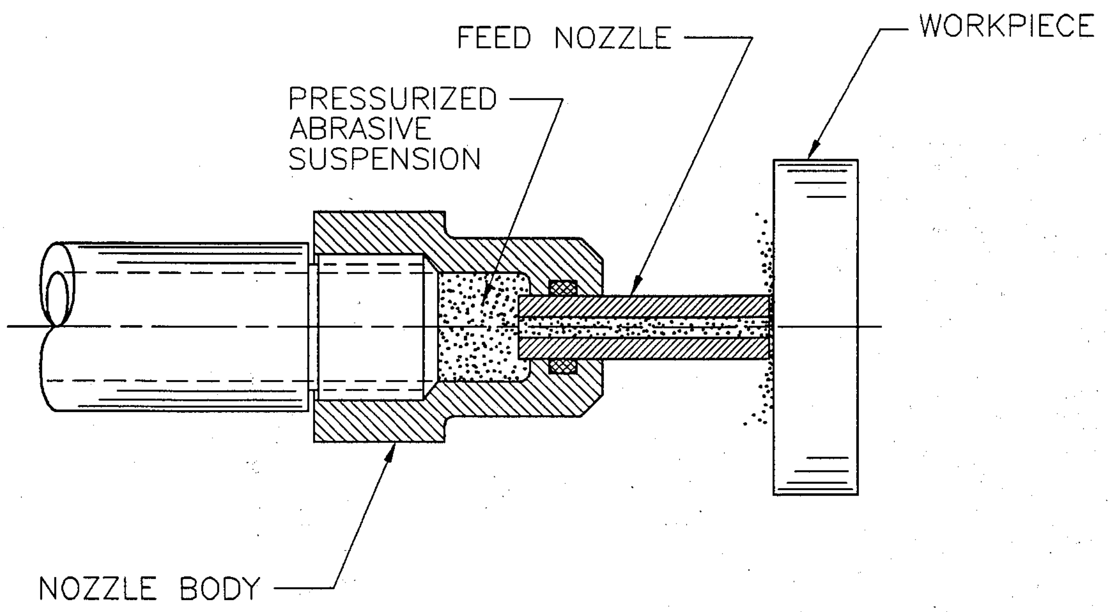


Figure 1. Novel Nozzle Concept for ASJ Polishing

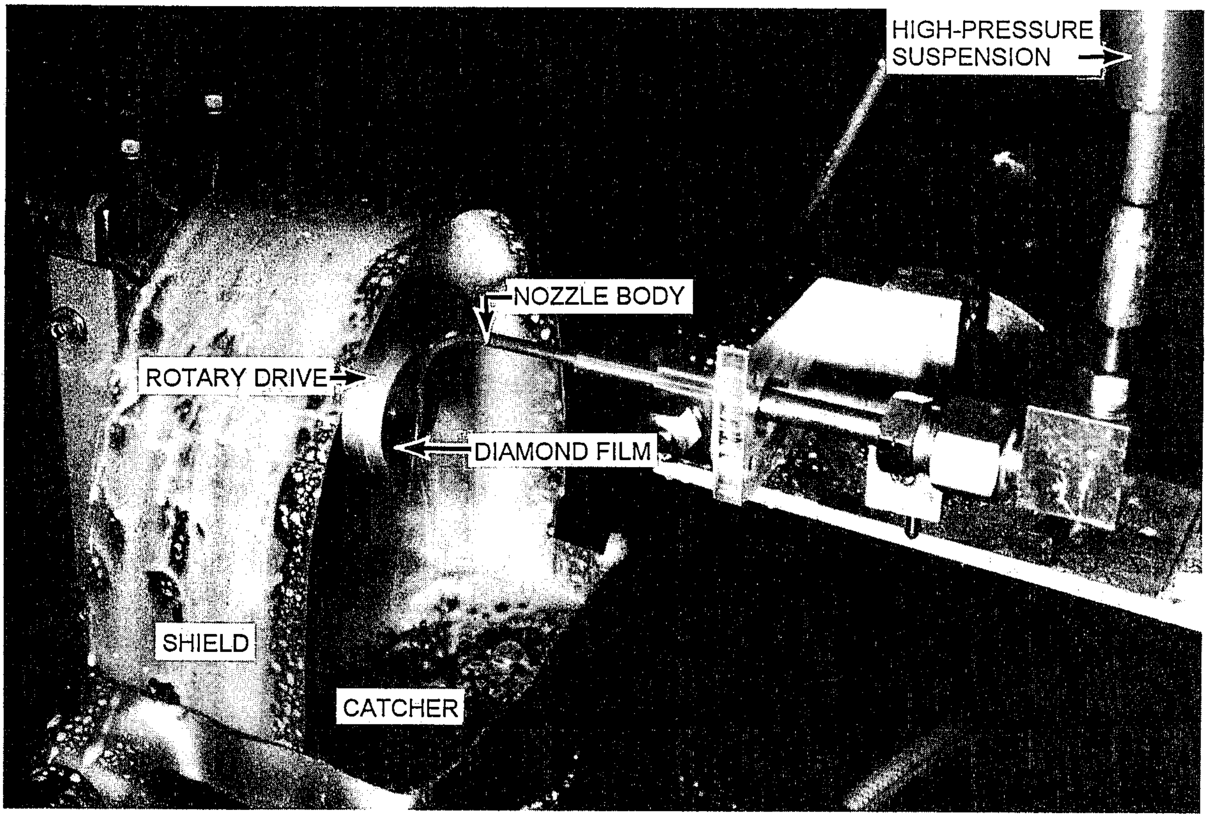
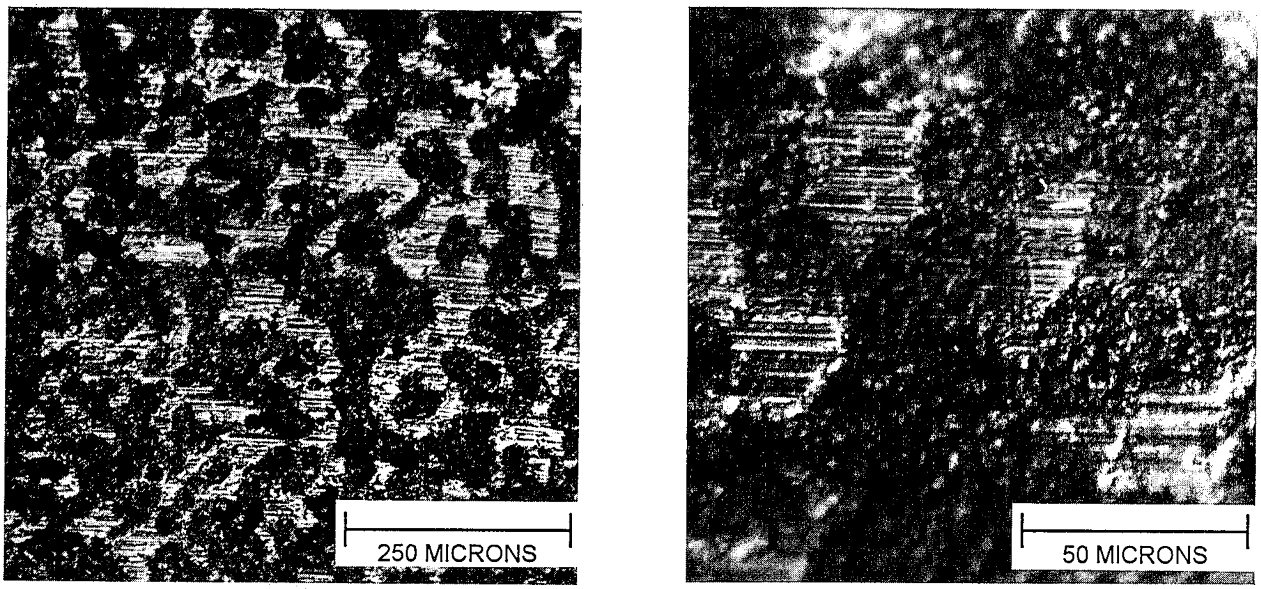


Figure 2. Polishing Nozzle



100x MAGNIFICATION

500x MAGNIFICATION

Figure 3. SiC Surface Polished with Radial Flow Technique

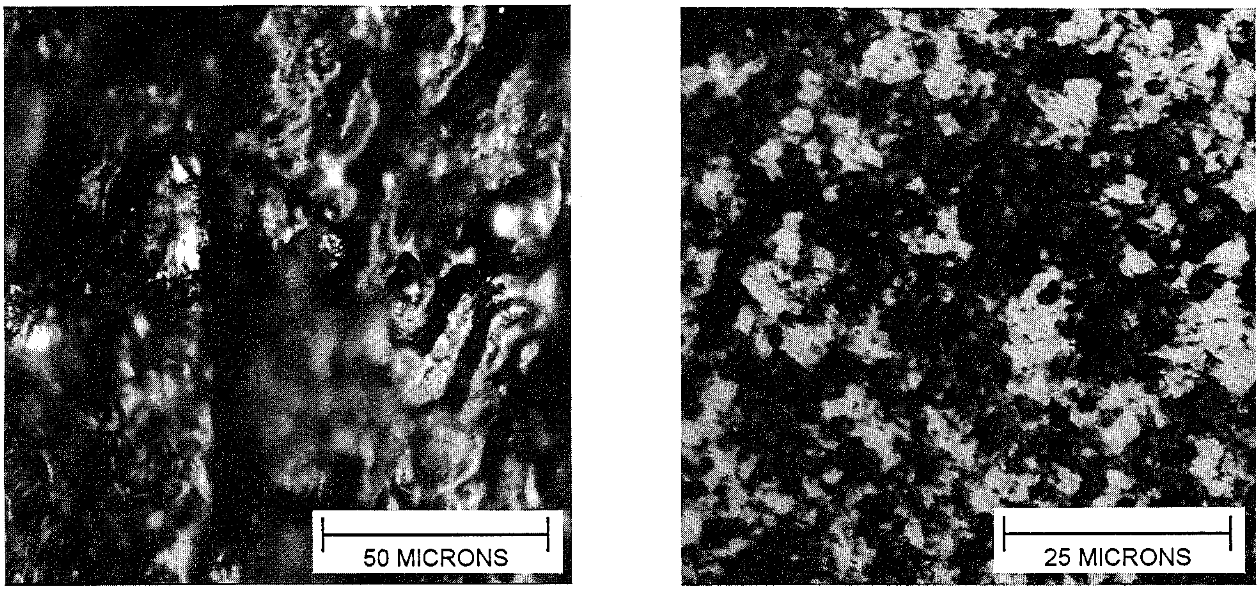


Figure 4. Progression of Polished PCD Surface Over Time Using Radial Flow Technique

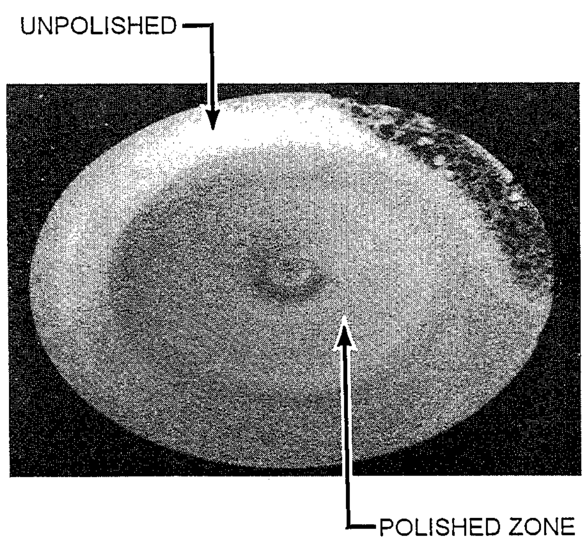


Figure 5. PCD Sample Polished with Radial Flow Technique

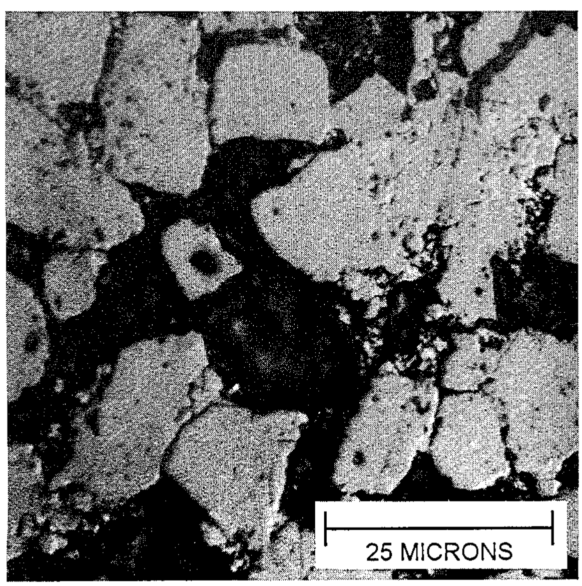


Figure 6. Surface of Diamond Composite Polished Using Radial Flow Technique

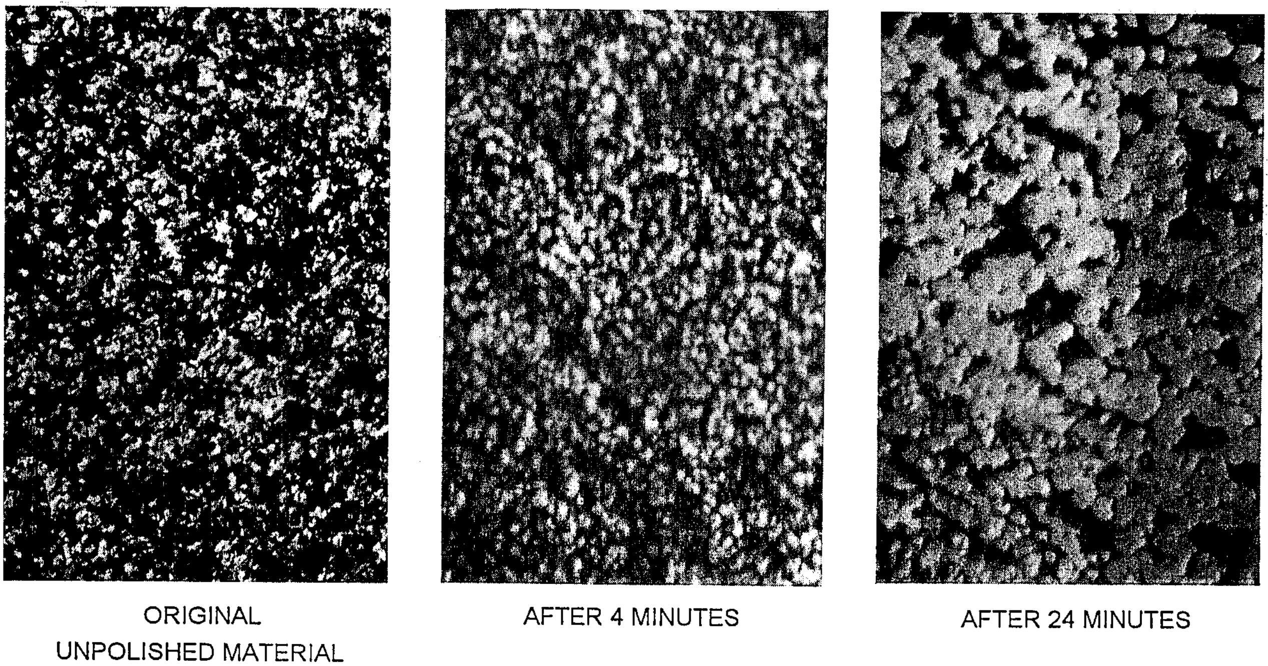


Figure 7. Progression of Polished CVD Surface Over Time Using Radial Flow Technique

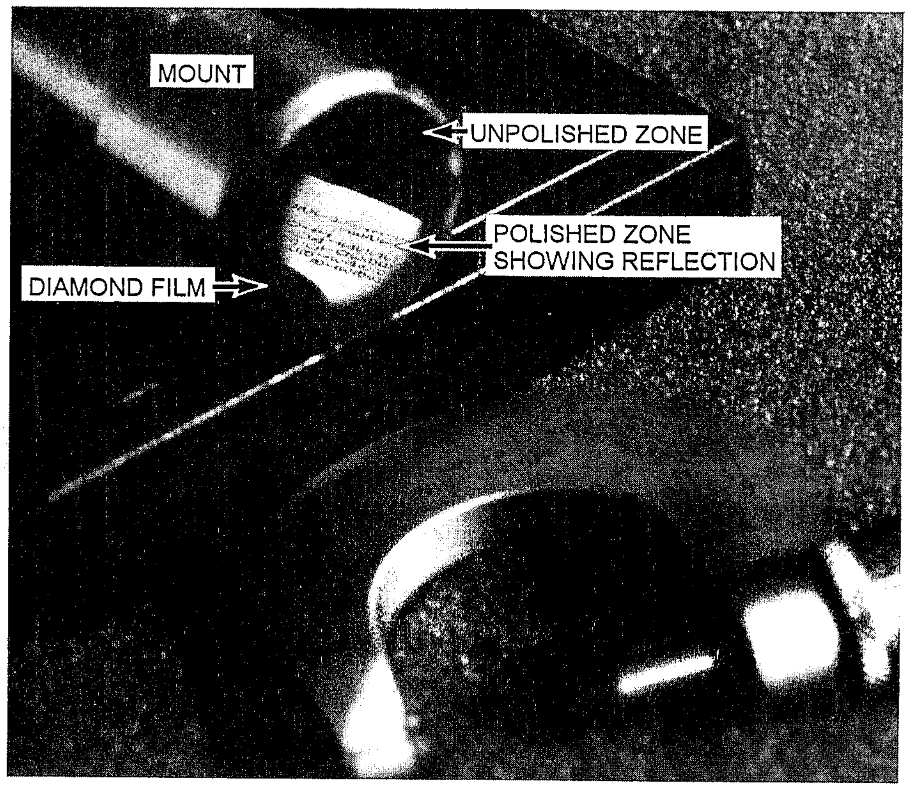


Figure 8. Polished CVD Sample with Reflection of Micrometer Scale in Polished Zone

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Paper 60

MACHINING OF TITANIUM USING WATER JET ASSISTANCE THROUGH THE INSERT

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ABSTRACT

A new machining system called Jet Assisted Machining (JAM) has been developed for the turning of titanium. It utilizes a high pressure water jet as both a source of coolant and a hydraulic chip breaker. Titanium has traditionally been difficult to machine because of its poor thermal conductivity, and its propensity to leech cobalt and carbon from the tool at high temperatures during turning operations. The turning of titanium produces long, stringy chips which must be periodically removed from the machine, making the turning operation labor intensive. Flood coolant and low pressure water jet directed at the chip are unable to overcome the extremely high compressive chip loads near the cutting edge, where high temperature is concentrated. The JAM system directs a 50 KSI jet of water through the cutting insert very near the cutting edge, where compressive chip loads fall below 40 KSI (compressive loads from chip loading at the tool face are very high - up to 400KSI are reported at the cutting edge but they decline expontially). The jet lifts the chip from the rake face, introducing water into the hot zone, reducing friction and temperature at the tool/workpiece interface. The jet also breaks the chip into small segments, potentially allowing for unattended machining.

Tool life experiments run at speeds ranging from 130 to 610 SFPM, feeds from .005 to .010 IPR, and depth of cut from .100" to .150" indicate tool life improvement of an average of 500%. These results indicate a cost saving through higher machine operation productivity. Because of the segmentation of chips, the need for a continuously attended machine is eliminated, resulting in a labor savings. A combination of these savings make JAM very attractive to commercial application.

Organized and Sponsored by the Water Jet Technology Association.

1. INTRODUCTION

Machining of metals is one of the most erosive processes currently found in manufacturing practice. Metal cutting or machining is a material removal process where a very hard, wear resistant cutting tool of a special shape is driven against a moving workpiece and the surface of the work is removed as a metal chip. This process generates a finished product of higher value exhibiting tightly controlled surface dimensions. The environment at the interface between the cutting tool and the workpiece is one of extreme pressure and temperature. The cutting tool, usually a hard metallic carbide (WC) bonded with cobalt or a sintered ceramic material (Alumina or silicon nitride), is a consummable part of the machining process. If the time that the cutter can be effectively used, its "tool life" is increased, process effectiveness improves. Improvements are twofold. First by reduced tooling costs and increased production rate, both leading to lowered production costs. Second, through closer dimensional control of the finished product leading to a final product higher quality.

In the modern machine shop, improvement in part throughput is the driving force for high productivity. Typically, throughput is increased by increasing metal cutting speed leading to higher metal removal rate (in^3/min). Higher speed, however, lead to higher tool-chip interfacial temperatures that worsen the wear rate of the cutting tool. This high temperature wear problem is exacerbated in the machining of titanium aero-space alloy, in particular the Ti-6Al-4V α-ß alloy.

Many of the materials that have been classed difficult to machine (eg. nickel and cobalt super-alloy and hardened steels) have benefited from the development of stronger and tougher cutting tool materials. These tooling solutions have lead to dramatic improvements in productivity. Titanium alloys machinists, unfortunately, have not identified similar successful tooling solutions. Production cutting speeds are still limited to approximately 200 sfpm [1 mps] when using the most appropriate cutting tool material (C2 grade carbide) and recommended lubrication techniques at normal feeds and depths of cut. The problem in high speed machining of titanium results from rapid, thermally induced, tool wear due to the chemical activity and very poor thermal conductivity of titanium when compared to steels [6,7] The use of the modern super-hard tooling seems to provide only moderate tool life improvements [8,9]. Temperatures during the machining of titanium alloys (Ti6Al4V) are reportedly over 900°C at cutting speeds of only 60 sfpm (0.3 mps) [8].

One area that has shown promise for improving machinability in titanium is the use of high pressure lubrication systems that can force cutting fluids for lubricating and especially cooling into the rake face and flank of the cutting tool. In this paper, a technique being developed at the Advanced Manufacturing Center of Cleveland State University for the introduction of a very high pressure stream of lubricant -- water at 40-50 KSI -- into the tool chip interface, will be described. The lubricating and cooling stream is conducted through the cutting tool itself for discharge at a location very close to the edge of the tool. This high pressure stream, in addition to providing a flow of coolant into the hot zone of the rake face, can also break or "float" the chips above and off the tool face. Introducing the coolant in this area, and removing the chips from the rake face, significantly reduce the apparent temperature on the tool face. In addition, lifting the chip away from the tool face can interrupt the diffusion cycle which is observed when cutting titanium [10]. This diffusion cycle is particularly dangerous during machining of titanium alloys as it transports tool constituents away from the flank and rake face of the cutter and into the chip, accelerating tool wear.

2. THE METALLURGY OF TITANIUM

2.1 Metallurgical Structure

Much of the difficulty in machining titanium alloys can be related to the metallurgical structure and chemical reactivity of the titanium alloys themselves. When cutting the α-ß titanium dual-phased alloys, different cutting tool loading conditions (cutting forces) are observed as the cutter passes from the hexagonal close-packed α phase through the body centered cubic β phase. This force variation, which occurs on a microscopic scale, may be quite small, but it can lead to microscopic chatter [15]. These changes in tool loading may cause problems on the tool edge and, under extreme conditions, even lead to edge chipping and eventual cutting tool fracture.

A second problem, a rapid temperature increase as the chip is formed (primary shear), leads to high tool temperatures. The temperature at the tool-chip interface is further elevated by secondary shear as the chip slides or "shears" across the rake face of the cutting tool. Since the thermal conductivity of the titanium alloy is poor, most of the thermal energy developed during machining is concentrated within the chip and is then absorbed by the tool. It is reported that as much as 80% of the heat generated during adiabatic shear can be absorbed by the tool [11] (compared to estimates of 30 - 60% of the generated heat being absorbed into the tool during cutting of steel [16]). These elevated temperatures lead to mechanical softening of the cutting tool and the possibility of plastic deformation of the tool edge. Should the tool edge be deformed, it can be rapidly worn away through contact with the workpiece or be fractured under the cyclic loading.

The combination of high interface temperature and chemical reactivity of titanium causes a third tool wear problem. As the temperature mounts over the contact area of the tool rake face, where intimate contact between the tool and chip exist, the diffusion of carbon and cobalt atoms from the C2 carbide tool and into the chip is favored. This atomic diffusion, which can be very rapid at chip-making temperatures, leads to depletion of tungsten carbide and the cobalt bonding material. As cobalt is removed, many grains of carbide can simply pull away from the tool and be dragged off with the chip. These sharp grains can further abrade tool material as the chip slides up the tool face leading to even more wear. Many researchers have shown that the diffusion of carbon and cobalt, as a result of the chemical activity of titanium and its alloys during machining, is a very important, if not dominant, wear mechanism in carbide cutting tools used to machine titanium alloys [9].

3. IMPROVING TITANIUM MACHINABILITY

It has been suggested that the best way to improve titanium machinability is through the addition of copious amounts of cutting fluids. The environment at the rake face of the cutting tool during machining (high contact pressure and temperature) make effective coolant coverage difficult. Therefore, a high pressure delivery system seem the best answer to achieve machiniability improvements for titanium alloys. Several elevated pressure coolant systems have been developed to try to overcome the severe conditions encountered at the rake face [11,20,21,22,23,25]. All of these systems, employ a remote nozzle location to target the coolant stream on the tool/chip interface. The system described in this paper is designed to force the water jet coolant stream directly into the tool chip interface through the cutting tool itself. The specially designed tooling incorporates an EDM-drilled jet channel that is angled through the C2 carbide insert to terminate in the tool/chip contact region very close to the cutting edge, see figure 1. The EDM channel geometry, a complex solid angular solution is controlled by four parameters: the elevation angle α, the asimuth angle **ß**, nose offset **T** and cutting edge offset **L**. A schematic of the modified cutter is presented in Figure 2. This system has been designed to provide a positive source of coolant, at sufficient pressure to break chips, right at the tool face where it is most needed to cool the tool body and interface region. Of course, cooler tools mean longer tool lives and less chance of plastic deformation of the tool edge, resulting in improved work piece properties and extended tool life.

4. EXPERIMENTAL DESCRIPTION

4.1 Experimental Conditions

The equipment utilized during titanium machining experiments is shown in Figure 3. An Ingersoll Rand water jet pump (maximum pressure of 55 KSI) provided a one gallon per minute stream of high pressure water to the modified, left hand, carbide tool holder by way of a 0.012 inch diameter sapphire jet nozzle located in the tool holder, see inset in figure 3. This 1 gpm water flow rate is significantly less than encountered with other advanced cooling systems, greatly reducing the volume of mist developed. A high pressure flow control valve is located directly prior to the tool holder. Machining experiments were performed on both a 5 horsepower and the 30 horsepower lathe seen in figure 3. Cutting speeds were varied from 130 to 600 surface feet per minute at 2 different feed rates and depths of cut. For operational safety, the tool holder was mounted in the reverse position (up-side down) to guarantee that the high pressure water jet was always pointed into the lathe bed. This safety consideration also required that the lathe be operated with reversed rotation.

All jet machining tests were compared to traditional (flood) cooling operations. Tool wear, tool life, machining forces and chip characteristics were evaluated at all experimental conditions.

5. EXPERIMENTAL RESULTS

5.1 Tool Wear, Failure Modes and Tool Life

Tool wear was microscopically evaluated at frequent intervals during testing. Specific results can be found in Lindeke, et al. [1,2]. The observed tool lives for both the JAM and flood cooling tests are presented in Table 1. The measured tool lives with Jet Assisted Machining increased, on the average, by 500% over the same flood cooling conditions.

Taylor tool life, a predictive equation for tool life at various speed and fixed feed and depth of cut is often used as a conveient comparison technique for various tooling solutions. Table 2 lists taylor constants n and C for the tool life equation:

$$VT^n = C$$

where:

- V -- cutting speed in sfpm
- T -- tool life in minutes
- n -- Exponent with a major dependence on tool material
- C -- Constant which depends on cutting parameters and work material

Figure 4 is the Taylor tool life plot of various cutting geometries while machining Ti6Al4V at a feed of 0.010"/revolution and a depth of cut of 0.100". The benefits of JAM in reducing the difficulty of machining Ti6Al4V are clearly evident for all cutting conditions. Cutting speeds, and hence productivity, could be increased 1.5 to 2 times with JAM tool lives equal to those of flood cooling.

In recently conducted optimization tests, it was found that channel conditions that provided a terminous close to the tool tip (T offset) and angled closer to the feed direction (ß angle) and more steeply to the rake face (α angle) provided the best tool life. Choosing the optimal channel geometry incresed the performance characteristics compared to the geometry reported on earlier [1]. Tool life for this cutting condition (at 0.10 feed and .100 doc) is included in Tables 1 and 2 and included on the tool life plot in figure 4. Further improvement over flood cooled cutting operations would be expected using this geometry.

5.2 Chip Characteristics and Control

On a macroscopic scale JAM is effective as a chip breaker (Figure 5). Under all cutting conditions when the T offset was controlled, the high pressure through-the-insert jet broke the chips into small fragments. At identical cutting conditions, long, stringy chips, resulted during flood cooled machining tests. This chip control is the result of the jet lifting the chip off the rake face and bending it until it fractures. The T offset geometry parameter was found to be critical in achieving acceptable chip control and at setting of T that exceeded the depth of cut by more than about 25%, fragmented chips could not be produced.

6. CONCLUSIONS

In this paper, a technique designed to provide effective cutting fluid flow to the rake face of a carbide cutting insert was described. This technique was found to be particularly effective for machining of titanium alloys. The approach to cooling and lubrication represents a radical and very effective departure from earlier coolant lubricant delivery systems that are operated at high pressure. The system described takes maximum advantage of the ultra-high pressure capabilities of a 55 KSI water jet pump to deliver a stream of water directly into the rake face contact area through the cutting insert itself. The small diameter and very powerful jet stream passes through the insert body via a jet channel 0.030 to 0.050 inches in diameter, that is EDM drilled at a compound acute angle in the carbide. This high pressure stream provide by a water jet pump, strikes the underside of the chip at a point very close to the cutting edge of the insert. Coolant stream placement here bends and floats the chip off the rake face. The stream also lowers the interface temperature as well as the temperature of the body of the insert itself. The cooler insert contributed to increased tool life and higher useful cutting speeds in turning operations on Ti6Al4V alloy.

Experimental studies employing this breakthrough cooling lubrication delivery system have been conducted and summarized here. Machining tests were conducted over a wide range of cutting conditions: speeds from 130 to 600 sfpm, feeds of 0.005 and 0.010 ipr and depths of cut of 0.100 inches and 0.150 inches. Tool life testing and force monitoring were performed on cutting inserts that employed the JAM technique of fluid application. In addition, each test condition was compared to a machining operation that used only traditional flood cooling techniques. Tool lives, cutting forces, and tool wear histories as well as chip production methodology were studied. Specific conclusions are summarized below:

1. Tool lives when cutting Ti6Al4V alloy, were increased by more than 1000% when JAM was used, compared to traditional flood cooling during harsh, but high productivity, cutting tests.
2. Cutting speed could be increased 1.5 to 2.5 times and have similar tool lives with JAM compared to traditional flood cooling.
3. Using JAM conditions with channel geometries that are "original" and "optimal", chips were fractured under all machining conditions tested. Chip fracture was the result of the water jet pressure on the back of the chips causing severe chip bending. Fractured chips would allow unmanned operations in machining Ti-alloys.
4. Using JAM, the high pressure water flow was less than 1 gpm at 40-50 KSI. The misting problem typical of other high pressure lubrication systems was greatly reduced.
5. Tool life was found to be optimal for channel geometries that a steep and toward the feed direction.
6. Chip control was found to depend on the L-offset parameter. If L greatly exceeds the depth of cut, chips can not be broken.

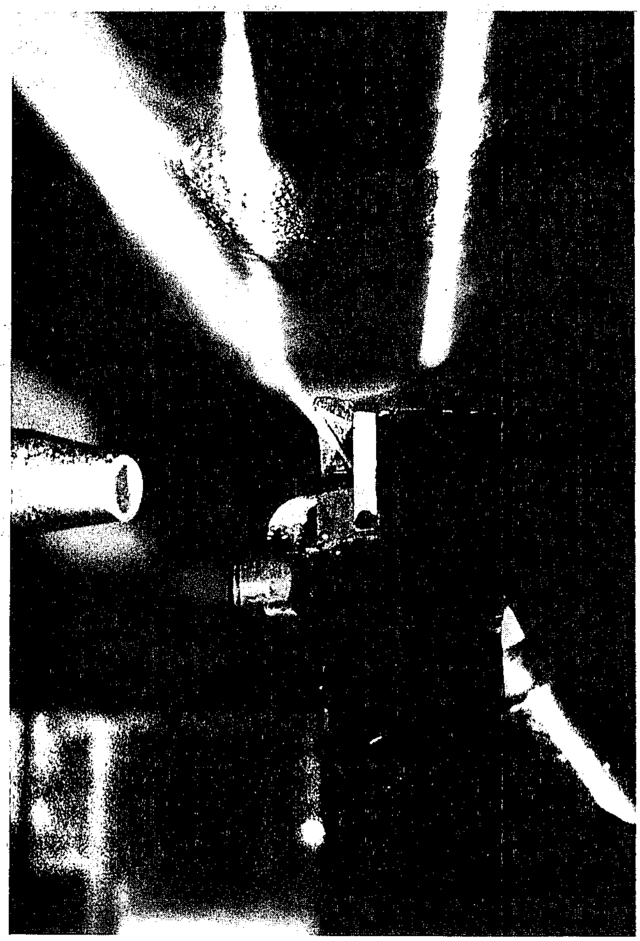


Figure 1: Photograph of the water stream exiting the carbide cutting tool rakeface

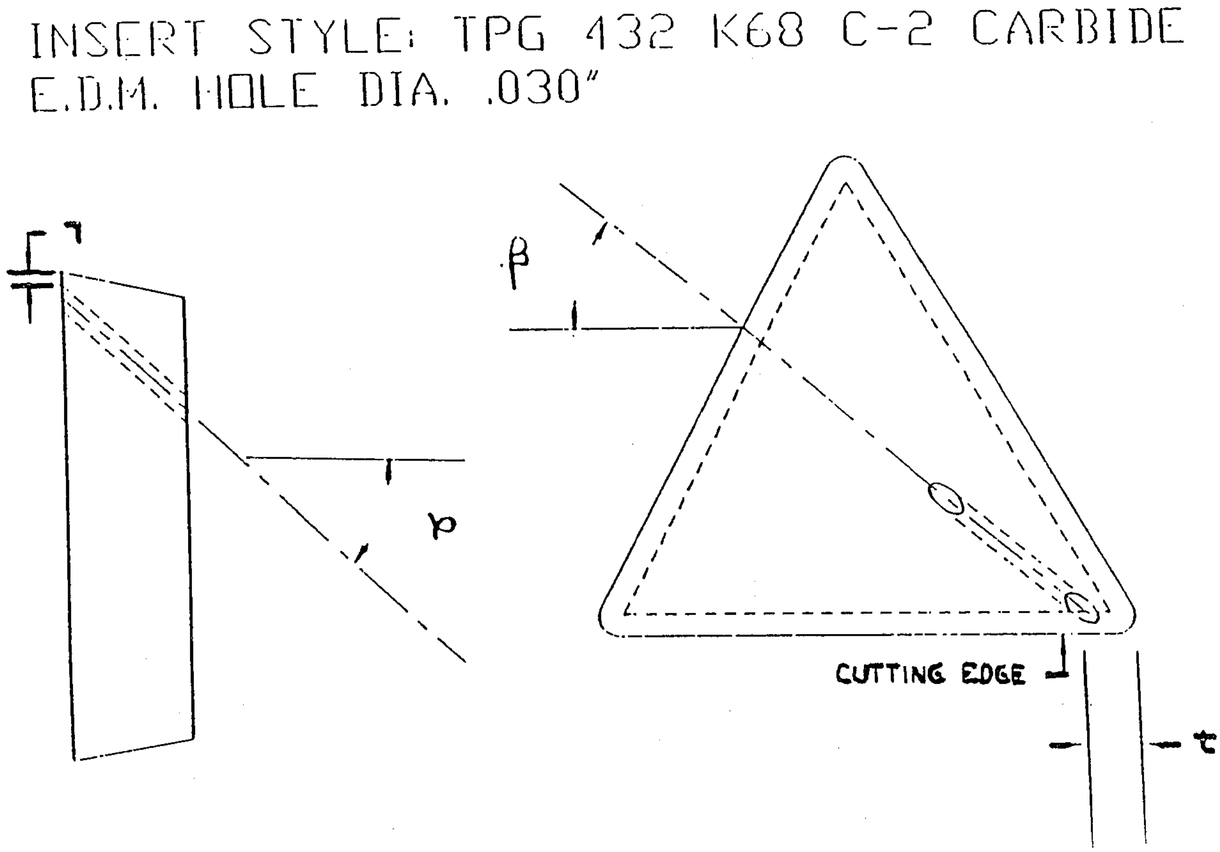


Figure 2: Schematic of the modified triangular carbide cutter. α is elevation angle; ß is asimuth angle; T is tool nose offset; L is cutting edge offset.

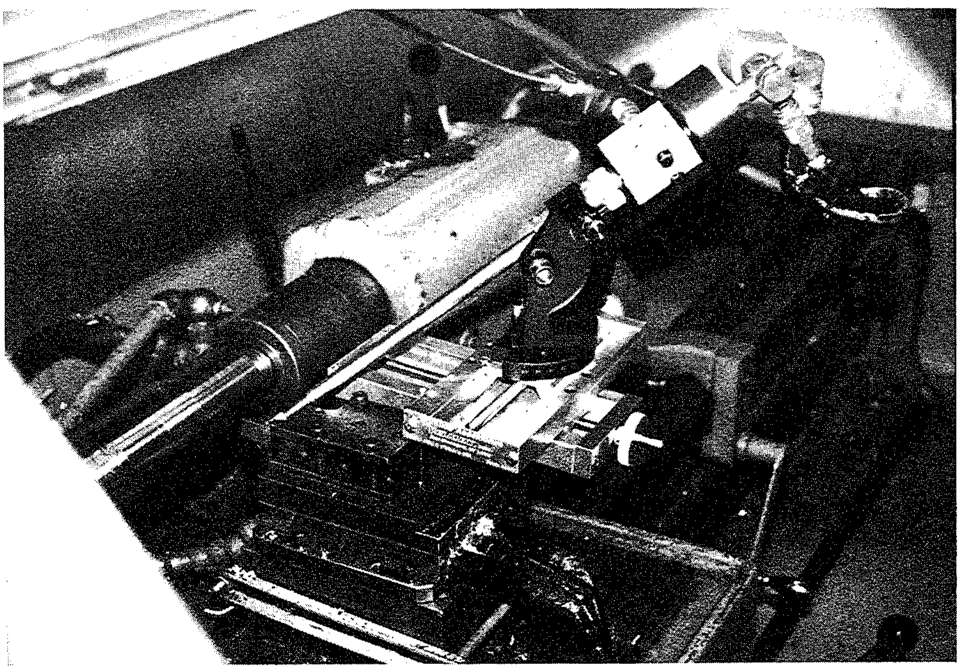


Figure 3: Photograph of the laboratory experimental setup. Note Jet pump, 30 hp lathe and modular jet delivery system (insert)

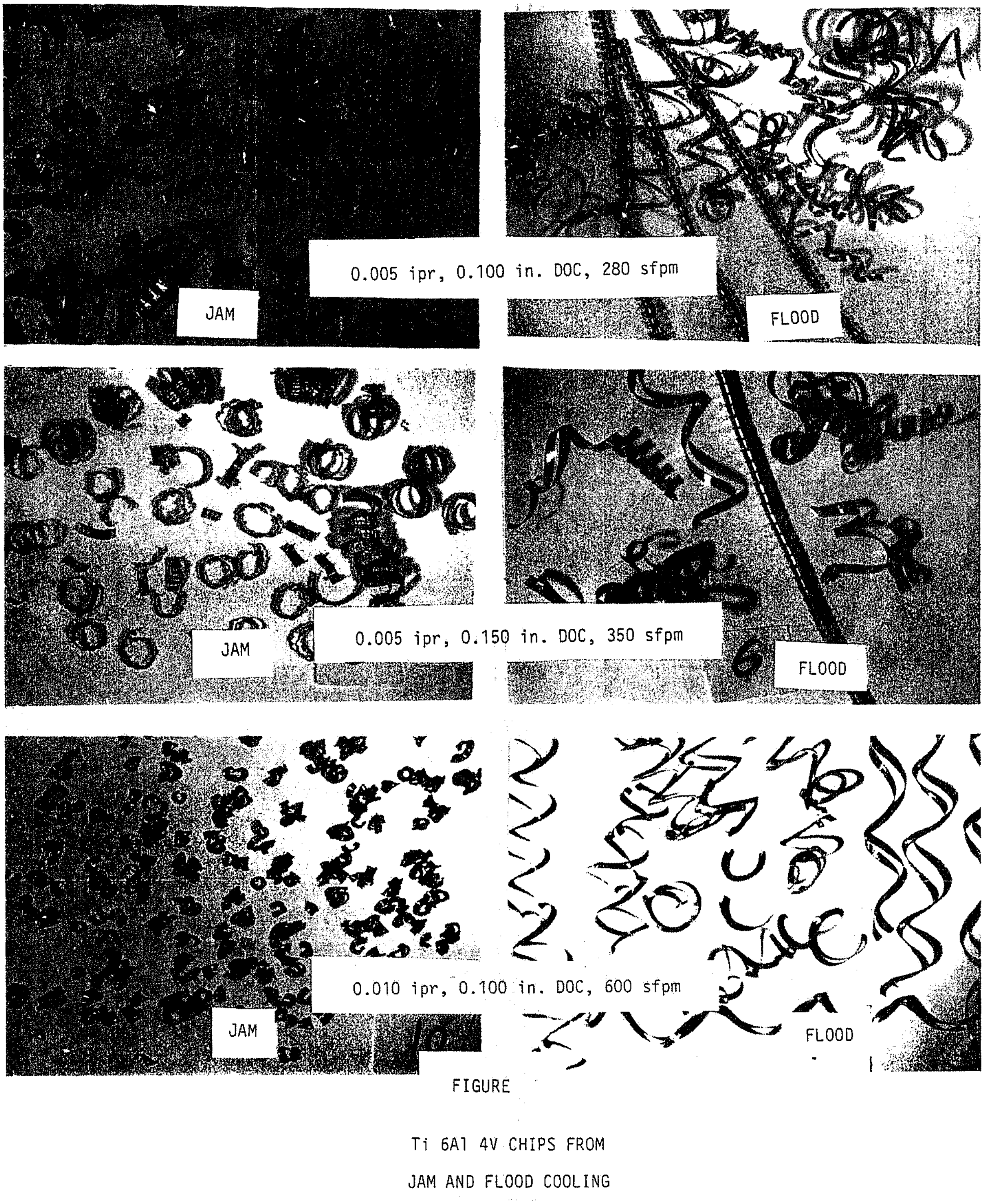


Figure 4: Typical fragmented chips (a) produced using JAM vs chips produced during Flood cooled operations (b)

TABLE 1: Observed Tool Lives for machining Ti6Al4V alloy with C2 carbide tools

Condition	Channel Geometry	Speed(sfpm)	Feed(ipr)	DOC(inch)	Tool Life (min.)
JAM	"original"[a]	350	0.005	0.100	15.5
Flood		350			3.0
JAM	"original"	600			2.75
Flood		600			1.0
JAM	"original"	350	0.005	0.150	17.50
Flood		350			2.50
JAM	"original"	600			2.00/1.20
Flood		600			0.63
JAM	"original"	350	0.010	0.100	5.85/5.5
JAM	"optimal"[b]	350			8.20
Flood		350			1.93/2.00
JAM	"orig"/0.030[c]	500			4.00
JAM	"optimal"	500			3.60
Flood		500			0.13
JAM	"original"	600			1.00/1.15
Flood		600			0.08/0.07

[a] Original Channel: α: 46°, ß: 41°, T: 0.120, L: 0.060, Dia: 0.050"

[b] Optimal Geometry: α: 40°, ß: 50°, T: 0.080, L: 0.060, Dia: 0.030"

[c] Orig/0.030: same as ([a]) except channel diameter is 0.030"

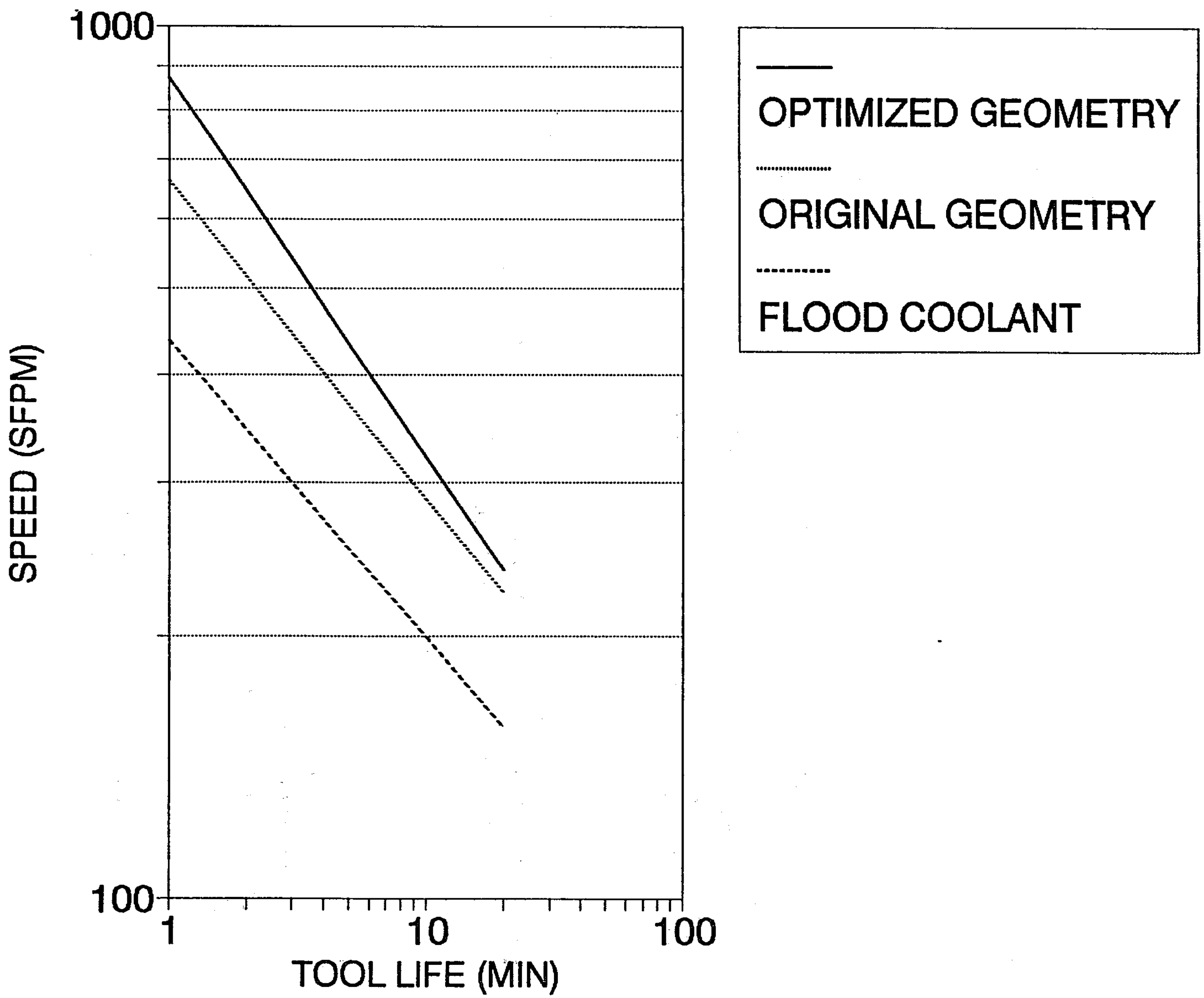
TABLE 2: "Taylor Tool Life Constants for Various Tooling Conditions turning Ti6Al4V, feed: 0.010ipr; DOC: 0.100"

$$VT^n = C$$

TOOL Identification	n	C
0.050" dia Org. Geometry	0.344	617[d]
0.030" dia Org Geometry	0.362	664
Optimized Tool Geometry	0.433	871
FLOOD Cooling	0.343	438[d]

[d] extracted from Lindeke, Schoenig, et al [1]

Figure 5: Taylor tool life plot for Ti6Al4V at feed: 0.010ipr, DOC:0.100 for Various JAM tools and flood cooling operations.



7. ACKNOWLEDGEMENT

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Paper 61

THE REMOVAL OF EXCESSIVE RESIN FROM SEMICONDUCTOR LEADFRAMES WITH SPOT-SHOT WATERJETS

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ABSTRACT

Integrated circuits are commonly protected by resin encapsulation. The excessive resins leaked out from the metal mold during encapsulation process must be removed in order to secure an acceptable package quality---the lead finish. Waterjetting can successfully be used for this excessive resin removal (usually called "deflashing") and is recognized as the most feasible solution to other currently used techniques such as chemical and media blasting in this time of increasing environmental concern. Furthermore, the precisely controlled SPOT-SHOT waterjets with high oscillation, can effectively remove this excessive resin on fine-pitch leadframes with high lead count and thin, fragile packages. The removal of the annoying small, tightly lodged "dam junk" particles (hereafter called "dejunking"), which is not usually successfully accomplished by means other than die punching, can also be accomplished by use of this system. The proper conditions for removal of dam junk, however, are determined only experimentally by trial and error, at present. This approach is time-consuming and inappropriate in many occasions for fine-pitch leadframes. In order to overcome this problem, a new concept which can evaluate the "likelihood" of dejunking with oscillating waterjet has been introduced and the validity of the concept was confirmed by waterjet testing.

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1 INTRODUCTION

Excessive resins, which leak out from the metal mold to the surface of the leadframe during the encapsulation process of semiconductors, are distinguished into resin bleed, flash and dam junk by their color, thickness and location as shown in Fig. 1. Resin bleed is thin and transparent, whereas flash is darker and thicker. Dam junk is formed in the area between the package, the leadframes and dam bar. (The dam bar is a part of the leadframes which stops the mold compound from flowing out between leads [1].)
The removal of excessive resins, or "deflashing", has been accomplished mainly with chemical, dry and wet media blasting methods for more than 20 years. Waterjet deflashing is a comparatively new technique whose substantial development has started in the late 1980s. The cleaner operating environment and lower operating cost of waterjet deflashing attracted customers to employ this new technique.
The ability to remove dam junk, or "dejunking", is another important feature of waterjetting. This dejunking is not usually successfully accomplished by other than die punching. The SPOT-SHOT waterjet, whose accurate control of the waterjet allows it strike only the target area, enabled the system to precisely target dam junk. The softer resin package of any type of the integrated circuit is avoided and not subjected to hazard.

Rapid progress has been made recently for the development of plastic QFP (Quad Flat Package) with a very fine lead pitch and high lead count. Figure 2 and 3 show the typical configuration of QFP and their development plan [2] respectively. Leadframes with 0.5 mm lead pitch are currently being treated on a production basis and leadframes with 0.4 mm and even 0.3 mm lead pitch will be available for routine commercial production soon.
This progress, however, has generated new technical problems. One of these problems, the quality of the lead finish, is an industry-wide concern. In order to achieve satisfactory lead finish, the leadframe must be free of resin. The precisely controlled SPOT-SHOT waterjets, which do not strike the package as dry and wet media blasting do, can effectively remove all resin, including dam junk, from fine-pitch leadframes with high lead count and thin, fragile package.
At present, however, adequate deflashing and dejunking conditions must be determined experimentally by considering the effects of scores of parameters, such as pressure, flow rate, traverse speed of waterjet etc., for each kind of leadframe.
This empirical trial and error method of selecting the appropriate waterjet conditions is time-consuming and sometimes impossible for fine-pitch leadframe deflashing.
Consequently, a basic understanding of the mechanics of dejunking for fine-pitched ICs is mandatory. Using oscillating nozzles for

(a) wider area coverage by a single nozzle and (b) compensation of the misalignment between waterjet and the target area, may further make the selection of the conditions difficult. One of the shortcomings of using an oscillating nozzle is the appearance of swirl patterns on the waterjet locus when faster traverse speed is required for higher production. Due to the swirl patterns, the waterjet does not strike the target area uniformly, causing irregularities in the dejunking.
In order to eliminate these dejunking irregularities, an appropriate method, based on a new concept: the "likelihood" of dejunking with oscillating waterjet, has been introduced.

2 PURPOSES OF DEFLASHING

The recent trend toward fine-pitch leadframes has resulted in a requirement for increased scrutiny of plating quality and coverage. The bending point of the lead continues to approach closer and closer to the resin package. In order to achieve high-quality plating, lead surfaces must be free of resin, flash and junk. Resin contaminated surfaces results in the following problems:

- Inferior plating quality due to the interference by flash and resin bleed
- Solder bridging
- Inferior lead coplanarity
- Lead deformation during trimming and forming of leadframe
- Damage to the metal mold
- Circuitry failure caused by the detachment of resin particles (bleed and junk) during the mounting process.

3 ADVANTAGES OF WATERJET DEFLASHING OVER OTHER TECHNIQUES

Waterjetting compares favorably to other methods of deflashing in the following ways:

- Environmental impact is reduced by the use of abrasive-free water.
- Health dangers (silicosis) to employees are eliminated.
- Operating cost are dramatically reduced by the elimination of solid media.
- Dejunking is possible by using SPOT-SHOT waterjetting alone or in combination with pretreatment.
- Thin mold packages and fine-pitch leadframes can be dejunk ed and deflashed.

4 WATERJET DEFLASHING SYSTEM

4.1 Waterjetting System

Waterjetting systems are classified into the following two groups:

- Total surface waterjetting systems
- SPOT-SHOT waterjetting systems

As the name implies, in the total surface waterjetting system, waterjets strike the target surface area of the leadframe.
In the SPOT-SHOT waterjetting system, the waterjet can be accurately directed to the target area. Therefore, this system is well suited for the deflashing, as well as dejunking, of leadframes with fine-pitch and thin packages.

4. 2 Total Surface Waterjetting System

Total surface waterjetting systems are used for the removal of the resin bleed and flash of transistors, diodes and ICs.
The system consists of the high pressure water delivery pump unit and deflashing equipment. Figure 4 shows the mechanism for total surface waterjetting, which consists of the leadframe clamping mechanism, the transport belt and the oscillating nozzles. Each leadframe is tightly clamped on one side of the frame by the clamping mechanism at the entrance to the deflashing chamber. The other side of the frame slides along the guide rail when the transport belt moves. This clamping mechanism is attached to the transport chain belt which carries the leadframes from the entrance to the exit through the waterjetting and blow-drying stations in an in-line fashion. Figure 5 is an automatic total surface waterjetting machine. Figure 6 shows the deflashing of IC with total surface waterjetting.

4. 3 SPOT-SHOT Waterjetting System

The SPOT-SHOT waterjetting system is a breakthrough in deflashing techniques. As the pitch of leads becomes narrower and packages become thinner, deflashing without any lead deformation or package damage becomes increasingly difficult. Finer pitch leadframes make it also more difficult to remove dam junk by any means. This difficulty is eliminated or considerably reduced by SPOT-SHOT waterjetting. Figure 7 shows the SPOT-SHOT waterjetting with an oscillating nozzle, a multi-orifice nozzle is normally used to remove excessive resins from all packages on one leadframe at the same time in order to increase productivity. Figure 8 shows the cross-sectional drawing of the oscillating nozzle. The patented mechanism enables the unit to obtain the same jet locus for each of the multi-orifice jets while the nozzle is oscillating. The nozzle is installed on the X-Y table which is driven by precise pulse motors and guided by a programmable controller, thus the waterjets can accurately strike the target area.

Figure 9 shows see-through view of the SPOT-SHOT waterjetting machine. SPOT-SHOT waterjetting provides precise target area positioning, a stable leadframe transport system and a programmable nozzle system which follows the exact paths designated by the user. Figure 10 shows the example of the dejunking of fine-pitched QFP 160 with 0.65 mm lead pitch.

5 DEJUNKING (REMOVAL OF DAM JUNK) WITH OSCILLATING WATERJETS

5.1 Basic Model of Dejunking and their Patterns

When a theoretical analysis of dejunking by waterjet must be established, it is necessary to consider the basic mechanical model for it. The basic model can be defined by replacing the waterjet with the locally distributed static force shown in Fig. 11 and which corresponds to the case when the resistance force of dam junk against removal is measured with a mechanical micro press. In this case, if the dam junk is stiff enough, the perpendicular force acting on the dam junk is transmitted through dam junk to the boundary surface between dam junk and surrounding leadframe but if dam junk is not stiff, it breaks into a few pieces by internal stress. Thus the process of dejunking can be divided into following two patterns in order to simplify the further analysis.

pattern (A) : The dam junk is pushed off from the leadframe as if it slides on the boundary surface, maintaining the entire shape of dam junk.
pattern (B) : The dam junk is broken into a few pieces and removed , occasionally leaving some of fragments still attached to the leadframe.

The dejunking pattern can be predicted, empirically, by the configuration of the dam junk, i.e. the thickness, length and breadth. Figure 12 shows the classification of the above mentioned dejunking patterns. Among them, the pattern (A) corresponds to the leadframes of narrower pitch, which are regarded with more interest because this is the current trend of the development of IC devices. Therefore, the dejunking mechanics of the pattern (A) will be analyzed here.

5.2 Mechanics of Dejunking

In the case of the pattern (A), the dejunking can be assumed to be initiating at the point of the highest shearing stress level at it boundary and then separation propagates as the force continues to act on its surface, though the exact mechanics of the separation has not been clear. Figure 13 is the enlarged

photo of the boundary surface of a mass of dam junk which was not removed by waterjetting but the damage by waterjet can be clearly observed along the boundary. This suggests that the above assumption of dejunking process might be correct with much certainty.
Strict analysis of the dejunking process must also take into consideration the adhesion of the epoxy resin which constitutes the dam junk to lead metal for each dam junk mass, including the effect of irregularities of their surface shape and roughness on the adhesion. Figure 14 shows enlarged photos of the cross section of leads between which dam junk is lodged. Irregularities on the surface, such as taper and roughness, can be observed. Because of these irregularities, the resistance force against removal varies by a factor of three to four when measured by micro press. Actually however, this strict analysis is impractical and therefore more simple analytical method should be introduced.

5.3 "Effectiveness" of the Force acting on a Dam Junk with Waterjet

A concept of the "effectiveness" of the force acting on the dam junk with waterjet will be introduced and then by using it, the "likelihood" of dejunking will be evaluated. This is considered to be independent of the properties of each dam junk or lead, in order to simplify the evaluation of dejunking in practical application. Due to elasticity of the epoxy resin, the stress distribution at the boundary differ depending on the position where the force is applied. Figure 15 shows the waterjet induced stress distribution calculated with FEM (Finite Element Method). This difference of stress distribution means that the force, even if having the same magnitude, has different effect on the separation of dam junk depending on the points which are determined by jet locus.
In this simplified method, it is assumed that dejunking is determined by the total shearing force acting on the boundary surface and jet impinging duration time on the dam junk.
This assumption is based on the empirical knowledge that the dejunking initiates at the boundary (but not at the root of dam junk) in almost all cases and also the dejunking can be improved by decreasing a jet traverse speed even when applied force is considerably small. Based on the discussions above, the "effectiveness" of the force induced by waterjet can be expressed by the weighting coefficient mentioned below.

The surface of dam junk is divided into small elements and the weighting coefficients are calculated for each element as the multiplication of the following two coefficients: (a) stress weighting coefficient which is based on the stress distribution at the dam junk boundary obtained by the FEM analysis and (b) area weighting coefficient which is defined by the equation (1),

which indicates the coverage of jet core area over dam junk.
In Fig. 16, the stress weighting coefficient of dam junk is shown for a QFP (Quad Flat Package) type LSI used for this study.
In Fig. 17, the coverage of jet core area over dam junk is shown. This will change with the movement of nozzle center. The area weighting coefficient is calculated for each computation time step in accordance with the coverage conditions.

$$C_{i\,area}=\frac{A_i^*}{A} \qquad (1)$$

The weighting coefficient, which indicates the "effectiveness" of the force induced by waterjet, is expressed as the multiplication of these two coefficients for each computation time step.

5.4 "Likelihood" of Dejunking with Oscillating Waterjet

The "likelihood" of removal for individual dam junk can be evaluated with the weighting coefficient defined above in combination with the determined jet locus, which is expressed as a series of points shown in Fig. 17.
According to the assumptions on a dejunking mentioned in 5.3, the dejunking "likelihood" can be expressed by the following "dejunking ratio" (hereafter called DJR).

$$DJR=\sum_{i=0}^{n} C_{i\,stress}\times C_{i\,area}\times\frac{100}{n} \qquad (2)$$

Where,

$C_{i\,stress}$: stress weighting coefficient derived from stress distribution (constant within one element)

$C_{i\,area}$: area weighting coefficient derived from jet coverage (computed at each time step)

n : total number of the points that compose the jet locus for one dam junk

Computations of DJR were made for 50 continuous dam junk masses and the average of these were considered as the representative

DJRs. The jet loci were calculated with the following parameters.

- traverse speed : 10, 20, 30 mm/s
- eccentricity : 0.2 mm
- nozzle oscillation : 1800 rpm
- nozzle center position : 0.05 mm pitch taking the root of dam junk as 0-line

In this calculation, the deviations of the values of DJR were also considered. Because of the disaccord of lead pitch with the cyclic jet locus caused by nozzle oscillation, the values of DJR of each dam junk has deviations and these deviations are not negligible when jet traverse speed is set relatively high in order to get higher production. Although the distribution of DJR value was far from normal distribution, the standard deviation of individual DJR is calculated with in a range of ± σ in order to evaluate the deviation tendency. This is shown in Fig. 18. It is assumed that the higher values of DJR gives the more "likelihood" of dejunking by waterjet but it must be noted that the DJR defined above does not necessarily mean an actual possibility of dejunking. As DJR are defined based on the pattern of stress distribution and jet locus, it makes no sense to discuss only with DJR if a dam junk can be removed or not without the absolute value of the force to be applied.
It is the result of actual dejunking test that may finally decide the necessary intensity of the force; i.e. the water jet pressure, because the absolute value of adhesion strength varies with individual cases as is discussed in 5.2.

5.5 Dejunking Tests with the SPOT-SHOT Waterjet

Dejunking tests were conducted with the SPOT-SHOT waterjet in order to verify whether or not the "likelihood" of dejunking based on the above calculation correlates well with actual dejunking test results. The test conditions were described below and other conditions were the same as mentioned before.

- nozzle diameter : 0.18 mm
- pressure : 40, 45, 50 and 60 MPa
- stand-off distance : 40 mm

Test results are shown in Table 1 as a percentage of the numbers of completely removed dam junk over the total numbers of dam junks tested. The total number of the dam junk masses was 120 for each test.
Figure 19 shows the comparison between DJR values and dejunking test results tabulated in Table 1. As all dam junk masses were removed completely in the case of lowest traverse speed, 10 mm, it can be concluded that the DJR values for the nozzle center

position 1, 2, 3 are greater than the threshold condition of dejunking. In the case of 40 MPa pressure, however, the fact that no dam junk was removed suggests that the threshold force or minimum waterjet pressure exists in order to realize the dejunking independent of the DJRs. In the case of traverse speed 20 mm/s and pressure 60 MPa, though the nozzle center position 3 has higher mean DJR value than that of the position 1 as seen in Fig. 19 (b), the test result gives lower dejunking percentage. This is because, due to the larger DJR deviation, some of the dam junk in position 3 has a lower DJR value than the dejunking threshold value. This gives us an useful suggestion that the deviation of DJR, as well as the mean value, is also important for practical application. In fig. 19 (c), a good correlation is obtained between the dejunking percentage and calculated DJRs in the case of 30 mm/s traverse speed.

5. 6 Discussion

The comparisons between the calculated values of DJR and the dejunking test results described above, suggest that the method proposed in this paper seems to provide sufficient accuracy, from practical viewpoint, for the prediction of the "likelihood" of dejunking and thus the "effectiveness" of the force acting on a mass of dam junk by a waterjet. This analysis also suggests that not only the mean value of DJR but also the deviation of DJR is important. The nozzle center position should be selected where the deviation of DJR is as small as possible, even if the mean value of DJR may be reduced to some extent, in order to remove the dam junk without any residue. By evaluating the values of DJR, it may be possible to eliminate or considerably reduce the time-consuming selection of waterjet conditions by tedious trial and error adjustment of jet traverse speed, nozzle oscillating speed, nozzle position relative to target area, nozzle eccentricity etc.. Therefore, this approach is especially applicable to the deflashing and the dejunking of fine-pitch leadframes.

6 CONCLUSIONS

The deflashing and dejunking (removal of dam junk) of IC leadframes with high-pressure waterjets has been reviewed. As fine-pitch leadframes continue to be developed, the removal of resin bleed, flash and the especially annoying, small, tenacious dam junk becomes increasingly complicated and difficult. This difficulty was ameliorated considerably by the introduction of SPOT-SHOT waterjetting. The selection of the proper SPOT-SHOT waterjetting conditions, however, is time-consuming and inappropriate in many cases for fine-pitch leadframes because the selection is made experimentally by trial and error. In order to overcome this difficulty, an analytical method is presented in this paper. Though this method is not based on the strict analysis of fracture mechanics and gives only the "likelihood" of dejunking, it will be very useful not only for the selection of fine-pitch leadframe dejunking conditions but also for the development of the SPOT-SHOT waterjetting equipment for further finer-pitch leadframe dejunking.

ACKNOWLEDGEMENTS

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(Unit %)

traverse speed		10mm/s			20mm/s			30mm/s		
position of nozzle center		①	②	③	①	②	③	①	②	③
pressure (Mpa)	60	100	100	100	100	100	88	58	100	82
	50	82	100	100	57	78	75	29	98	75
	45	75	100	100						
	40	0	0	0						

Table 1 Test Results of Dam-Junk Removal

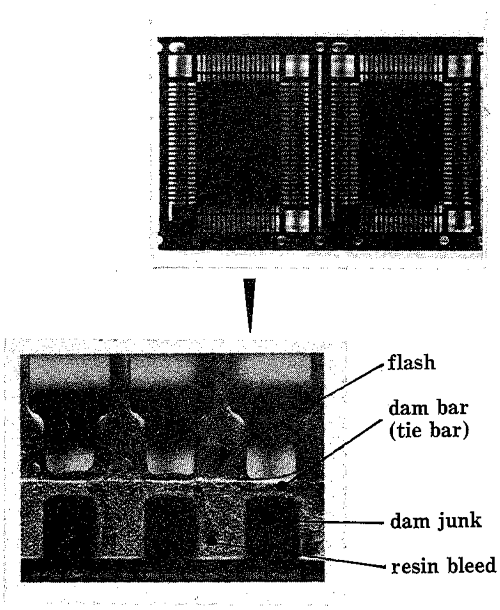


Fig.1 Definition of Resin Bleed, Flash and Junk

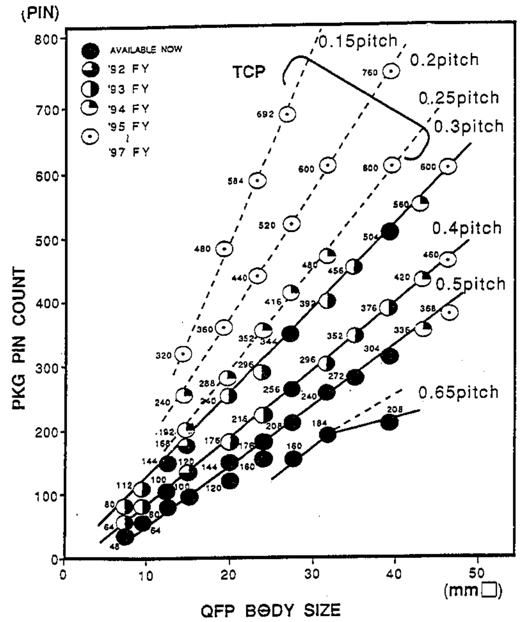


Fig.2 QFP Development Plan [2]

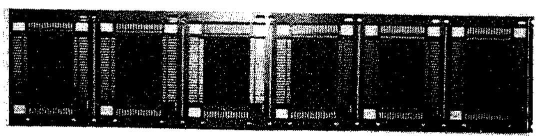


Fig.3 Configuration of Typical QFP

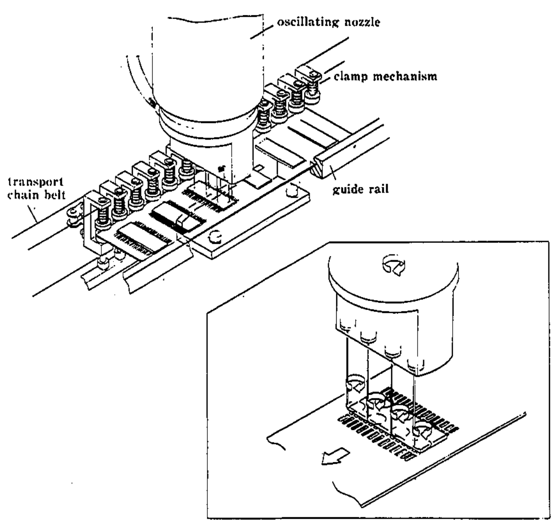


Fig.4 The Mechanism of Total Surface Waterjetting

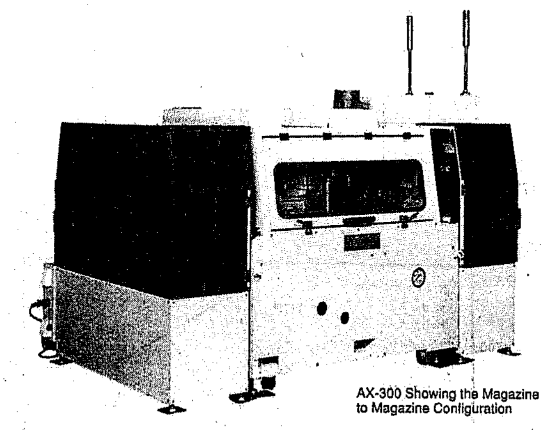


Fig.5 Total Surface Waterjetting System (AX-300)

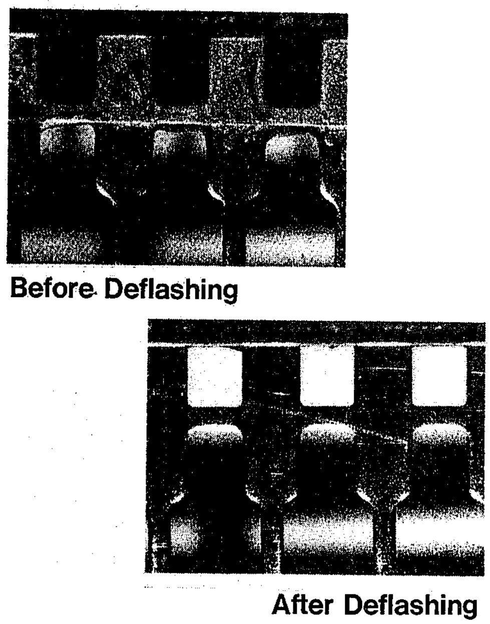


Fig.6 Detail of a Leadframe Deflashed by the the AX-300

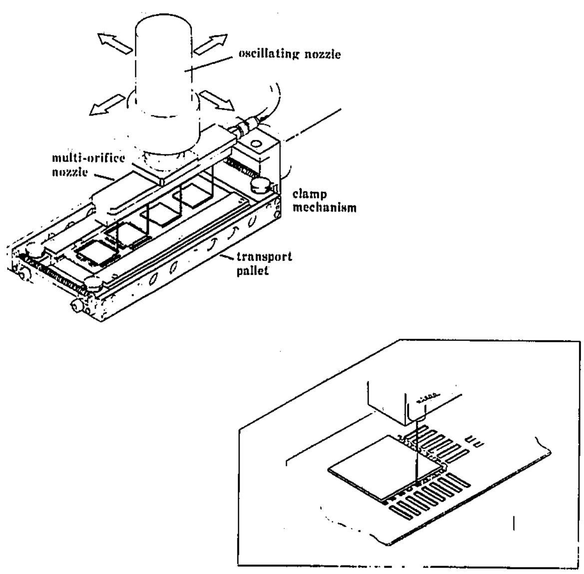


Fig.7 SPOT SHOT© Waterjetting with an Oscillating Nozzle

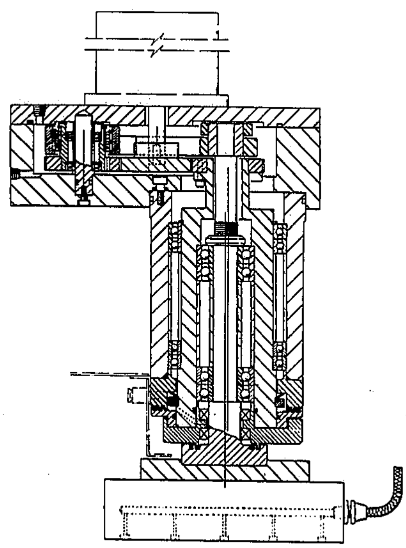


Fig.8 Oscillating Nozzle with a Multi-orifice Nozzle Head

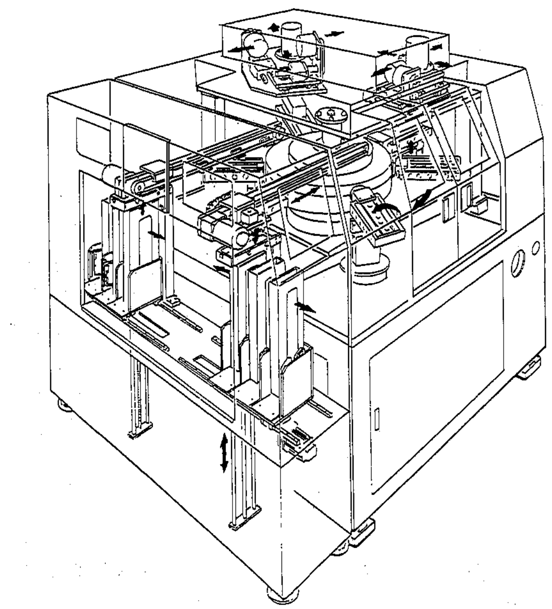


Fig.9 See Through Diagram of SPOT-SHOT© Waterjetting Machine (AX-100-K)

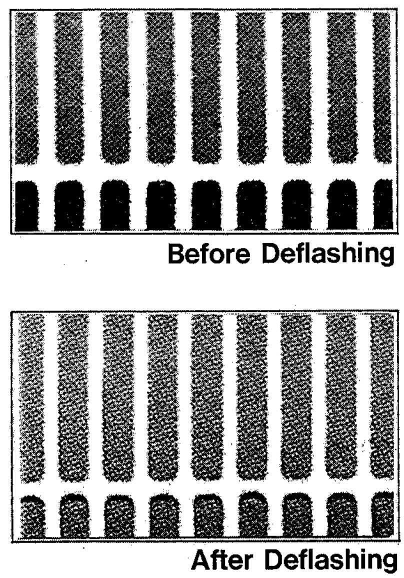


Fig.10 Dejunking of Fine-pitched Leadframe QFP 160 with 0.65mm Lead pitch

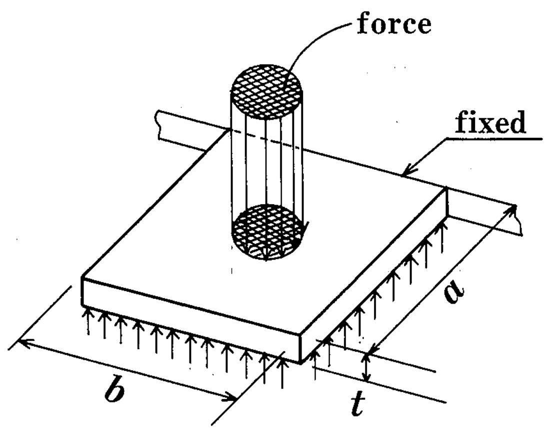


Fig.11 An Ideallized Model of Dam junk Removal

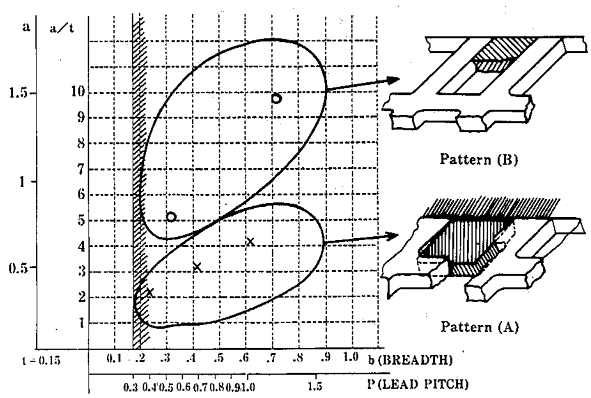


Fig.12 Removal Patterns for Damjunk

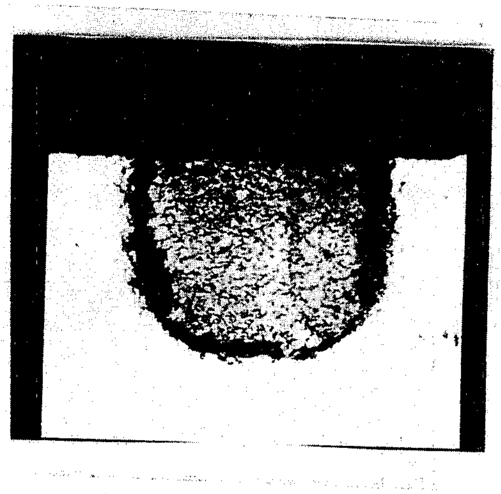
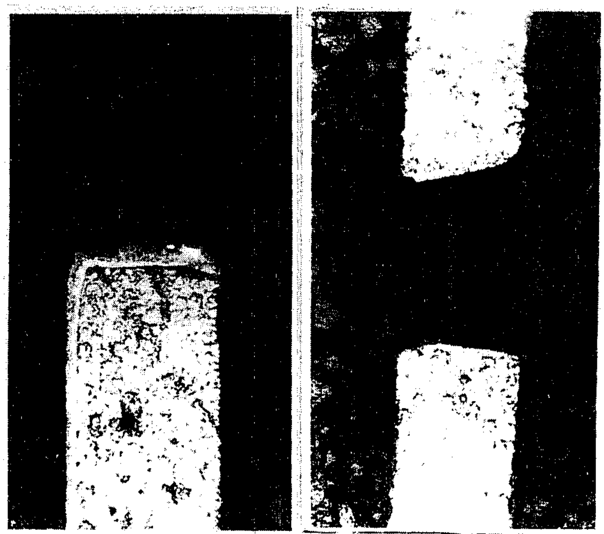


Fig.13 The Enlarged Photo of the Dam Junk damaged by Waterjet (×70)



(a) Rough boundary surface (b) Tapered boundary surface

Fig.14 The Enlarged Photo of the Cross Section of Leads

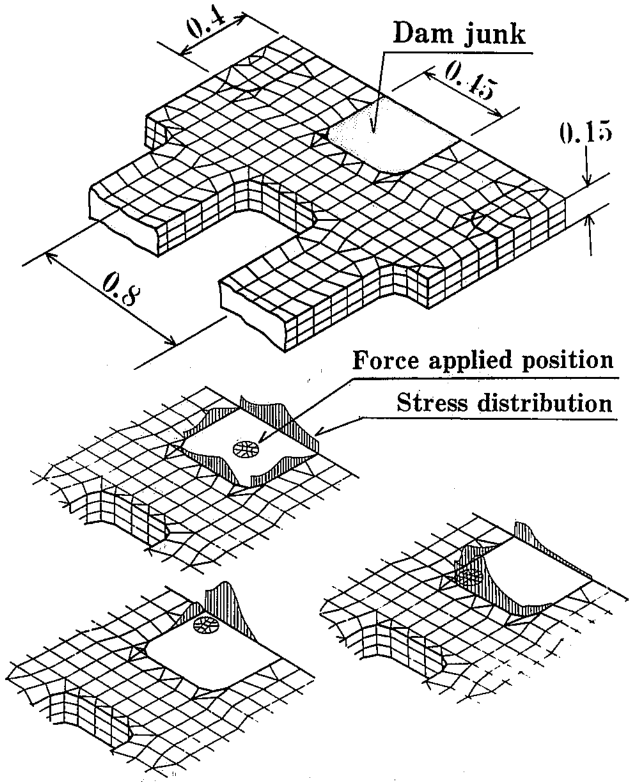
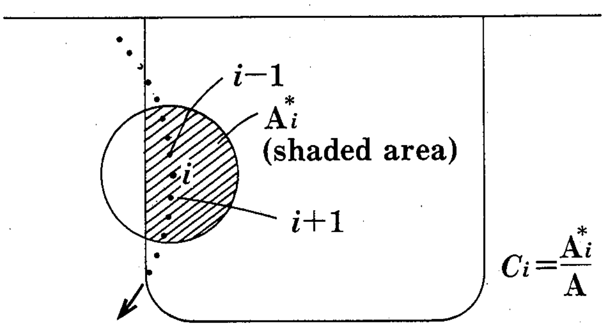


Fig.15 FEM Model and Stress Distribution

0.29	0.10	0.29
0.56	0.42	0.56
1.00	0.72	1.00

Fig.16 Weighting Coefficients from Stress Distribution



$A=\frac{\pi}{4}d_n^2$ d_n: Nozzle Diameter

Fig.17 Weighting Coefficient from Jet Coverage

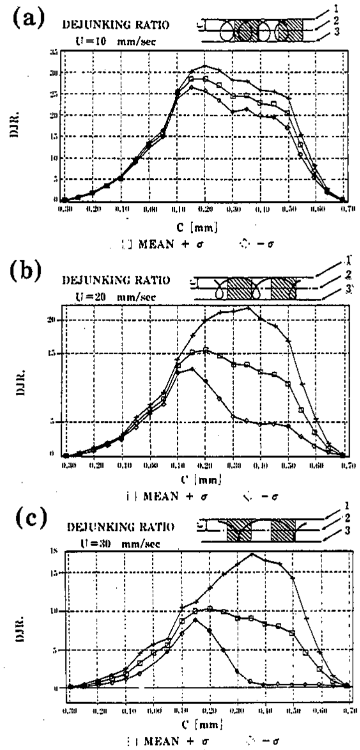
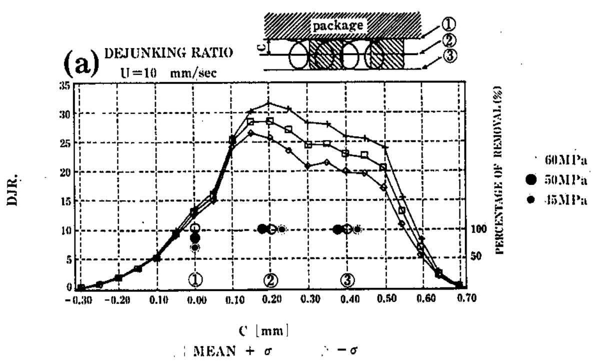
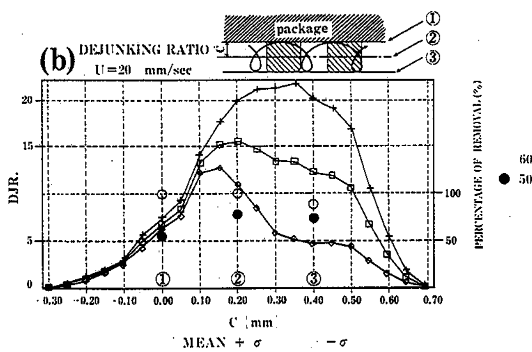


Fig.18 Calculation Results of DJR.





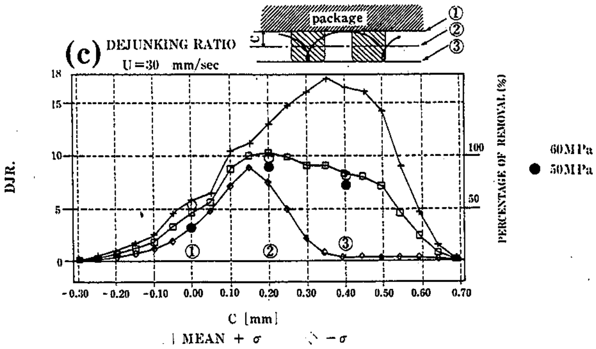


Fig.19 The Comparison between DJR Value and Dejunking Test Results tablated in Table 1.

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Paper 62

A NEW ABRASIVE-WATERJET NOZZLE FOR AUTOMATED AND INTELLIGENT MACHINING

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ABSTRACT

This paper presents the results of an R&D study and observations leading to the development of a new advanced abrasive-waterjet (AWJ) nozzle system. This nozzle will allow machine-tool like operations with quick and automated nozzle change capability. The nozzle is designed as a cartridge that can be quickly and easily interchanged. A separate alignment station allows cartridges to be aligned and adjusted off-line. The new nozzle also incorporates sensors for orifice health and abrasive flow rate. All services for water, abrasives, and sensors are attached to one side of the nozzle body for ease in manipulation.

Organized and Sponsored by the Water Jet Technology Association.

1. INTRODUCTION

The objective of the work presented in this paper was to develop and build an Intelligent Abrasive-Waterjet (AWJ) Nozzle. This system reduces the skill level required of the operator, improves the consistency of the AWJ process, and allows automated operation over a wide variety of AWJ process conditions.

The first task in this work was to examine the problems with current generation AWJ nozzles and generate a set of requirements for the Intelligent Nozzle system. The hardware development efforts were based on this nozzle assessment and concentrated in two areas: process sensing and control and the mechanical components that comprise the nozzle. These development efforts produced the Intelligent Nozzle prototype. This system was used for laboratory testing as well as several demonstration machining tasks.

In the following, the nozzle assessment is discussed first. Then, the sensor development is discussed, followed by the nozzle design and prototype implementation.

2. ASSESSMENT OF CURRENT AWJ NOZZLE PROBLEMS

As AWJ applications have progressed from simple cutting to more complex operations, certain aspects of the nozzle design and operations have needed improvement. These problems exist at both the component and the system level. An assessment was made of the current nozzle technology in order to develop a set of requirements for the Intelligent Nozzle. The results are summarized in Table 1.

The Intelligent Nozzle will require certain characteristics to overcome the problems listed in Table 1. To clarify these characteristics, a set of requirements for the Intelligent Nozzle was developed. These requirements apply to components as well as system operation and are listed in Table 2.

Unfortunately, the AWJ process is also subject to external disturbances that affect the quality of the process. Some of the requirements in Table 2 are better met by monitoring and correction. Another set of sensors to monitor and stabilize the AWJ process is also needed. A list of these sensors is presented in Table 3.

3. SENSOR DEVELOPMENT

3.1 Abrasive Flow Rate Sensor

A number of methods for measuring the abrasive flow rate in an AWJ were considered. An acceptable sensor would provide a measurement of the abrasive mass flow rate with an accuracy of better than ±5% and be invariant to abrasive size and type as well as ambient temperature and humidity. For ease of calibration, it would be best if the sensor response were linear as a function of abrasive flow rate. The four primary candidates are listed below:

1. *Opacity sensor* - Measures the optical transmittance through the abrasive feed tube. The abrasive flow would block the light transmission in proportion to the mass flow rate.

2. *Charge transfer* - Measures the amount of electrical charge passing through the abrasive feed tube per unit time. The electrical charge is carried by the abrasive particles, so the charge transfer rate would be proportional to the mass flow rate.
3. *Hopper weight change* - Measures the rate of weight change of the abrasive hopper or a smaller subhopper.
4. *Momentum transfer* - Measures the momentum change of the abrasive stream by placing a weight sensor in the path of the particles.

The momentum transfer method was selected for development to measure the mass flow rate directly by placing a force sensor in the path of the abrasive particle stream. The abrasive particles free-fall from the metering valve and are deflected by the sensor. The force on the sensor is proportional to the change in momentum of the stream of abrasive particles. The change in momentum is in turn a function of the mass flow rate.

A force sensor was constructed for this application because of the high sensitivity required and the harsh abrasive environment. The force sensor is constructed by measuring the deflection of a spring. In this case, the spring is a cantilever beam, with a strike plate at the free end to act as a target for the abrasive stream. Figure 1 shows a photograph of the abrasive flow sensor.

A differential pair of eddy current displacement sensors is used to sense the beam deflection. The use of differential sensors provides a very stable gain and offset calibration. Of particular importance is the gain stability over time and temperature.

Figure 2 is a graph of the linearity test results for the abrasive flow meter. Six different abrasive sizes and types were tested, each at several abrasive rates.

3.2 Orifice (Jewel) Health Sensor

A physical measure of the quality or health of a waterjet is the coherence length. A long coherence length provides the most efficient and stable machining conditions and is therefore most desirable. The coherence length is the distance from the jewel to where the waterjet begins to break up into droplets. A bad jewel will have a coherence length of zero, while a good jewel will have a coherence length approaching 2 inches. By monitoring the health of the jewel, the coherency of the waterjet can be inferred.

Two methods of monitoring the health of the waterjet jewel were selected for evaluation. The first was an acoustics-based approach, looking for changes in the acoustic signature to infer changes in the shape of the waterjet as it forms in the jewel. The second approach was to monitor the vacuum level in the mixing chamber, located just below the jewel in the nozzle. This pressure-based approach was selected for further development.

A preliminary parametric study was conducted to determine the relationship between the pressure-based sensor reading and the following parameters:

- Waterjet coherence length
- Abrasive feed rate
- Mixing tube diameter

- Waterjet pressure
- Jewel size

Figure 3 is a chart showing the results from one series of tests. These tests were done using a 0.016-inch-diameter jewel, a 0.047-inch-diameter mixing tube, and mesh 60 garnet. The figure shows the relationship between coherence length, pressure sensor reading, and abrasive flow rate. Note the primary relationship between the coherence length and the pressure reading with only a minor dependence on abrasive rate. The dependence becomes less apparent at short coherence lengths. This graph is very typical of the remainder of the test data taken for different jewel sizes. Based on these data, a pressure-based jewel health sensor was determined to be feasible.

To incorporate a jewel health sensor, the machine controller would incorporate a calibration utility to record a pressure-based sensor calibration reading. Alarm trigger points are manually set above and below the average calibration reading. This arrangement has proven to be an effective monitoring system.

In future work, consideration should be given to a more extensive parametric study to develop a detailed model of the expected vacuum level as a function of process parameters.

4. NOZZLE DESIGN

The nozzle design task required solutions to many of the problems identified in the assessment of current nozzle technology. These solutions included:

- Providing a quantifiable alignment system that is separate from the nozzle assembly.
- Developing a method for automated changing of the static nozzle components (jewel size and mixing tube) in a manner analogous to tool changes on conventional machining centers.
- Incorporating vacuum assist for abrasive feed and flushing water for cleaning the mixing chamber.
- Integrating the sensors developed for process monitoring and control.

Figure 4 shows a diagram of the Intelligent Nozzle system. The system consists of the following major components:

- Nozzle body
- Nozzle cartridge
- Cartridge alignment station
- Cartridge loading station
- Intelligent nozzle controller
  - Computer and software
  - Interface and junction boxes
- Abrasive flow monitor
- Jewel health sensor

4.1 Nozzle Body

The nozzle body (Figure 5) contains a mounting recess for the cartridge and provisions for all of the process connections. The abrasive feed, flushing water, and vacuum assist lines connect to permanent ports on the sides of the nozzle body. The ultrahigh-pressure (UHP) water flows through a port on the top of the nozzle body and through a settling chamber before reaching the jewel. Seals for each port are integrated in the nozzle body to allow flow to the cartridge assembly. The body contains a recess for mounting and locating the cartridge to lock it into the nozzle body.

4.2 Cartridge

The cartridge assembly (see Figure 5) is a modular unit that plugs into the nozzle body; Figure 6 shows a photograph of the cartridge installed in the nozzle body. The cartridge assembly is comprised of the body, the mixing tube, and the jewel cap. The body contains the mixing chamber and has locating features and matching ports to mate properly with the nozzle body. The mixing tube is mounted into the cartridge body using precision collets to eliminate any inaccuracies. The jewel cap supports the jewel and has a spherical mating surface with the cartridge body. This spherical mount allows the jewel to be aligned with the mixing tube. The jewel cap also provides the sealing surface for the UHP connection with the nozzle body.

4.3 Alignment Station

The alignment station is used to adjust each cartridge assembly so that the waterjet fires down the center of the mixing tube. The alignment station also provides a system for adjusting the jewel with respect to the mixing tube that is

- Separate from the nozzle body and therefore the AWJ application.
- Quantifiable in the results.

The station (Figure 7) has three main components: the cartridge mount, the optics package, and the catcher. The cartridge mount provides features to register the cartridge that are identical to those on the nozzle body (see upper insert on Figure 7). The cartridge is locked in place, and UHP water is provided via a sealing system. The optics package contains a 30x alignment scope to view the jet stream as it exits the carbide (see lower insert on Figure 7).

The scope has a reticule so that the results of the alignment can be quantified. The catcher dissipates the waterjet energy, and a vacuum system removes any mist or steam from the viewing chamber.

4.4 Loading Station

The cartridge loading station is designed to serve the same function as a tool changer on CNC machine tools. The system developed in this work was only meant to demonstrate the concept of cartridge changes.

The loading station (Figure 8) clamps the cartridges in a rigid frame. The manipulator provides enough force to push the cartridge into the nozzle body during pickup. Once the cartridge is seated, cartridge lock is activated in the nozzle body. The pneumatic clamp is then released, and the manipulator lifts the cartridge out of the station. Replacing the tool is done in the reverse sequence.

4.5 Intelligent Nozzle Controller

The Intelligent Nozzle controller (INC) performs two basic functions:

- Display and monitoring of the jewel health sensor.
- Display and monitoring of the abrasive flow rate sensor.

A system implements these functions as well as providing the operator interface (Figure 9) and communications interface with the manipulator controller.

A PC-based computer is used to integrate the monitoring and display functions and to display the sensor outputs and status information. Optically isolated binary I/O is used to interface the INC with the manipulator controller. In this work, the INC was interfaced to an industrial robot controller as well as a CNC machine tool controller. It is through the binary I/O interface on the INC that jewel health and abrasive flow alarm set points can be commanded and monitored.

Signals from the abrasive flow monitor and the jewel health sensor are routed to a junction box located adjacent to the INC. When error conditions are noted by the INC (i.e., the jewel is bad or the abrasive flow is out of tolerance), digital output lines are activated to indicate such; these output lines can be used to stop the cutting process if desired. These signals can be interpreted by the manipulator controller and the appropriate course of action taken.

5. NOZZLE SYSTEM EVALUATION

The Intelligent Nozzle system was evaluated in the field at General Electric Aircraft Engines (GEAE). This evaluation included machining trials in a manufacturing environment as well as carefully controlled laboratory experiments. The results of the GEAE tests were thoroughly analyzed using statistical methods. From these results, many conclusions were drawn about the performance of the system:

- The Intelligent Nozzle system was found to provide significant reductions in the setup time required for cuts.
- The accuracy of the cartridge collet system was found to be within ±0.0033 inch.
- The abrasive flow sensor was measured to be accurate within 0.04% of the actual flow rate, but performance was somewhat affected by disturbances such as vibration or the tilt angle of the sensor.
- Although the Intelligent Nozzle cutting efficiency was not significantly greater than that for a commercial nozzle, the overall productivity was significantly higher because of the ease of use.
- The jewel health sensor was effective in measuring the health of the jewel and is seen as a practical tool for triggering the system to stop.

- The ability to prealign cartridges at a separate alignment station was useful. Improvements were recommended for the optics and lighting to maximize the benefit of this device.

7. CONCLUSIONS

The Intelligent Nozzle system is a next generation AWJ nozzle for implementing advanced machining processes. The system includes:

- Nozzle body and interchangeable cartridges
- Process sensors and computer monitoring system
- Cartridge loading station
- Cartridge alignment station

Additional features, such as the vacuum assist and computer controlled pressure ramp, are incorporated in the nozzle design and its controller.

The Intelligent Nozzle system has many advantages over current commercial systems, including the following:

- The system provides significant reductions in setup time.
- The jewel health sensor is effective in measuring the health of the waterjet.
- Overall productivity with the Intelligent Nozzle is significantly higher than with current generation nozzles.
- The abrasive flow sensor is accurate to ±0.04% of the nominal flow.
- Direct reading of the mass flow rate is of significant benefit to an operator.
- Prealigning the cartridges at a separate station is useful in reducing setup time and improving process consistency.
- Automated cartridge changing means that multiple AWJ processes can easily be implemented in a single application.
- Automated process monitoring reduces greatly the amount of operator interpretation and intervention.

ACKNOWLEDGMENTS

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Table 1. Nozzle Problems

Component	Problem Area	Description
Waterjet Orifice	Manufacture	Hole concentricity and perpendicularity to mounting surface.
	Holder	Use of soft seals is not deterministic.
	Wear	Jet quality deteriorates as the orifice wears.
	Fracture	Most frequent orifice failure mode.
Settling Chamber	Turbulent flow	Upstream turbulent flow adversely affects waterjet coherency.
Mixing Chamber	Wear	Wear at the bottom of the orifice holder can lead to nozzle failure.
	Stagnant zones	Abrasive particles become trapped in low-flow zones.
Mixing Tube	Wear	Wear affects cutting edge location at workpiece and leads to mixing tube replacement.
	Manufacture	Difficult to produce an inner diameter with acceptable size and concentricity errors.
Abrasive Delivery	Hose	Abrasive delivery from the hopper to the nozzle is limited by abrasive line length, bend radius, vertical lift, flow, and particle size. Delivery is also affected by moisture, nonuniform abrasive size and contamination.
Alignment	Nozzle alignment	Alignment requires experienced personnel.
	Jet alignment	Align the AWJ to the manipulator's reference axis, usually the z-axis.
Manipulator-Nozzle Interface	Fluid delivery	Manipulators not designed to gracefully accommodate the abrasive and UHP water tubing.
	Abrasive delivery	No standard.
	Automatic nozzle changer	Not available.
	Tool crash	Mixing tube is brittle and can be easily damaged if it strikes workpiece.

Table 2. Intelligent Nozzle Requirements

Component	Requirement
Waterjet Orifice	Manufacturing methods that reduce the orifice angularity and concentricity errors to acceptable values.
	New materials, design geometries, and failure analysis techniques to extend orifice life.
Settling Chamber	Smooth flow Reynolds number near 2000.
Mixing Chamber	Minimize wear.
	Method to purge trapped abrasive particles during and immediately after use.
Mixing Tube	New materials to extend mixing tube life.
	Predictable wear.
	Manufacturing methods that reduce the concentricity and hole size errors to acceptable values.
Abrasive Delivery	Uniform flow of all types of abrasives to manipulator-mounted nozzle.
Alignment	Quantitative nozzle alignment.
Manipulator-Nozzle Interface	Abrasive and fluid plumbing compatible with manipulator.
	Automatic and quick nozzle changer.
	Protect nozzle from crashes and abrasive rebound.

Table 3. Potential Intelligent AWJ Nozzle Sensors

Sensor	Variable	Description
Nozzle Sensors	Jet health	Monitors the condition of the waterjet orifice.
	Abrasive flow	Measures the flow of abrasive particles to the nozzle.
	Mixing tube exit diameter	Measures the mixing tube exit diameter.
	Nozzle alignment	Determines the position of the waterjet within the mixing tube.
	Jet alignment	Determines the variance between the AWJ vector and the alignment reference axis.
	UHP water pressure	Measures the UHP water pressure.
	UHP water flow	Measures the UHP water flow.
	Air flow	Measures the abrasive particle transport air flow.
	Air temperature	Measures the abrasive particle transport air temperature.
Machining Sensors	Kerf width	Measures the kerf width at the workpiece.
	Standoff	Measures the standoff between the nozzle and the workpiece.

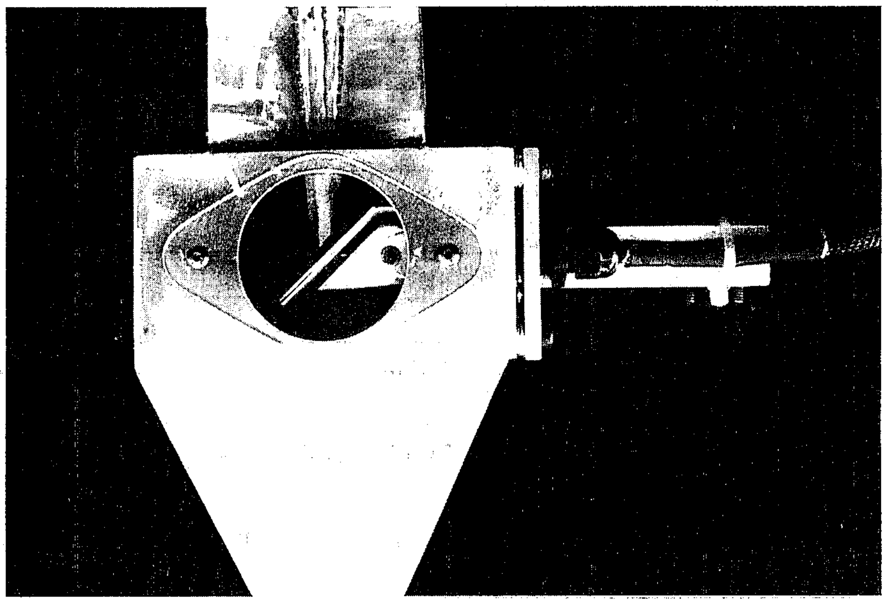

Figure 1. Abrasive Flow Rate Sensor

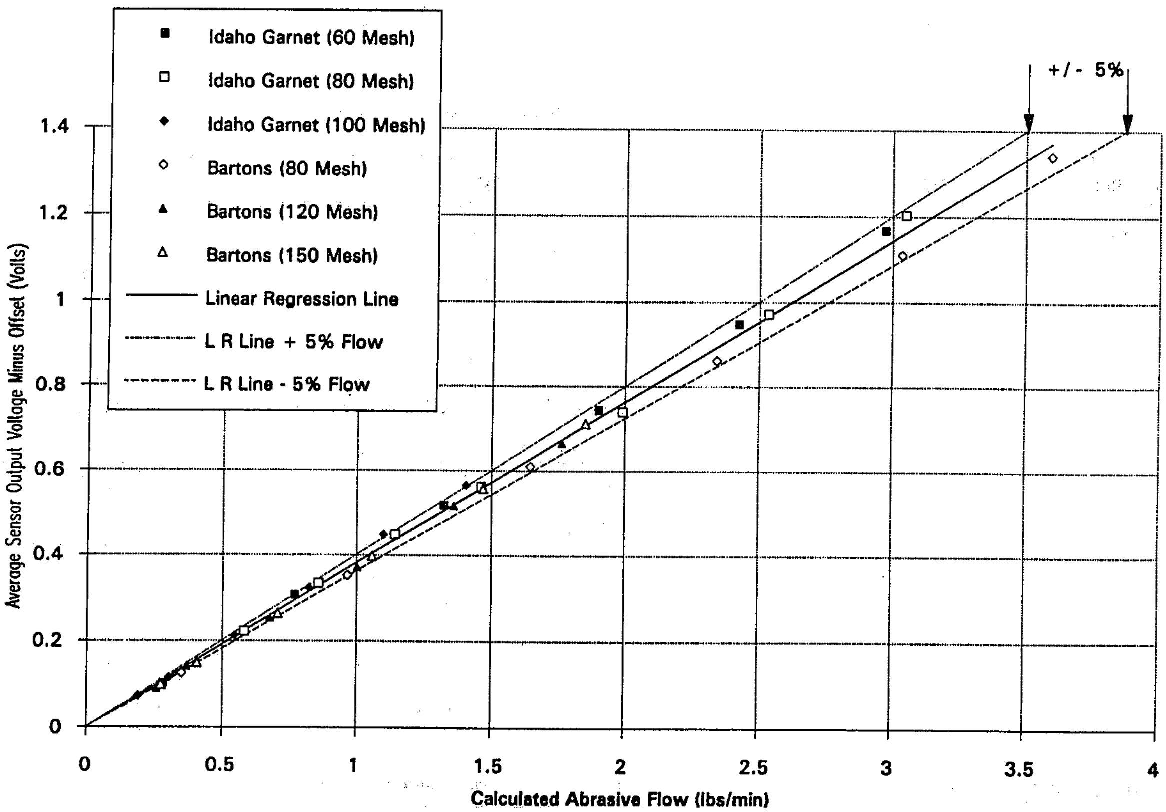

Figure 2. Abrasive Mass Flow Rate Sensor Response

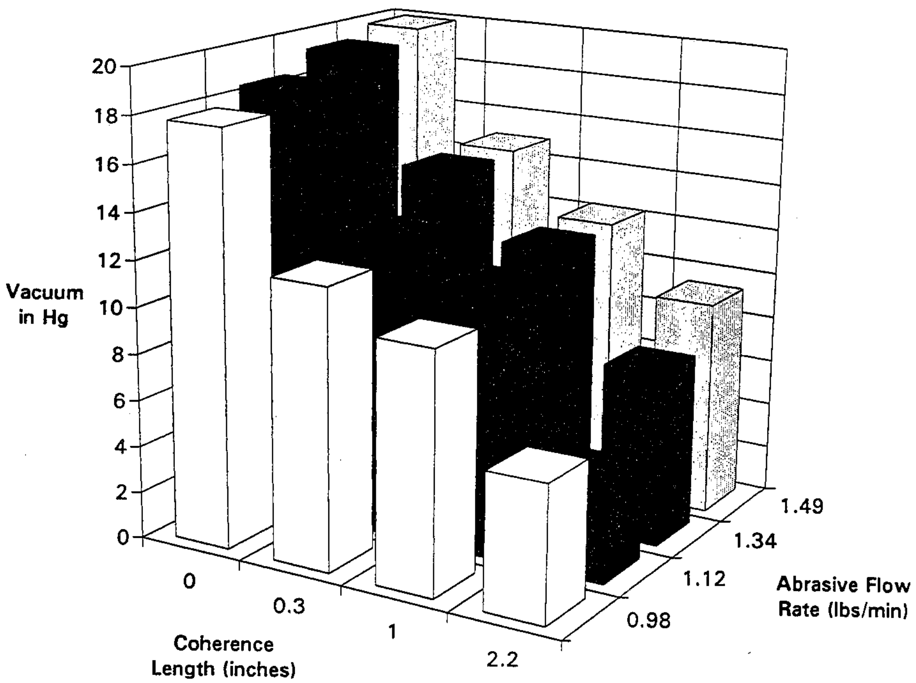

Figure 3. Pressure-Based Sensor Response

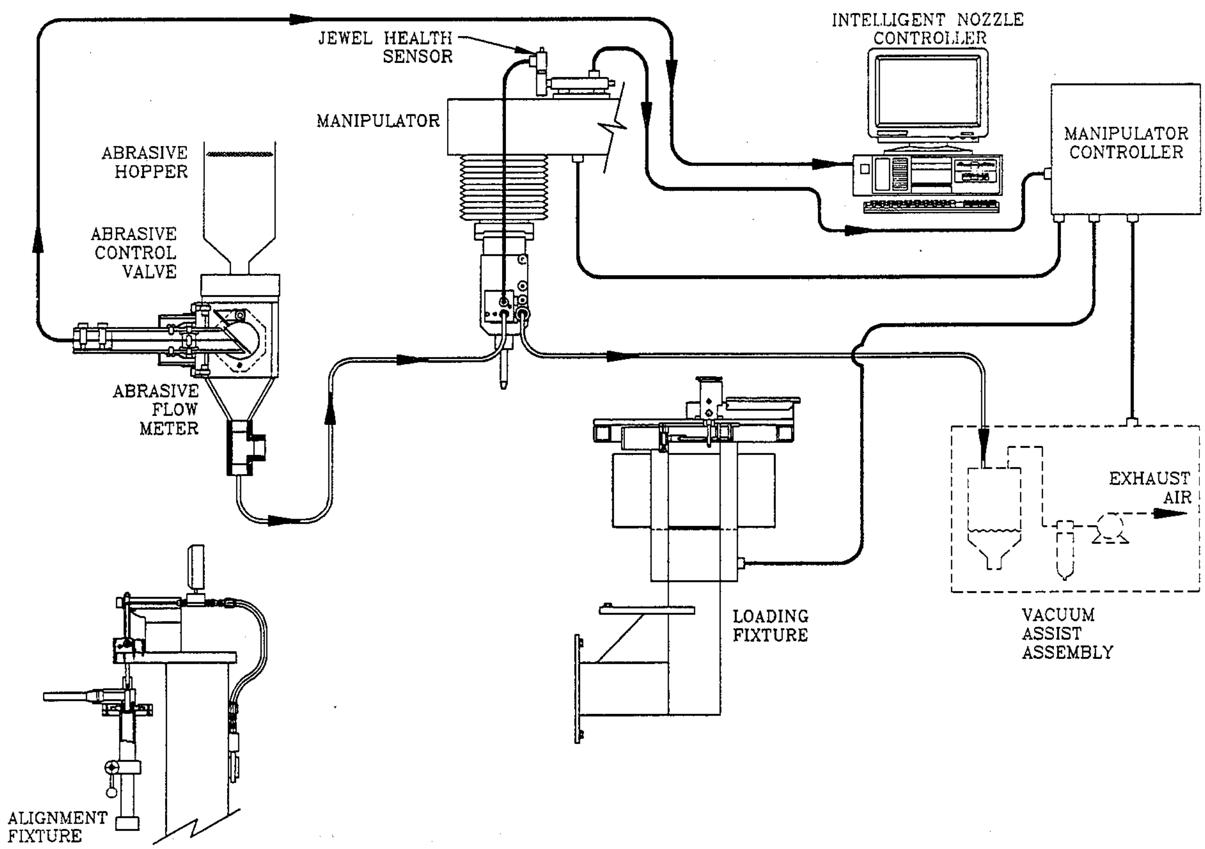

Figure 4. Intelligent AWJ Nozzle System

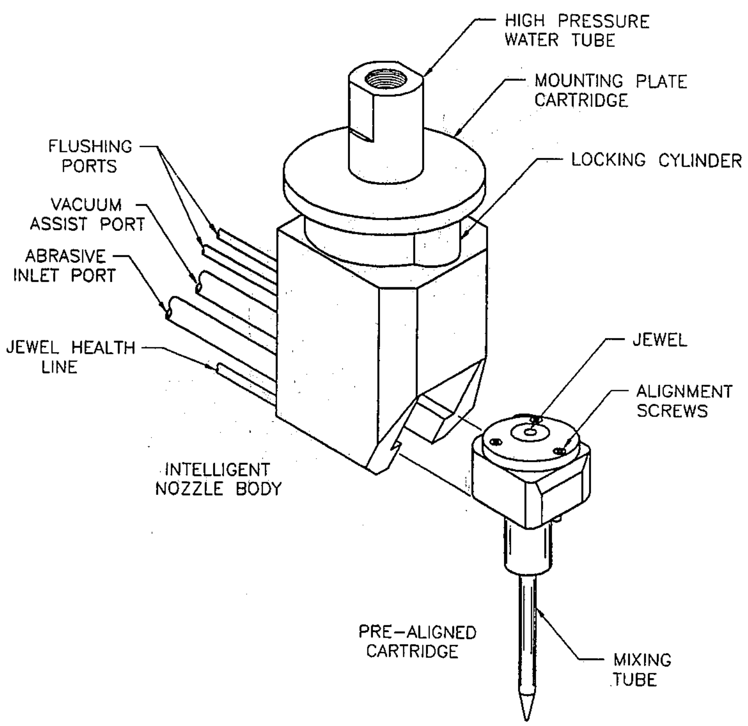

Figure 5. Schematic of Intelligent AWJ Nozzle Assembly

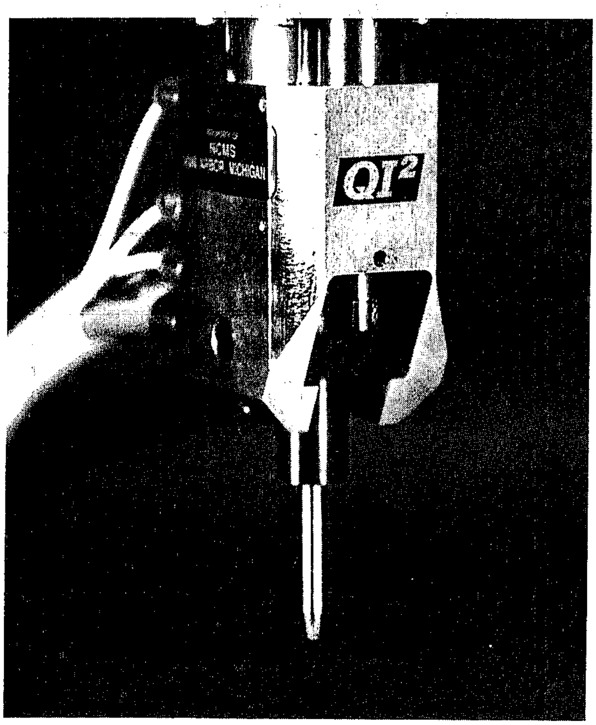

Figure 6. Intelligent AWJ Nozzle with Cartridge Installed

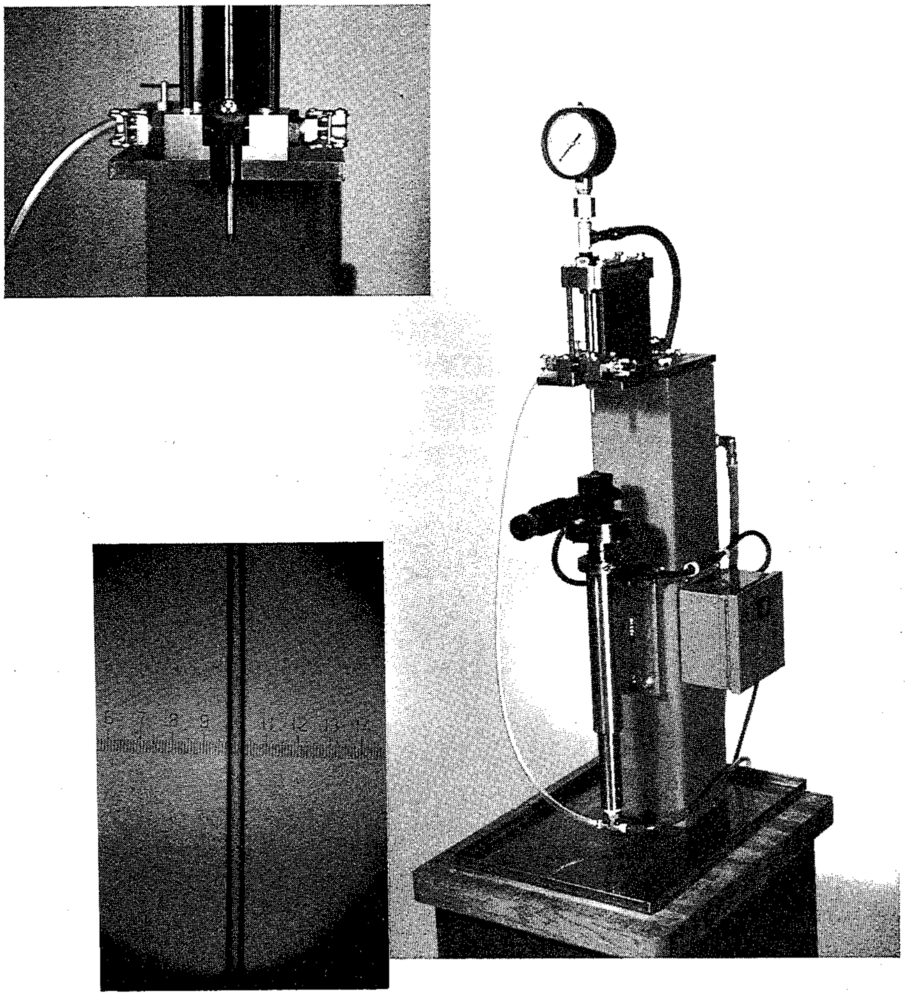

Figure 7. Alignment Station

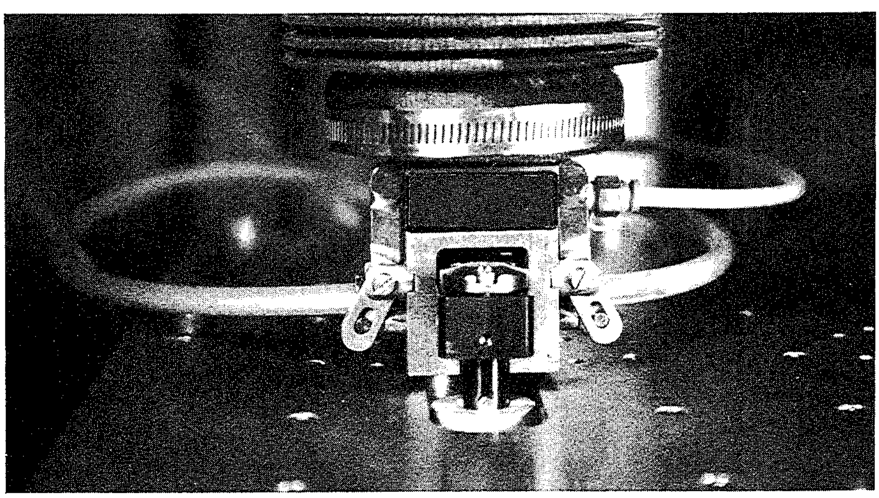

Figure 8. Loading Station

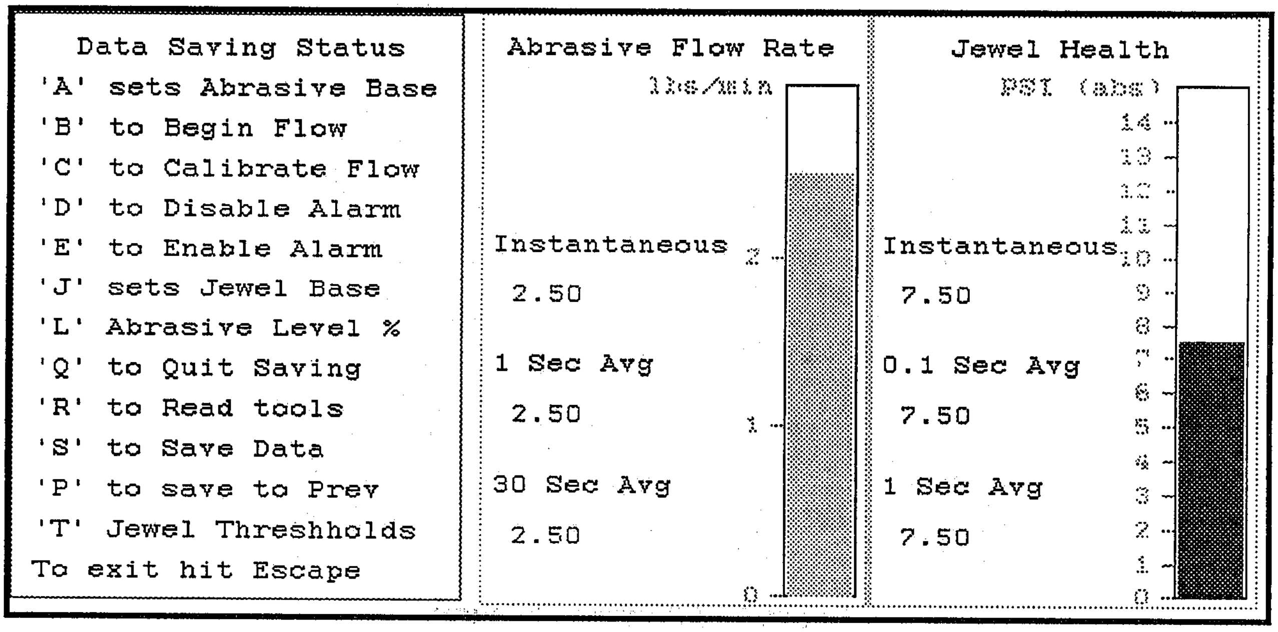

Figure 9. Controller User Interface

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SUCCESSFUL IMPLEMENTATION OF TWO & THREE DIMENSIONAL HYDRO MACHINING, ABRASIVE & NON-ABRASIVE, WITHIN AUTOMOTIVE AND AEROSPACE INDUSTRIES

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ABSTRACT

Exploring the potential benefits of waterjet cutting applications warrants the review of some of the more popular waterjet processed parts. Modern transportation in the form of automobiles and airplanes with their complex shapes and compound materials requires new innovative processing techniques. Automotive with its high volumes and relatively frequent style changes makes programmable watercutting attractive in comparison to a 3-dimensional die cutter or multiple 2-dimensional die cutters, which are more attractive than hand trimming. Aerospace components on the other hand are being trimmed with abrasive waterjets because of the tough new composite materials that are rough on standard edge tools. Programmable systems can position trim lines without the use of manual guide jigs. With conventional trimming tools, routers, saws, etc. the process becomes very operator intensive and drastically increases chances for error.

Automotive components that are currently being processed amount to just about anything that is molded. One of the earliest applications was Automotive Carpets, both woven and non-woven materials. To give you an example of how difficult the material is to process, let me ask a question. Have you ever tried to drill a hole through carpet with your electric drill? The thread wanted to roll up around the drill bit without shearing and it normally causes damage to areas other than actual trimming location. Waterjet, being an omni-directional cutting media, is normally not affected by such restrictions. Waterjet cutters can trim the carpet with ease ranging from piercing small holes to articulating the entire outside perimeter; or jumping from hole to hole very quickly. Molded, non-woven materials such as trunk liners are a good candidate for water cutting, as opposed to die presses or manual trim dies, because of the complex curves and compound angles. These products are typically polyback, thermal-formed parts that are actually cooled in shape to finish the molding process.

AUTOMOTIVE COMPONENTS

Interior Trim:
- -Door Panels
- -Instrument Panels
- -Headliners
- -Carpets
- -Consoles
- -Arm Rests
- -Trunk Liners

Acoustical Products:
- -Sound Deadeners

Acoustical products used inside of the engine compartment and as headliner substrates are popular waterjet processed materials. Most of the headliners, hood insulation blankets and other noise reduction materials that are molded to shape are prime candidates for waterjet cutting.

Headliners, as an example, made of molded fiberglass are tough on standard edge tools and easily damaged by the impact of press action. A fallout problem is created by the compaction and subsequent shear action of a die press. This fallout consists of small broken fibers where the die blade actually crushes the material and breaks it leaving dust like particles in the trim edge that doesn't occur with a waterjet. The small glass fibers shear very well with a waterjet and leave little if any broken fibers in the trim edge.

Composite foam materials cut very well because of the almost zero distortion caused by a waterjet and the excellent shearing action the waterjet has with multi-layer materials. The newest entrants are composites which are compiled of a vinyl top cover, reinforcement (glass or polyester fibers which the waterjet trims extremely well) with a semi rigid foam core poured or injected in the mold. Once molded to shape, these products can be trimmed to a finished or near finished state in one operation. In many instances, more than one model of finished goods can be created by cutting different features and openings in a common blank; with the waterjet these simply represent program changes, whereas in a die press each feature represents a hard die set and possibly a separate die press to complete.

Other interior trim components that lend themselves to waterjet trimming are instrument panels, door panels, quarter trim package and consoles where a rigid frame or substrate support an outer skin of vinyl with a foam core forming a composite sandwich. This is one of the most widely used methods of controlled depth cutting for waterjets. The waterjet is configured to operate with variable pressure. Low pressure is used for trimming vinyl and foam only while the pressure can be raised for cutting through all layers including the rigid plastic substrate. In comparison, utilizing a more conventional trimming method incorporates the use of hot trim dies which are very difficult to fine tune in the development process. It also becomes costly and time consuming to make engineering changes. The programmable waterjet can be modified through simple program changes to insure proper fit and finish in a matter of minutes, as opposed to weeks of grinding and welding on the trim die.

Molded vinyl products often have variations between parts created by the use of multiple molds that aren't identical. The foam curing process is typically the bottle neck in a foamed component product line. Small variations in the cure of the foam and small variations in the molds can cause the vinyl cover to float in relation to the substrate. Waterjets can be programmed to maintain proper fit and finish of assembled components by adjusting for tool variations. Die presses on the other hand must register off the substrate which may not maintain desired fit and finish on the exterior skin.

CNC Controlled Waterjets offer many advantages over conventional methods which can consolidate multiple operations. Conventional processing can involve multiple pieces of hard automation drilling machines for holes, die presses for through cuts, and hot die presses for trimming vinyl. The waterjet may have a somewhat extended cycle time, however, it can reduce handling by consolidating multiple operations into one.

New materials are evolving into the manufacturing environment which create new processing challenges. Designers are utilizing these new materials to fulfill their weight reductions and structural enhancement requirements. Fuel efficiency is the driving force behind these aerodynamic and structural changes. The strength of composite structures equal steel, but are far more difficult to process with standard edge tools. The continual improvement in reliability and ability to process these advanced composites has opened up additional opportunities for waterjet cutting and abrasive waterjets. Listed below are a few of the rigid components being processed.

AUTOMOTIVE STRUCTURAL PARTS

SMC, RTM, Glass Reinforced Reinforced Polyproducts:	-Springs -Bumper Support Beams -Underbody Frame Components

AUTOMOTIVE OUTER BODY PANELS

SMC, RTM, Polyethelenes, Polypropelene:	-Hoods -Doors -Fenders -Vinyl Roof Preforms -Back Panels -Header Panels

AVIATION COMPONENTS

Composite Parts:	-Wings -Alerons -Stabilizers -Structural Members, Ribs, Spars -Fuselage Parts
Metal Components:	-Metal Matrix -Aluminum -Titaniums -Stainless Steel

Composite structural materials are time consuming and expensive to process with standard edge cutting tools. Resins have a tendency to load up in cutters causing premature failure of router bits, mill cutters, drills and saw blades. This in turn creates additional maintenance changing tools and lost production. Dust is also created that is difficult to collect and these airborne particles are hazardous to employees and abrasive to machinery.

The development of the abrasive waterjet allows processing of these materials and consolidation of multiple processes into one operation. Molded parts often require trimming because the process creates a near net shape rather than finished edge, or leaves flash at mold parting lines. Perimeters can be trimmed either for full thickness cutting or flash removal. Holes can be pierced and openings cut all in one operation.

Automotive products are typically very high production volumes; but once the final configuration is determined, you will probably run this same version repetitively until the next engineering change occurs or model change. Aviation on the other hand is high variety with extremely low volumes. Flexibility versus productivity becomes the driving force behind most equipment considerations -- what gives the greatest return on investment over the short term and long term.

Equipment considerations again are dependent on part configurations and process parameters.

Processing of 2-dimensional parts typically comes down to an evaluation of material. It is impossible for a piece of equipment that must articulate its way around a shape to match the thruput of a die press, but in many instances the thruput of one product may not be the only consideration.

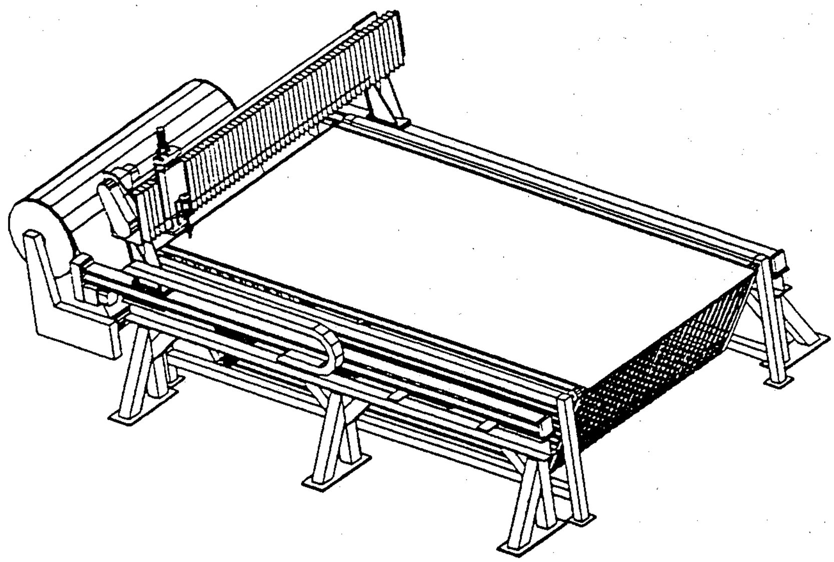
How much variety is processed?	-Part configuration? -Model changes? -Set-up time? -Die costs?
How many varieties of material are processed?	-What is the cost of material? -What are the remnant costs?
What is the cost of inventory storage?	-Work in process? -Storage space? -Delivery requirements?

These are a few of the considerations to keep in mind in evaluating the manufacturing process. The advent of the CAD System has changed the product design function forever. New products can be brought to market much quicker and new machines and controls are required to utilize this information.

CAD/CAM Systems offer enhanced design capabilities that allow for shapes to be generated electronically and put into an NC format which can be run on a 2-axis positioning system. These shape files can now be stored for easy access and creation of cut files.

Inventory can now be controlled by looking at production requirements. Order management, weekly, daily, hourly requirements can be used to create cut files based on delivery. Production becomes truly order driven. Nesting systems work in conjunction with material management. A cut file is generated and the software is given the task of making best utilization of available material based upon production requirements.

Two Dimensional Cutting Systems, when working in conjunction with manufacturing management systems and CAD/CAM packages, offer fast responsive manufacturing systems to comply with today's Just-In-Time (JIT) inventory control.



Sizing a 2-dimensional cutting system is usually based upon the largest blank size you wish to process.

Width	_____	= Y Axis Travel
Length	_____	= X Axis Travel
Thickness	_____	= Z Axis Travel

However, blank sizes and material costs will have a great effect on material handling, not only in gantry travels but also material handling configuration. What next must occur is to determine a practical size to handle that is most cost effective and meets quality standards. In some instances this may be flat sheets to be cut to size or it may be roll goods that require a sophisticated unrolling system linked to the Nesting Program that measures the quantity of material entering the cutting envelope.

The next area of concern should be the cutting area and how the material is being supported during that trimming process. The biggest single consideration in designing a material support table is to minimize splashback that may damage the product. If your cutting involves abrasive, the material support table must be designed to take this into consideration, as an abrasive waterjet will cut any material that comes in its path.

Another intricate portion of a water cutting system is waste water containment and collection. As a basic minimum it is desirable to remove all of the suspended solids in the waste water before dumping to plant sewage water. Additional filtration may be required to meet local codes, but for the most part it is less costly to dispose of water than filter it to the purity necessary for recycling (.5 microns).

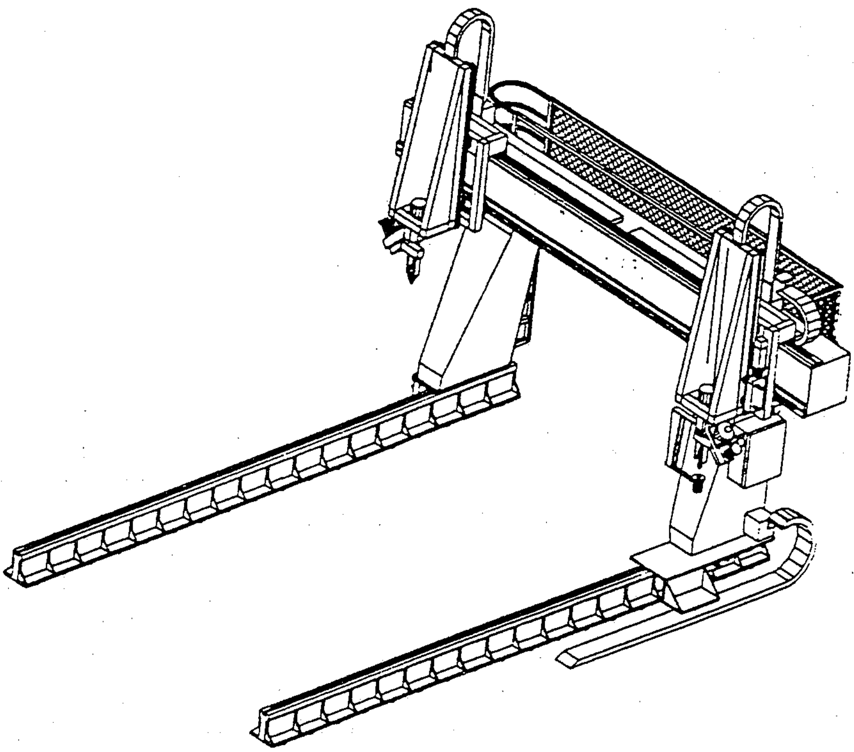
The next material handling function involves finished part recovery and scrap removal. As a material handling function it is necessary to consider how you will get finished goods off of the trimming surface. If this is an operator function, safety precautions should be taken to lock out the robot and waterjet while this individual reaches to pick up finished goods and scrap. If goods are being automatically conveyed into the work envelope then the conveyor or shuttle should allow for automatic removal.

Three Dimensional Cutting Systems are used in either blanking operations where angle cuts are used to cut a 3-dimensional shape from flat material or for trimming molded parts. These systems are typically broken up into two basic categories: Cartesian Coordinate Systems or Gantry Style Units and Articulated Arms or Robotic Coordinate Systems.

To date programming requirements have fallen into two categories that really seem to be based on quantity or volume of parts to be run. If a machine is going to predominately be set up to run one or just a few parts of high volume, a teach-to-learn unit may be sufficient with good repeatability. However, if you are going to run high variety of shapes, you typically do not want to sacrifice machine time for programming or editing, so positioning accuracy becomes important. Accurate programs can be generated offline and downloaded to the work envelope without significantly affecting production with machines that position accurately from direct numerical control.

Gantries are typically built in two versions: Teach-to-Learn or Precision Off-Line Programmable Systems. Under this Teach-To-Learn style of programming a partholding fixture is loaded in the work envelope and via a pendant or remote terminal the machine is jogged through the pattern and this path stored in memory. Once a program has been generated, the repeatability is the machine's ability to run this pattern over and over accurately at the same feedrate. If a unit is going to run the same part repeatedly for an extended period of time, it may not matter if you take hours fine-tuning a program.

Precision Systems on the other hand give you the ability to accurately run a part program created on an external source such as a CAD Programming System. A post processor is generally needed to enable a program path to be generated for the machine to run from drawing data. The post processor is specifically configured to account for the actual workings of a particular machine. Robotic positioning systems capable of excellent positioning accuracy will have good repeatability as well but make sure that you understand the difference. The Machine Tool and Robotic Industry Standards define repeatability and positioning accuracy somewhat differently.



Care must be taken to protect surfaces of the part from exit water that may cause damages upon contact. Water deflection can be taken care of within the part holding fixtures or tooling by incorporating wear plates and energy absorbing deflectors. Fixturing plays an important part in achieving consistently accurate trimmed parts. Fixturing must have the ability to repetitively position the parts for processing.

In many instances poor part location can cause trim lines to wander thus creating questions toward process reliability. Part holding fixtures must have the capability to bring the part to a known location and, in many instances, correct for inconsistencies between multiple molds.

In the case of extremely flexible manufacturing systems detailed dedicated part fixturing may not be the case. Low volume, high variety systems typically use less sophisticated fixturing than high volume systems due to the fact most are equipped with part locating systems.

Typical part locating systems include vision systems for identifying what part and where it is located in the work zone or on the fixture. Laser scanning can be utilized to determine where a specific feature or target is on a part, identifying its location within the work zone. Touch probes are a mechanical method of accomplishing part location. With this feature an operator will either jog the machine to a location and run a preprogrammed probing cycle or utilize a pendant to physically move the probe to a target point. Once part location is known you can adjust the machine's programmed path to the actual part location. Offsets may be utilized if actual location is a simple shift in the X, Y or Z coordinates to a preprogrammed path. If the part contains a rotation or skew to its actual location, as opposed to its theoretical location, a transformations package will enable you to adjust the trim path to the part's new location. In this case a computer system is used to move all of the program points to the actual location of the part within the work envelope. These functions can be quick when working with small amounts of data; or time consuming on large amounts of data.

Laser gauging systems can be utilized to identify process variables such as warpage and shrinkage, therefore adjusting final process information to actual part location or adjusting programmed data and trim path to actual surface configuration as compared to the designed or theoretical surface.

We have discussed a few of the equipment features and configurations available, as well as some of the applications utilizing the technology today. But how do you determine if this is a viable process for your production? The first requirement is to determine if your material will process with high pressure water or abrasive waterjet. Send samples to one of the application labs operated by an equipment supplier. If acceptable results are achieved, you are ready to look at the process in greater depth. If not, you may not be a candidate for waterjet cutting. Look for other methods.

Flexible manufacturing is the buzz word that everyone wants to use when discussing their capacity to react to this extremely volatile economic climate. What we are producing today may change completely next week or month or next year. The important goal is to take into account as many different disciplines as possible when evaluating your products' manufacturing costs in comparison with new technology.

ACCOUNTING:

- What are current direct costs?
- Is there a current equipment value?
- What schedule will the equipment be depreciated on?
- What is company's required Return On Investment (R.O.I.)?
- What is manufacturing process costs?

Compare waterjet and conventional methods to produce like volumes and thruput.

CAPITAL COSTS

Water jet:	Conventional:
-Machinery	-Machinery
-Fixturing	-Fixturing

MAINTENANCE

Flexibility:	vs.	Dedicated:
-Waterjet Machinery		-Hard Machinery
-Fixturing		-Die Casts
-Consumables		-Blades
-Parts.Orifices		-Sharpening
-Seals, Ext.		
-Variable Costs		-Variable Costs

Engineering changes are costly and time consuming to handle. However, when dealing with a waterjet this is simply a programming change. Hard tooling may require weeks or months of machinery modification.

The goal of most manufacturers, whether producing consumable goods or machinery, is to provide the highest quality product at a competitive price therefore distinguishing your company's capabilities over your competitor and creating the true "Win/Win Environment".

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Paper 64

HIGH PRESSURE INTEGRATION OF WATERJET SPECIAL SYSTEMS

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ABSTRACT

This paper relates to the problems of designing, manufacturing and implementing special cutting systems for waterjet cutting. "Special" Systems are defined as high-pressure cutting equipment that is designed and manufactured to suit a special customer requirement, usually on a one-off basis. This paper will cover typical systems from the intensifier pump to the waste-water collection system.

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HIGH-PRESSURE INTEGRATION OF SPECIAL SYSTEMS

This paper relates to the problems of designing, manufacturing and implementing special cutting systems for waterjet cutting. "Special" systems are defined in this paper as high-pressure cutting equipment that is designed and manufactured to suit a special customer requirement, usually on a one-off basis. It will cover typical systems from the intensifier pump to the waste-water collection system.

The key to successful waterjet systems design is to eliminate unknowns before beginning the manufacturing progress. Following is a typical list of product/system considerations that require pre-design answers:

DESIGN CRITERIA/CONSIDERATIONS

- Definition of product(s) to be cut (sample cuts)
- Size(s) to be cut (keep in mind future requirements; consider future product to be cut)
- Number of parts or pieces per hour
- Size, pressure, and number of cutting nozzles
- Space available for installation (provide detailed drawings showing access requirements)
- Other customer requirements (sound level, safety electrical, etc.)
- Duty cycle (8-16-24 hrs./day)
- Use of diamond or sapphires orifices as related to production requirements (the diamond orifice has a 10-1 life ratio over the sapphire orifice)
- Location of intensifier pump in relation to the cutting station (3/8-inch or 9/16-inch plumbing run requirements).
- Water sampled for quality and recommendations made for system requirements
- Location of electrical controls, from very simple to PLC and CNC
- Location of drain(s) (should be identified early in the design phase)
- Location of pneumatic supply lines to suit the traffic patterns of the manufacturing plant and the machinery
- Voltage requirements
- EPA requirements (i.e. is closed loop water filtration required?) See Figure #1
- High-pressure plumbing considerations
  - Coils (from a minimum bend radius of 9/16-inch, on 1/4-inch tubing to other more common sizes as shown in Figures 2 and 3
  - Swivels (inline, dual axis, single axis, parallel axis, bearing mounted, in sizes of 3/8-inch and 1/4-inch) (see Figure 4)
  - High-pressure hose rated for 55,000 psi and tested at 100,000 psi burst.
  - High-pressure nozzle/tubing connections (see Figure 5)
- High-pressure nozzle type (see Figure 6)
- High-pressure on/off valve type
- Nozzle movement, product movement, or both (see Figure 7)
- Safety precautions (guards, shields, mats, etc. (see Figure 8)
- Waterjet catcher considerations (see Figures 9&10)

- Maintaining access for cleanup and maintenance
- Designed to be user friendly, with the following factors in mind:
  - Location of push-button station
  - Height of system for operator convenience
  - Noise level
  - Ease of loading and unloading
  - Operator manuals with highly specific technical information
  - Maintenance manuals for guidance
  - Operator training
  - In-plant pre-system buy-off
  - After-sale follow-up
- Status of product at time of cut (i.e. hot, cold wet, etc).
- Pressure required to cut material(s) (for example: is dual-pressure or multiple-pressure ramping required?)
- Nozzle size for future requirements
- Number of cutting nozzles for future needs
- Should the effluent discharge from the waterjet catcher go to drain or be recycled?

When these types of questions have been answered, an engineer can begin designing the system. The following example illustrates a typical process of eliminating the unknowns.

- *Type of product.* Let's say it's candy produced in 36-inch long pieces that need to be cut into 6-inch pieces.

- *Status of the product.* (Hot, cold, etc.) We find out that the product temperature is about 80° to 90° F at the time it is to be cut. It will be dry, but a little soft at the warm temperature. If at all possible, an engineer should visit the manufacturing plant. A visit will supply the engineer with valuable information on physical layout, product consistency, potential cutting equipment layout, and other critical factors.

- *Nozzle Size.* A sample of the product should be obtained for sample cutting. The sample cutting should always be accomplished at the closest actual conditions of the system requirements. Sometimes it is impossible to duplicate the product cutting other than at the production site. The choice here is to ship trial equipment to the site for the trial cutting (the preferred method), or assume, usually from prior similar product cutting, that a certain pressure and nozzle size will accomplish the job. The usual advantage of test cutting is to establish the lowest pressure and smallest orifice size needed to cut the product at the maximum speed required to produce the desired quality of product.

- *Number of nozzles.* Because we have established the product cutting parameters and we know the production requirements, we can now look at potential equipment design to establish the required number od cutting nozzles. This will also have a bearing on the intensifier model that will be required for the system.

- *Preliminary design*. The design engineer will have to establish the preliminary design at this time. Cutting parameters versus the actual quantity requirements usually dictate conveyor speeds, number of nozzles, and other decisions. Other design features must also be considered at this time.

- *Will the nozzle(s) require frequent on-off cycles?* If so, how frequently? Should high-pressure parts fatigue be considered in the systems design? (The Instajet device was found to greatly increase the fatigue lifetime of high-pressure components.)

- *How can we best ensure safe operation?* The operator should be able to safely change orifices or adjust the cutting parameters while the other adjacent equipment is still functioning. Locations of safety switches and guards must be considered. High duty cycles (24-hour operations) may require backup equipment and the use of diamond orifices for long periods of uninterrupted cutting.

- *Waterjet catcher*. This is often one of the critical links in the total system design. Things such as kerf material building up in the catcher, excess product wetting, product support during the cutting process and catcher size as related to the system configuration, can dictate success or failure of the entire operation. Figure 9 shows a catcher for a slitting machine.

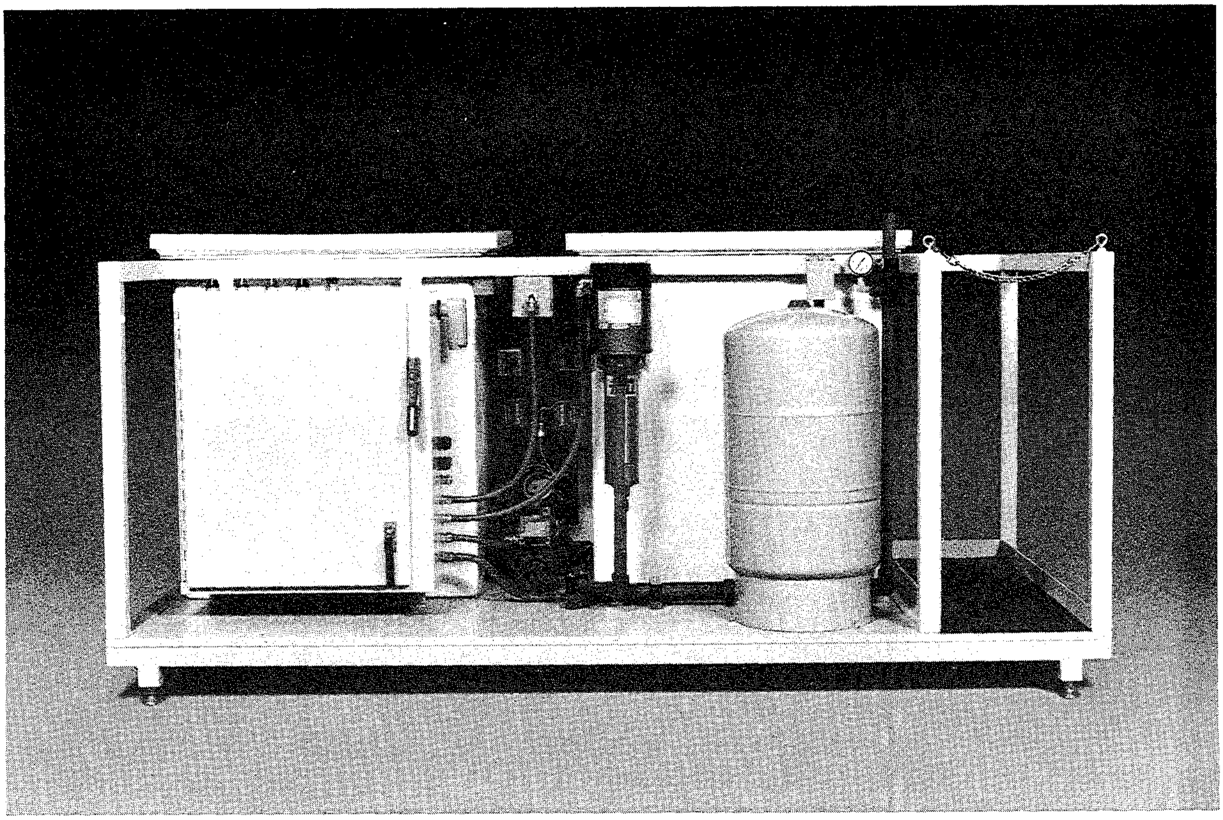
- *Drainage requirements*. Waste water from the waterjet catcher is often discharged to a floor drain. When undesirable contaminants are present in the discharge water, additional filtration or closed-loop filtration may be required.

- *Site-dimensional data*. When all equipment configuration requirements are established, site-dimensional date may be drawn up. This information is important to the customer. It could affect material flow, traffic patterns, drain locations, electrical supply, and more. The equipment layout will also dictate the high-pressure plumbing configuration. Plumbing runs longer than 150 feet should be done with 9/16-inch high-pressure tubing. Safety again should be a consideration in the high-pressure plumbing scheme. Any plumbing runs that are accessible to operators should be shielded.

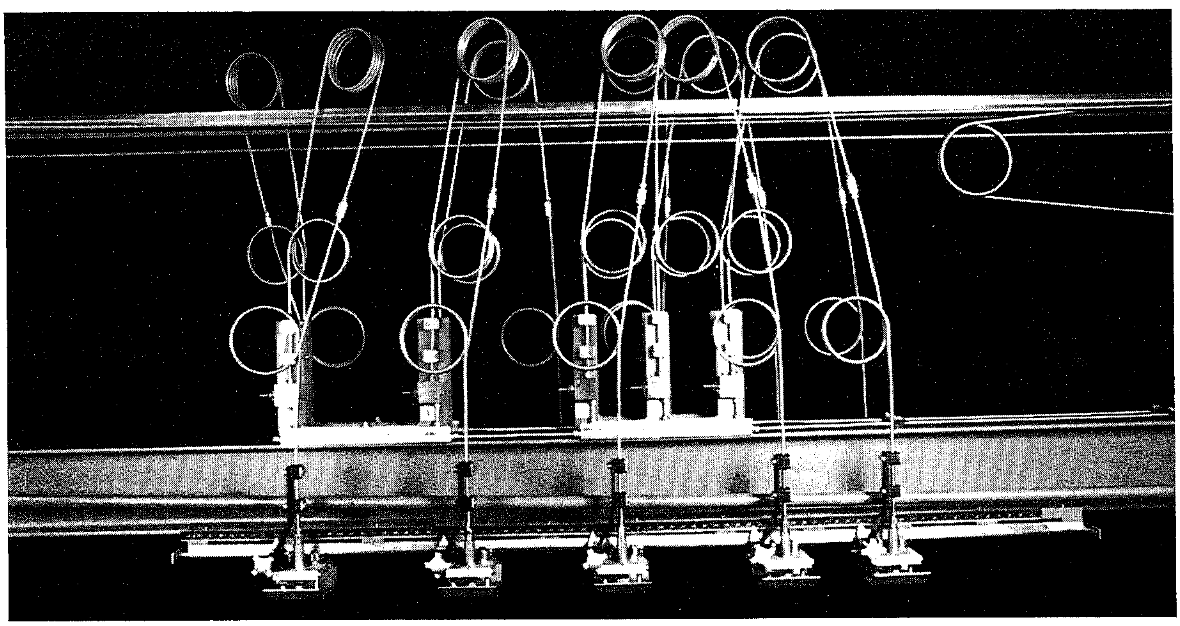
- *Water analysis*. The supply water should be analyzed to ensure maximum orifice life, check valve life, and other component life affected by water quality-standards. (Closed-loop treatment system depicted in Figure 1.)

CONCLUSION

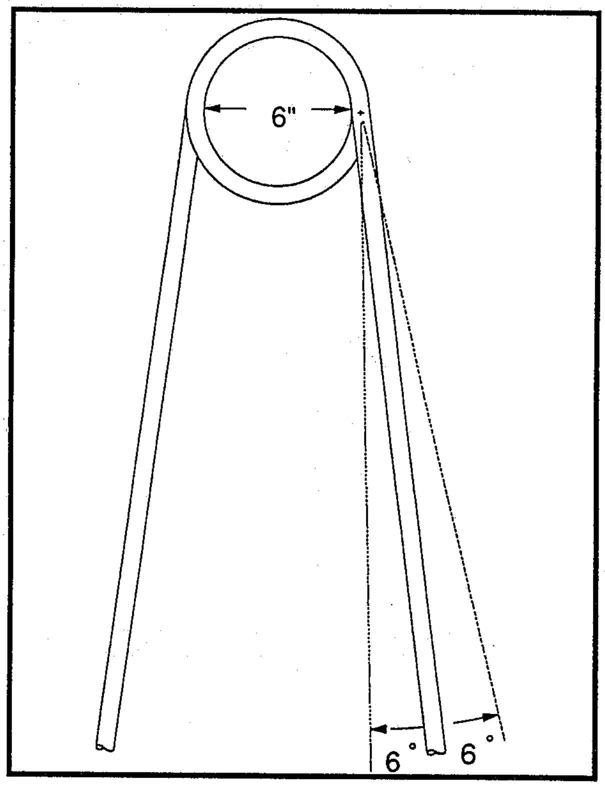
A system is properly engineered, manufactured and inspected will satisfy the customer's requirementsand will provide a win - win situation for the buyer and the seller. (see Figure 9)



Closed-Loop Water Treatment System
Figure 1



Coils
Figure 2



High Pressure Coil
Figure 3

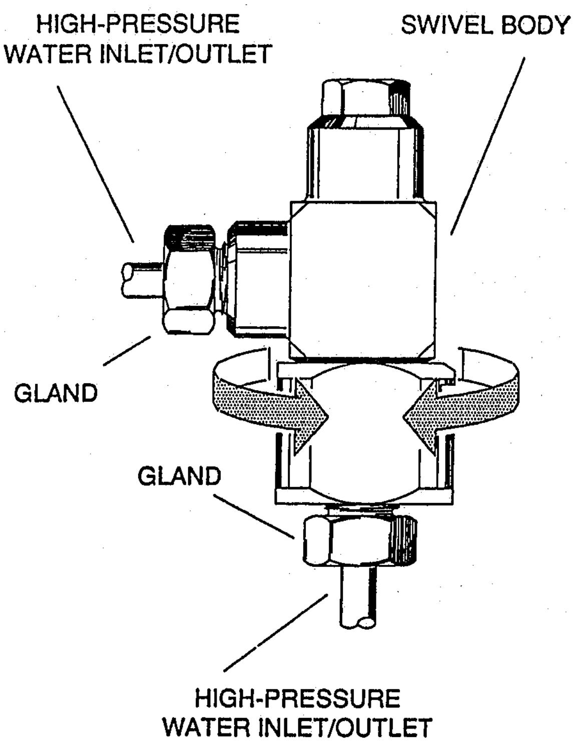
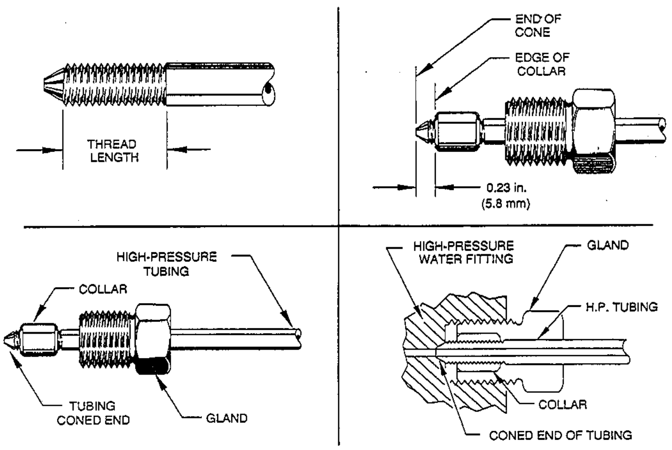
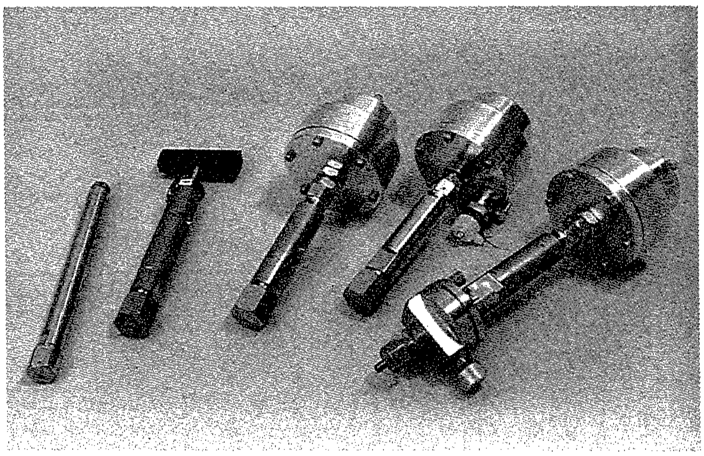


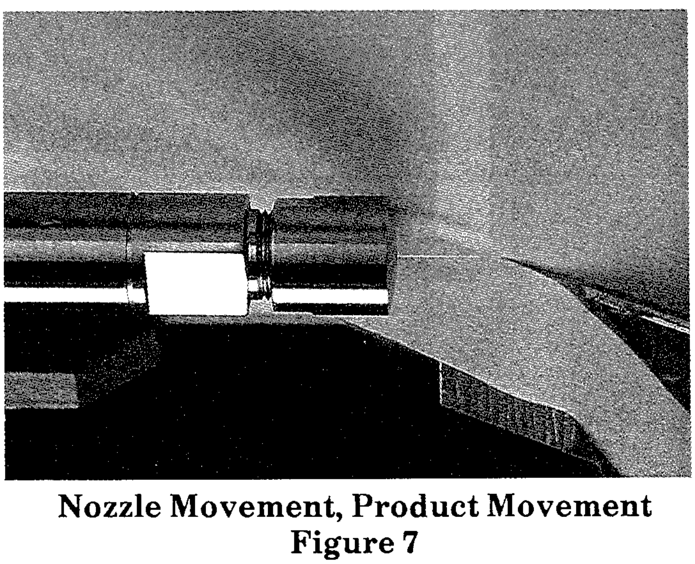
Figure 4



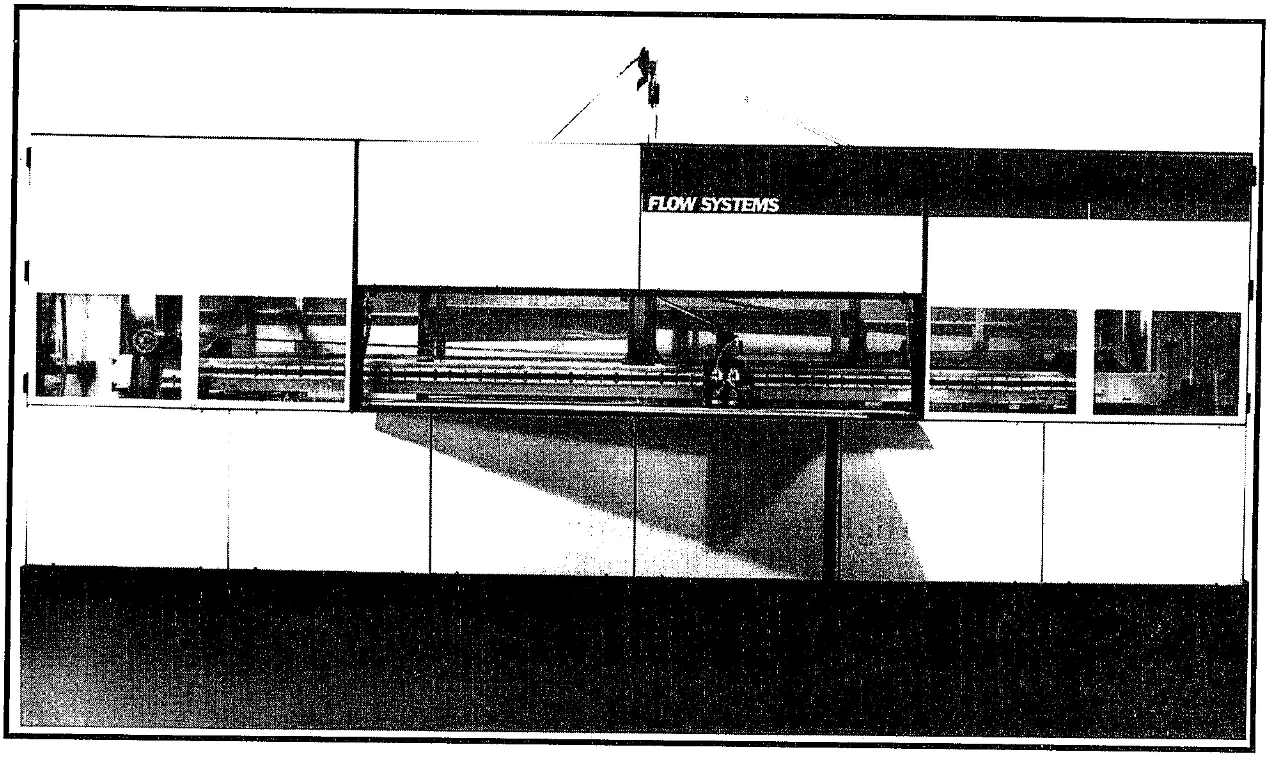
High Pressure Tubing Connections
Figure 5



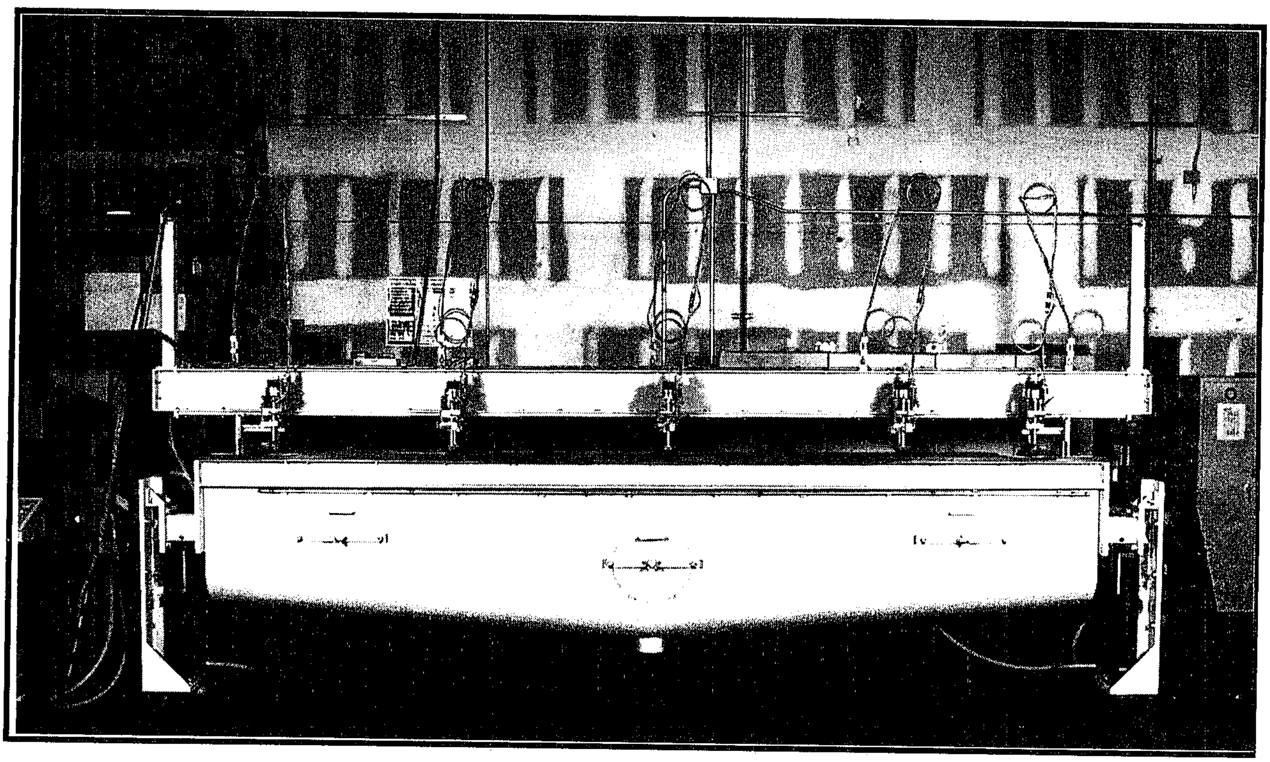
High Pressure Nozzles
Figure 6



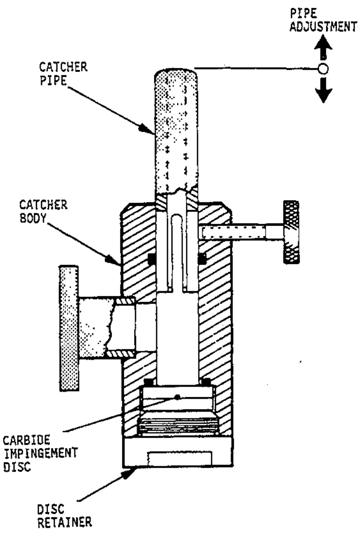
Nozzle Movement, Product Movement
Figure 7



Enclosed System
Figure 8



System Configuration – Waterjet Catcher
Figure 9



Waterjet Catcher
Figure 10

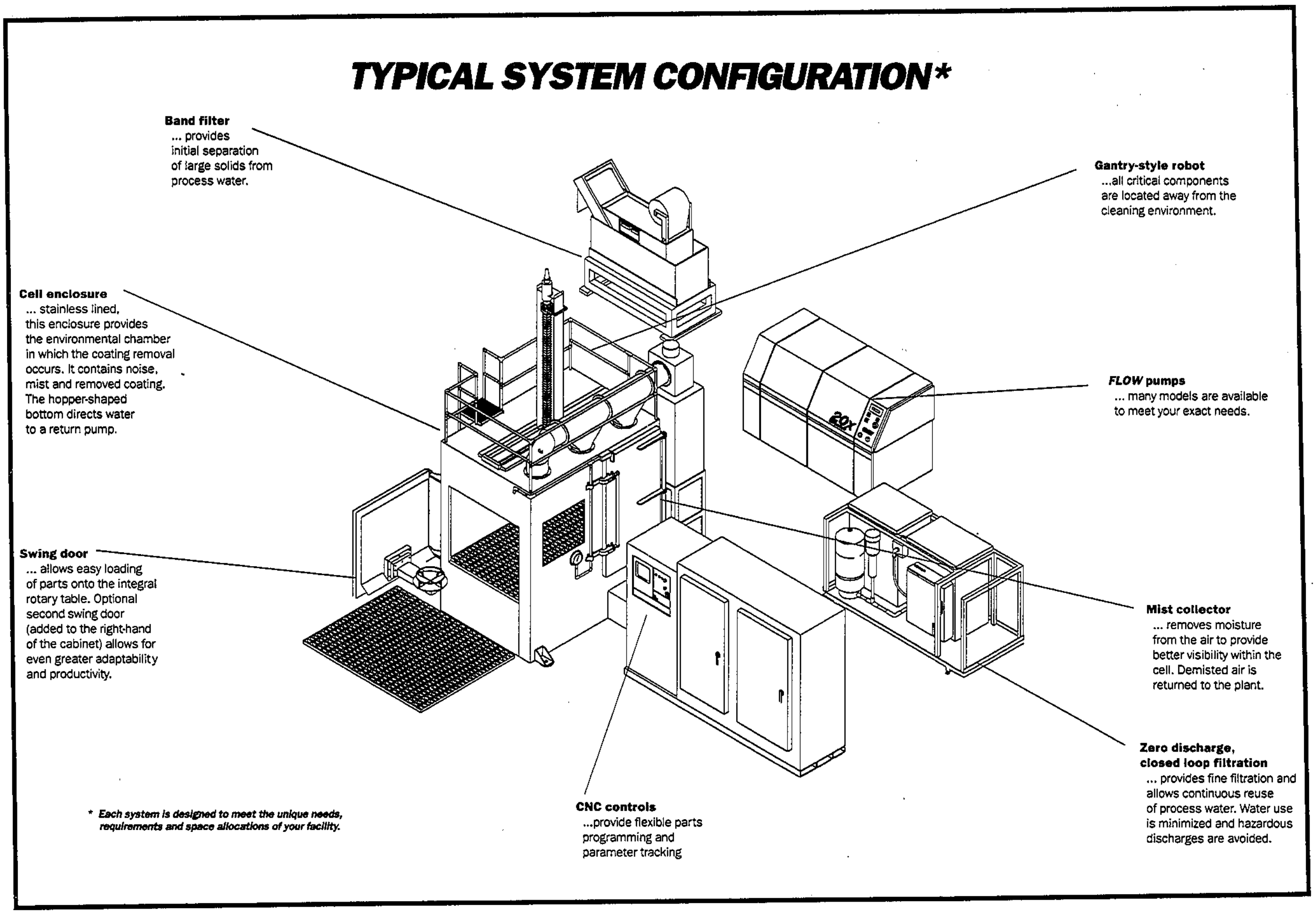


Figure 11

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Paper 65

ON THE ADAPTIVE CONTROL CONSTRAINT (ACC) OF HYDRO-ABRASIVE JET MACHINING

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ABSTRACT

The utilization of real-time control techniques and strategies to constrain or optimize Hydro-Abrasive Jet Machining (HAJM) makes possible to adapt this process to variable and unpredictable operating conditions. When HAJM process is represented by a control model that takes into account non-linearity and uncertainty, and an Adaptive Control (AC) system controls the operating parameters, based on the measurements of the actual machining conditions and on suitable control strategies and algorithms, it is possible to get a level of unmanned automation, productivity, flexibility, precision and quality, higher than utilizing only Computer Numerical Control (CNC) techniques.

This paper presents and discusses the approach followed, the results of the analysis, synthesis, implementation and validation of an Adaptive Control with Constraint (ACC) subsystem for HAJM, integrated into a CNC architecture. The paper analyzes the structure of this ACC for HAJM, based on HAJM theoretical and semi-empirical models and on AC self-tuning algorithms, and the role of the control and controlled variables, the implementation by means of a biaxial force transducer and an iconic graphic software development environment for data acquisition, processing and communication, the integration into the CNC architecture and the experimental validation.

Organized and Sponsored by the Water Jet Technology Association.

1. INTRODUCTION

The potential of Hydro-Abrasive Jet Machining (HAJM) for two and three-dimensional cutting, trimming, piercing and machining of a wide spectrum of materials, is still not fully exploited in terms of productivity, quality, flexibility, economy, unmanned computer automation and integration. HAJM offers many advantages, as the possibility of omni-directional non-contact cutting, change of contour, shape, patterns and angles with a precise and clean workpiece edge, the preselection of process parameters and variables to get desired results. Process variables, as water pressure, jet speed or water flowrate, abrasive mass flowrate, standoff distance and feedrate can be easily programmed and on-line controlled, using conventional Computer Numerical Control (CNC) techniques.

CNC systems have been extensively applied to HAJM in order to greatly reduce operator input and resulting in a significant improvement in productivity. However, as discussed by Mathias et al. (1980), Stute (1980), Weck (1980), Ulsoy et al. (1983), Masory and Koren (1983), Lauderbaugh and Ulsoy (1989) for machining processes as milling and turning, and by Mazurkiewicz and Karlic (1987) and by the authors (1992) for HAJM, on one side, a common drawback of these system is that their operating parameters are prescribed by a part-programmer and consequently they depend on his experience and knowledge. On the other side, further improvements can be obtained by means of the on-line acquisition and processing of process variables, to adapt the working process of a workunit in operation to variable working conditions by varing the process parameters or the machining setting data, in such a way that, despite the effects of unpredicted or unknown and variable error factors, such as changes in the set process variables, machinability or differing size of the unmachined workpiece, as thickness variation, the part can be produced in an economic and efficient way.

HAJM process has to be represented by a control model capable to take into account non-linearity and uncertainty. In order to increase the level of unmanned automation, productivity, flexibility, and high machining quality, in terms of kerf attributes, as depth, width, surface roughness and conicity, particularly in the presence of unexpected variations of workpiece thickness or material machinability properties, advanced on-line control strategies, techniques and systems, as Adaptive Control (AC) and process identification, and suitable sensors can be adopted. These systems, called "technological AC systems" (Weck, 1980; Ulsoy et al., 1983) provide for automatic processing and adaptation of the operating parameters, based on the measurements of the actual process characteristics. As classified by Stute (1980), Ulsoy et al. (1983), and Fassois et al. (1989), typically technological AC systems can be classified into two types, respectively:

- systems using Adaptive Control with Constraints (ACC), which control machining parameters, e.g. feedrate, subject to process and system constraints, e.g. allowable force or power;
- systems using Adaptive Control for Optimization (ACO), which optimize an objective function, e.g. an economic function, or extremize a performance index, subject to process and system constraints.

Most of the AC systems developed in practice can be classified into the ACC typology and are applied to milling, turning and drilling. AC systems of the ACO type have been mainly developed for grinding due to the difficulties in formulating optimization models and realistic performance indices, in on-line measuring required variables in the process environment, and in on-line processing and computing the optimal solution (Groppetti and Comi, 1991).

Before a detailed discussion about the application of AC systems to HAJM, a point of terminology and classification must be clarified (Ulsoy et al., 1983, Lauderbaugh and Ulsoy, 1989). Fixed gain, or constant parameter process controllers for machining applications, that are usually feedback controllers, in the manufacturing literature are referred to as Adaptive Controllers, because they adapt the feedrate to change automatically during operation. This functionality is not standard in the commercial Computer Numerical Controllers, that, as known, allow the on-line control of the position along the programmed path at the set feedrate, and the feedrate override by the intervention of the operator.

While the manufacturing literature refers to these systems as AC, they cannot be classified as AC in the sense defined by the automatic control literature (Astroem and Wittenmark, 1990, Soedersrtroem and Stoica, 1989). In this literature AC systems adapt or adjust the controller parameters, or gains, or characteristics, to maintain or adjust the desired closed-loop servo-system or controller performance in the presence of process disturbances or variations.

The early version of these AC systems, and the ones generally in current use, are conventional constant parameter controllers. These systems may operate with low performance and become unstable, due to unpredicted process parameter changes, even if they have been properly designed in accordance with standard design procedures (Lauderbaugh and Ulsoy, 1989). Several authors have analysed and tested different forms of ACC systems for milling, turning, drilling and grinding (among the many others: Masory and Koren,1980, Stute, 1980, Weck, 1980, Ulsoy et al.,1983, Lauderbaugh and Ulsoy, 1989, Fassois et al., 1989). As discussed by the authors recently (1992), despite the fact that on-line modelling, identification and control of HAJM operation is necessary for its fully exploitation and unmanned automation, few research activities have been done to developing, implementing and validating suitable, effective and fast algorithms, and techniques for on-line ACC identification and control of HAJM.

The approach, followed by the authors for the development of an Adaptive Control Constraint (ACC) system for HAJM, is based on a representation of HAJM process by a control model, that has to take into account non-linearity and uncertainty, and on theoretical and semi-empirical models of the HAJM process for real-time AC and on an ACC self-tuning algorithm. The ACC system has been integrated, as a subsystem, into a control hierarchical architecture, developed and implemented by Groppetti and Comi (1991) for the automation and integration of an advanced CNC HAJM cell, that is a facility for machining experiments and further studies in the area of process computer control, integration and optimization.

The following sections present and discuss the analysis, synthesis and implementation of the proposed ACC system for HAJM, the role of the selected HAJM control variable, i.e. the jet feedrate, the role of the controlled variable, i.e. the vertical component of the impinging jet force, the kerf width, the kerfing surface roughness, the HAJM models and the ACC algorithms, and the software and hardware solutions identified, the experimental setup and validation procedure.

2. HAJM MODELING AND ACC ANALYSIS AND SYNTHESIS

HAJM process has been investigated by many authors in order to get a better understanding of the mechanism involved in the material removal process (Groppetti and Comi (1991). The main problem in HAJM model identification arises from the high number of process variables and from the intrinsic difficulties of the quantitative representation of the influence of some of them on the material removal mechanism. Some models, that take into account roughness and force, have been proposed by Hunt et al. (1987,1988), and a dynamical model has been proposed by Mazurkievicz and Karlic (1987). Capello and Groppetti (1992) have proposed a model based on an energetic semi-empirical approach. Another model, that predicts kerf width, has been proposed by Tan (1986).

All these models and further experimental analyses, executed by the authors, have demonstrated relationships and influences among the evaluated variables, as kerf width, maximum kerf depth, kerf conicity and kerf side roughness, and the typical machining parameters, as water pressure and jet speed rate, abrasive mass flow rate, jet feedrate, abrasive particle attributes and material machinability characteristics. These models present non linearities and uncertainty, that have to be taken into account during computer control design. Also disturbances have influences on process parameters, kerf quality, hydro-abrasive jet characteristics. The main disturbance effects are the following:

- jet deviation and deflection during jet / workpiece interaction,
- workpiece thickness variation,
- variation of the workpiece material machinability characteristics,
- abrasive particle characteristic variation,
- focuser wear,
- input and output transients.

Therefore, an Adaptive Control technique, based on regulator time-varying parameters adjustment, following process changes and time-evolution, has been analysed respectively for kerf depth, kerf side roughness, and kerf width on-line control. As known, of fundamental importance is the presence of the on-line estimation of the unknown parameters (Astroem and Wittenmark, 1990, Soederstroem and Stoica, 1989, Fassois et al., 1989). Therefore the Adaptive Control, implemented in the HAJM cell control architecture, makes possible to react to variations of machining conditions and to process disturbances.
In order to control kerf depth, kerf side roughness and kerf width, i. e. productivity and kerf quality, it is necessary to identify the variable to be regulated, the set point and the control variable: jet feedrate has been identified as control variable, whereas the controlled variable has to be identified, considering both quality and productivity phenomena, as surface quality along the kerf sides, and the kerf depth when cutting, piercing or machining.

For the implementation of the ACC, due to the already saturated real-time processing capability of the HAJM cell controller, and to the need of a fast and powerful development tool for a high level interface towards both the field and the user, and real-time data acquisition, processing and communication from/to the HAJM cell controller, an iconic graphic software development environment, based on the technique of the "Virtual Instruments" (VI), has been used. This tool makes possible the implementation of the self-tuning algorithm and the development of an ACC subsystem. This system has shown a good functionality in operation and has demonstrated that HAJM system automatically and promptly reacts to unexpected process variations, as workpiece thickness variations.

This makes possible virtually both HAJM unmanned operation and the attainment of the desired machining productivity, flexibility and quality level.

2.1 ACC of Exerted Force and Kerf Depth

Hunt et al. (1987,1988) have proposed a model that predicts the force F_z acting on the workpiece, resulting from jet feedrate u and workpiece thickness h, or kerf depth, based on the assumption that material removal rate is proportional to the applied energy or power, as demonstrated by Hashish (1984) and Capello and Groppetti (1992).

In fact, operating with constant water pressure and abrasive mass flow rate, from a multiple linear regression analysis of experimental data, a force expression can be defined as follow:

$$F_z = K_1 u + K_2 h + K_3 \tag{1}$$

where K_1, K_2, K_3 are coefficients to be evaluated experimentally, and the kerf side surface roughness:

$$Ra = D\ h + E\ u + F_Z \tag{2}$$

and

$$Ra = f(F_Z, u) = L - B\ u + C\ F_Z \tag{3}$$

where D, E, L, B and C have to be evaluated experimentally.

In order to take into account the dynamics of the material removal process and the transients, Mazurkievcz and Karlic (1987) have proposed a dynamical transfer function, for the modeling of the transient due to a step variation of a variable, to be used with static models, as follows:

$$G_{HC}(s) = \frac{1 - e^{-s\tau_A}}{s\left(1 + A\left(1 - e^{-s\tau_A}\right)\right)} \tag{4}$$

where A is a jet deflection factor and τ_A a time constant; eq. (4) has been approximated by:

$$G_{HC}(s) = \frac{F_z(s)}{u(s)} = \frac{1}{1 + s\ \tau_A} \tag{5}$$

where τ_A can be evaluated experimentally.

Considering eq. (5), with τ_A , τ_B time constants and K_1, K_2 gains:

$$F_z(s) = \frac{K_1}{1+s\,\tau_A} u(s) + \frac{K_2}{1+s\,\tau_B} h(s) \; . \tag{6}$$

Adopting F_z as controlled variable, it is possible to control F_z in order to have a through kerf in any condition, for different and unexpected workpiece thicknesses. It is also possible to use Ra as set point, and F_z as controlled variable, correlated to Ra, as proposed by Birla (1980), for conventional machine tools. Jet feedrate can be used as control variable, because it is easily CNC controlled.

Satisfying the rules for the implementation of real-time digital control system of a continuous process, suggested by Astroem and Wittenmark (1990), as AD / DA converters syncronized by the same CPU clock, ACC has been implemented by means of a PC external to the CNC (see Fig. 1). The ACC architecture shows a cascade with two closed control loops, the internal secondary loop of jet feed rate control with a band width higher than the band width of the external primary loop of the process.

Considering the fundamental subsystems, respectively the feedrate control loop, the force sensors, the HAJM process, and suitable time constants and gains, the following transfer function of the global process has been defined:

$$G(s) = e^{-sT_B} \frac{K_1 K_G}{(1+s\,\tau_G)(1+s\,\tau_A)} \; . \tag{7}$$

Using a PID regulator and a PID parameter tuning method, an algorithm for the evaluation of the PID parameters has been obtained and implemented in the PC, as discussed by the authors in (1992).

Because the HAJM process presents nonlinearities and disturbances, a RLS (Recursive-Least-Squares) identification algorithm has been adopted in order to estimate the parameters of the transfer function (7), to be input to the PID tuning algorithm (Soederstroem and Stoica, 1989). Fig. 1 represents the kerf depth and jet exerted force ACC block diagram.

2.2 ACC of Kerf Side Roughness

A kerf side Ra roughness ACC system can be an alternative to the kerf depth and jet impinging force ACC system. Because the on-line direct measure of this Ra roughness is difficult, Ra can be evaluated using the (3), and the transfer function assumes the following more complex expression, with suitable gains and time constants (Groppetti et al., 1992):

$$G(s) = e^{-sT_B} \frac{K_1 C - B(1+s\,\tau_G)(1+s\,\tau_A)}{(1+s\,\tau_G)(1+s\,\tau_A)} \tag{8}$$

The transfer function (8) can be implemented as the previous one (7).

2.3 ACC of Kerf Width

An ACC system of kerf width control can be developed in order to control the precision and quality of HAJM kerf. As known, kerf width depends on nozzle or focuser wear, and on HAJM process parameter variations. When a cut without scrap is not required, focuser nozzle wear can be compensated by CNC tool diameter software compensation standard routine, using an on-line measurement of jet diameter or of focuser wear, or the predictive evaluation of focuser life and wear during operation. A kerf width ACC can be based on the model proposed by Tan (1986). This ACC can control focuser nozzle wear and the influence of process disturbances on kerf width. In this case a solid state linear camera can be used, as jet diameter or kerf width sensor, and the same beforesaid algorithms can be applied for self-tuning (Groppetti et al., 1992).

3. KERF DEPTH AND FORCE ACC IMPLEMENTATION AND VALIDATION

In order to implement and experimentally validate the ACC algorithm, a prototype kerf depth and jet impinging force ACC has been implemented into the HAJM cell control architecture and validated, while the implementation of the other ACC and the experimentation of other ACC algorithms is still in progress. Setting a suitable force reference value, the ACC allows the control of the through cut in the presence of workpiece thickness variations. Therefore a biaxial force transducer based on load cells has been designed (see Figure 2), capable to detect on-line the vertical and horizontal components of the force exerted by the jet on the workpiece. The experiments have confirmed that the vertical component F_Z of the exerted force has a prominent role and can be assumed as controlled variable for the ACC system, as previously demonstrated by Groppetti et al. (1993). An iconic graphic software development environment implemented on PC has been used. This environment allows data acquisition, processing and communication by means of the Virtual Instrument (VI) technique (Betts, 1990, Labview2, 1990). A high level interface towards both the field and the user, and the integration with the HAJM cell controller have been developed. The VI technique allows to design a graphic control panel connected with a VI iconic block diagram, representing the program. Fig. 3 exemplifies this approach, showing the Control Panel implemented for the interactive control of the HAJM ACC process, that is activated switching from Manual to Automatic mode.

The main HAJM ACC program is the block diagram that is built in a schematic, modular and structured way, using a programming language, named G, by means of icons representing the VI, with I/O interconnections (see Fig. 4).
In order to integrate the ACC subsystem into the HAJM cell control architecture, for PC/CNC signal and data communication, the CNC system program has been modified by means of a custom software interface routine (Groppetti et al., 1992).

ACC validation phase has been executed by means of cutting experiments on 6061-T6 aluminium alloy specimens, with thickness variations, with typical cutting conditions (300 MPa pressure, 600 g/min abrasive mass flow rate, no. 80 mesh garnet abrasive, 400 mm/min feedrate). These experiments have demonstrated the functionality of ACC in operation in a real production environment and the validity of such an approach.
While without ACC for a given feedrate an unexpected thickness increase causes an incomplete cut with an increase of the vertical force acting on the piece (see Fig. 5-a), the activation of ACC

causes process identification, the estimation of transfer function parameters, regulator tuning, and the automatic variation of feedrate control variable (see Fig. 5-c), in order to constrain jet force controlled variable to a constant value, corresponding to a complete through cut also in the presence of unpredicted thickness variations (see Fig. 5-b).

4. CONCLUSIONS

The ACC approach, based on a RLS self-tuning algorithm, has been demonstrated by the implementation of a force and kerf depth ACC system in a CNC HAJM cell, capable to control kerf depth and through cut, even in the presence of unexpected process variations, as workpiece thickness variations. This ACC system increases automatically the productivity of the HAJM cell and the quality of HAJM process, and virtually it makes possible a fully automated and unmanned production environment, accounting for unpredicted changes in the machining conditons. The implementation and integration of the ACC system in the HAJM cell control architecture, by means of suitable sensors and actuators, by an iconic graphical development environment for on-line data acquisition, processing and communication to the CNC and high level user interface, has demonstrated the feasibility and validity of the approach, in terms of development and implementation time, ease of documentation, reliability and user friendliness. The implementation of other ACC algorithms for force and kerf depth control, of other ACC systems, based on kerf side roughness and kerf width as controlled variables, and the study of ACO (Adaptive Control for Optimization) algorithms, that allow the control and optimization of HAJM process, are in progress.

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NOMENCLATURE

F_z Vertical component of the force exerted on the workpiece by the jet
u Feedrate
h Workpiece thickness, or kerf depth
Ra Kerf side surface roughness
A Jet deflection factor

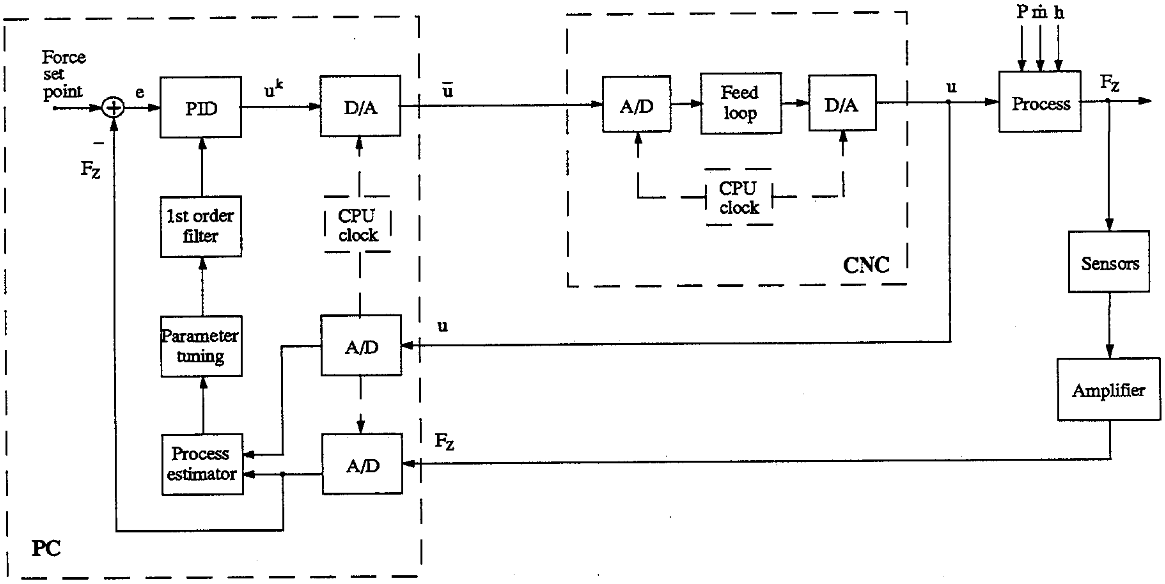


Fig.1. Kerf depth and force ACC block diagram.

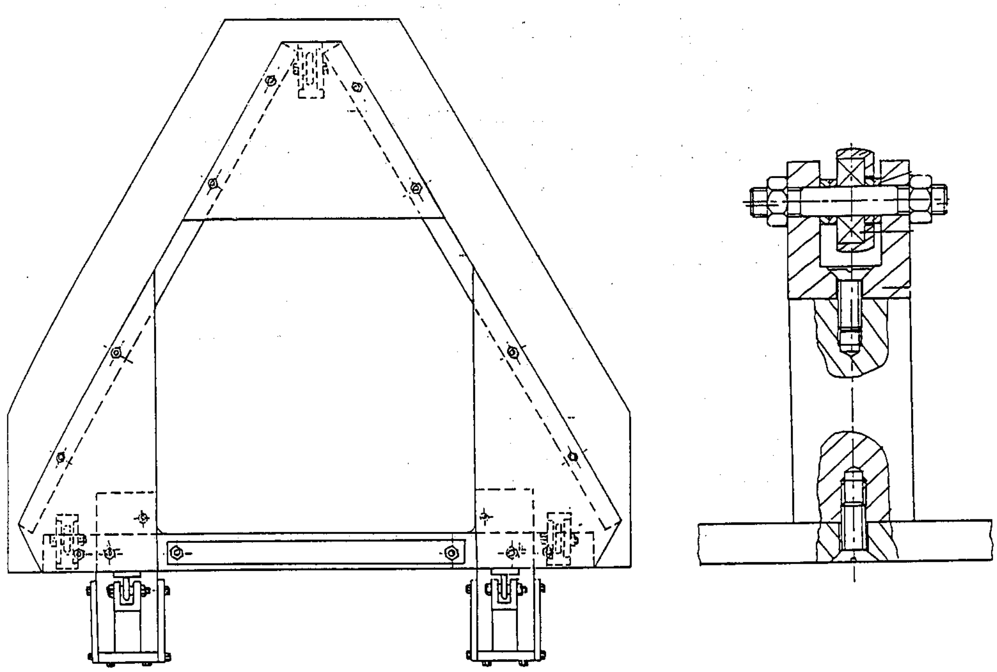


Fig. 2. Biaxial force transducer.

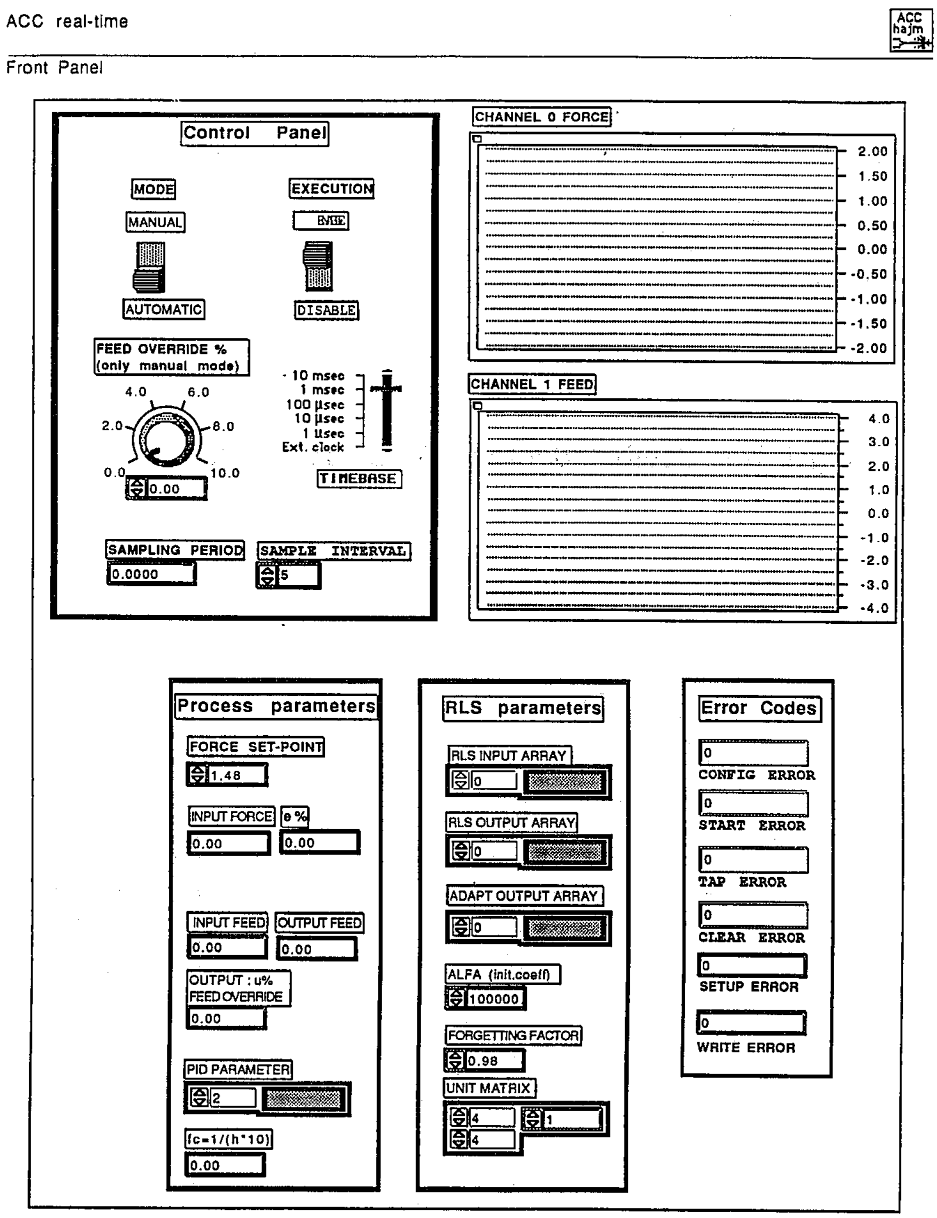


Fig. 3. HAJM ACC interactive front control panel.

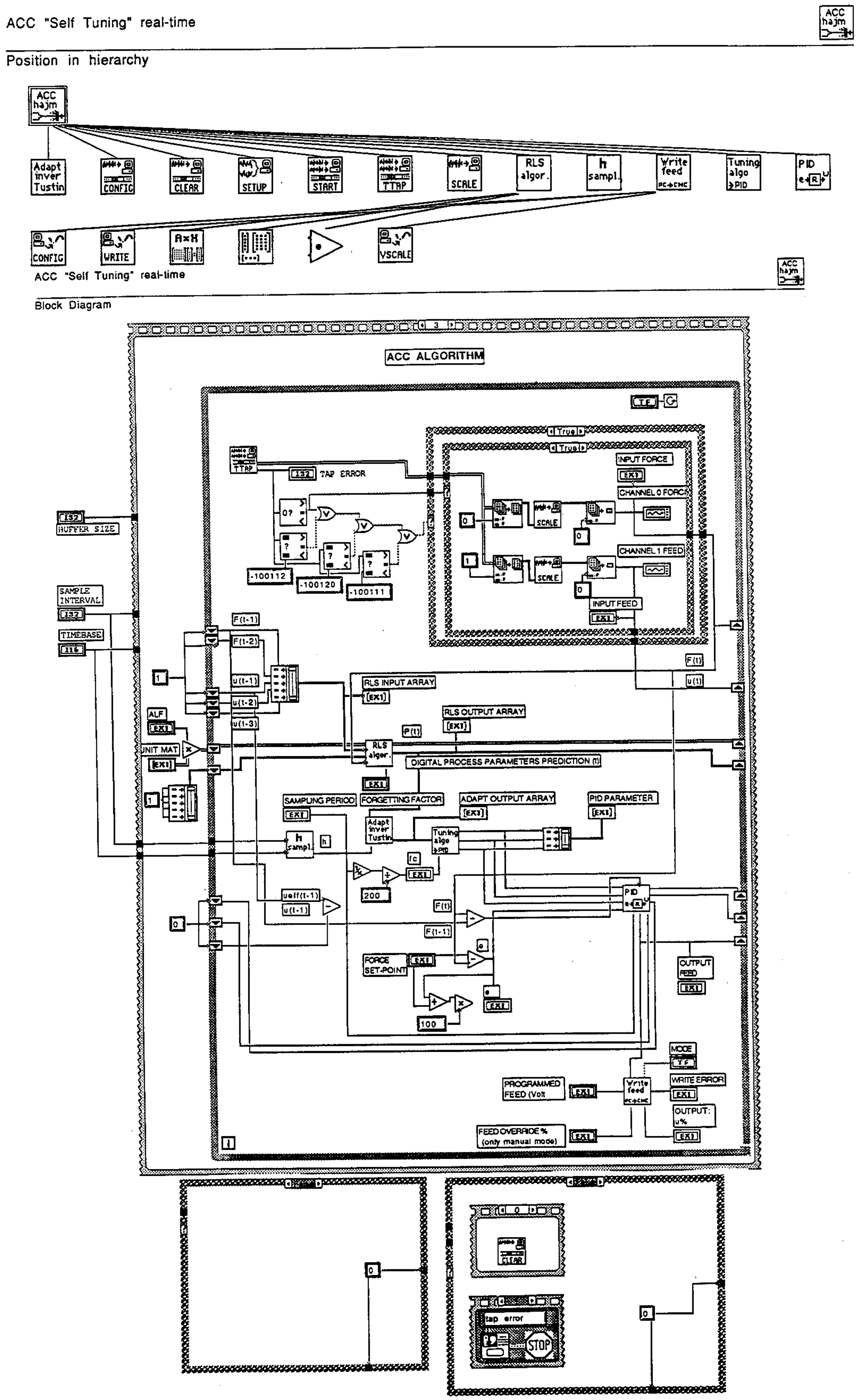
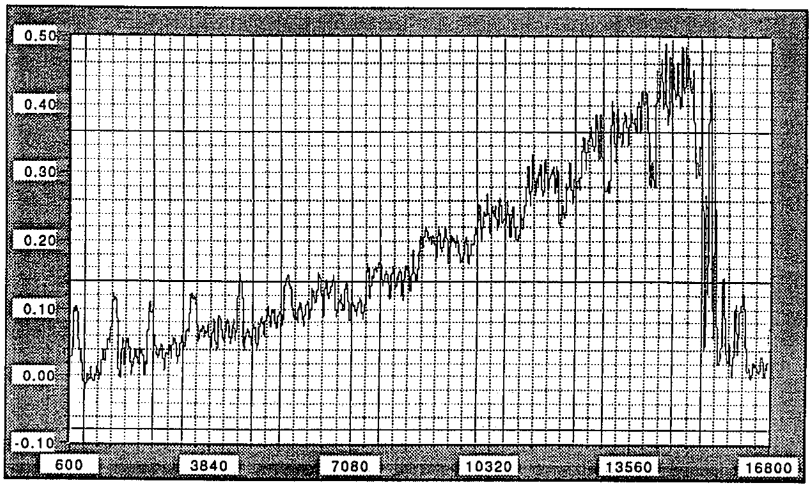
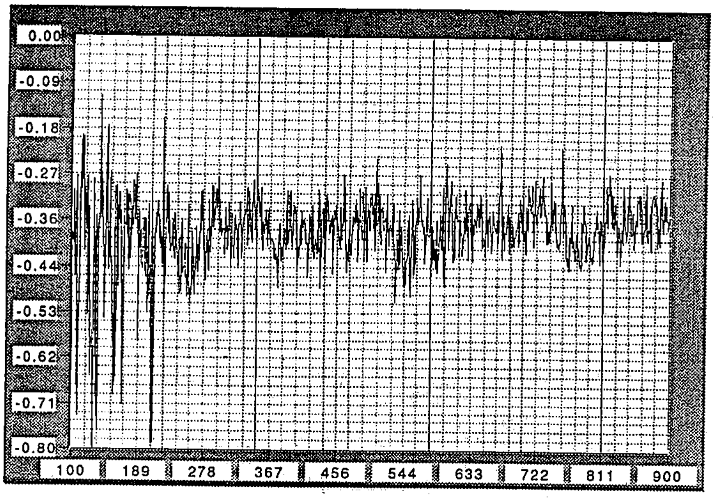


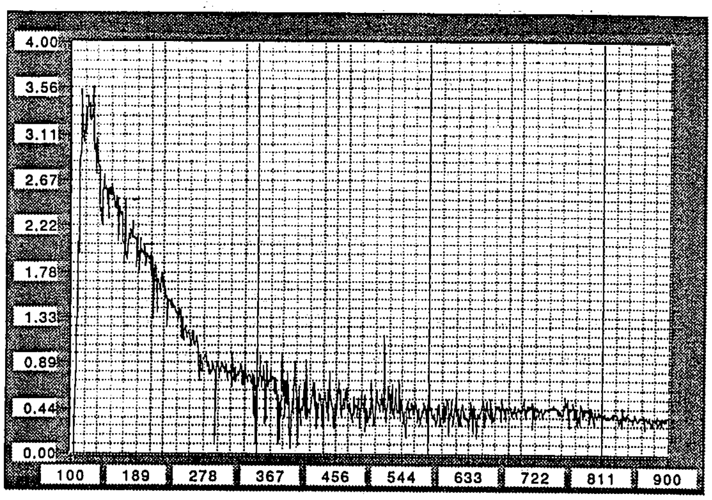
Fig. 4. HAJM ACC position in hierarchy and main program block diagram.



(a)



(b)



(c)

Fig. 5. Experiments of workpiece thickness increase: without ACC: (a) incomplete cut, force increase; with ACC: through cut, (b) constant force, (c) feedrate decrease.

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WATERJET MACHINING IN RELATIONSHIP TO DESIGN ENGINEERING FOR MANUFACTURABILITY

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ABSTRACT

Getting the job done correctly the first time and on time and within budget is the concern of every manufacturing company in the world. This has become an even greater issue in today's shrinking military/defense programs and the worldwide economic recession. Regardless of the manufacturing process to be utilized, coordination of initial part and tool design with manufacturing engineering is an absolute requirement. When new and non-traditional machining processes are introduced, then it becomes paramount that the special process requirements be seriously taken into account at the design conceptualization stage.

Waterjet machining has come of age and is now considered as an alternate machining process rather than an experimental method of material removal. This paper will explore waterjet as a true machine tool process, special considerations for tooling, achievable tolerances, surface finish, allowable geometries, best material suited for the process and machine cost factors.

WATERJET/ABRASIVE WATERJET MACHINING IN RELATION TO DESIGN ENGINEERING FOR MANUFACTURABILITY

I. Overview

Getting the job done correctly the first time and on time and within budget is the concern of every manufacturing company in the world. This has become an even greater issue in today's shrinking military/defense programs and the worldwide economic recession. Regardless of the manufacturing process to be utilized, coordination of initial part and tool design with manufacturing engineering is an absolute requirement. When new and non-traditional machining processes are introduced, then it becomes paramount that the special process requirements be seriously taken into a account at the design conceptualization stage.

II. Waterjet machining as a true machine tool process.

Since the late 1980's, the advancements in waterjet machining capabilities have allowed for producing finished, high precision components. More reliable high pressure pumping units coupled with long life ceramic cutting nozzles and precision abrasive media (usually garnet) metering systems provide us the means to achieve close tolerance completed and near net parts. Waterjet end effecters or tools have been integrated with high precision custom specified machine tools such as CNC multi-axis gantries. By using a total system approach which includes design engineering, computer part programming, tool and fixture design and fabrication, manufacturing and production engineering inter-related to the waterjet process has catapulted this new technology into a usable near to standard methodology.

III. Special Considerations for Waterjet Machining.

A. The process in summary. Water (filtered to .5 micro, deionized, or reverse osmosis purified) is pressurized by hydraulic intensification (by a 20 to 40 ratio) to 40 to 55 kpsi. The liquid is compressed by volume 13% and then travels via high pressure tubing to the cutting head assembly. The water stream is forced through a saphire or diamond orifice (.004" to .020" diameter). If abrasive media is required in order to remove the material being machined, then usually garnet of 50 to 220 mesh is introduce by venturi principle into a mixing chamber directly below the orifice. Finally the entrained garnet and water stream exits a ceramic nozzle (.020" to .070" I.D.) at 3000 feet per second. This tremendous concentrated energy beam is articulated by a CNC machine tool and achieves remarkable material removal and contouring with a diverse range of metals and composites.

B. The destructive nature of the process. Only a small portion of the energy of the cutting stream is exhausted by contacting and eroding the work material. After exiting through the material, the jet is still very powerful and continues to travel until it contacts another surface. (New research waterjets are being used to pocket mill, however this application is not ready for the factory floor.)

It is obvious that the destructive force must be captured or deflected. If not done there will be serious damage done to the part being machined and or to the tools or fixtures holding the material. The design engineer must take precautions and analyze the jetstream exit vectors so that unforseen scrap conditions do not occur.

IV. Tolerances achievable with waterjet machining.

The discussion of part tolerances when utilizing the waterjet process often becomes a heated debate. First, let us begin with the machine tool and the work envelope. In the early days (mid 1970's) most applications such as carpet cutting, automotive instrument panel trimming and sheet metal blanking did not require precision machines. For example robotic pick and place type pedestals or overhead gantries were used. Plus or minus one-sixteenth inch was acceptable for the part and positioning and repeatability of +/-.030" for the robot was just fine. Flat patterns were often done on retrofitted plasma arc of flame cutting 2 axis bridge or cantilever systems. When abrasive was required the tungsten carbide nozzles employed would wear rapidly (often within 2 hours) so that tolerances would further deteriorate due to changeouts and repeated indexing. Work envelopes were usually 2' X 6' X 12' for three dimensional work and 4' X 10' for flat work. It was not until about 10 years later (1986) that precision waterjet machining became an issue. The aerospace/defense industry pushed the waterjet system manufacturers and machine tool builders for the critical tolerances required to meet their needs especially with the new composite and metal matrix materials. Robots and flame cutters were replaced by true machine tools built to standards set by organizations such as the National Machine Tool Builders Association and the rigid specifications of the aerospace companies themselves. Today the work envelopes are as large as 5' X 12' X 40'. Linear positioning to +/-.005" is now standard and smaller systems have been built to hold +/-.1 degrees or even better. Mechanical backlash and reversal error has nearly been eliminated. Electronic compensation has further reduced motion error. It is now possible under dynamic conditions to position and repeat to within +/-.002" in a moderate volume (3' X 5' X 10').

In the very near future machine tools specified for the waterjet process will be able to position as accurately as any high precision multiaxis machine center (+/-.0005). However, there is another important factor to determining final part tolerance tool wear. Here we are talking about the hydro-abrasive action upon the nozzle and other considerations. Historically, nozzles were constructed of C2 tungsten-carbide. High grade garnet media with a mohs hardness scale range of 8-9 would enlargen the bore at a rate of .002" to .005" per hour or more when using a rough grade with a high flow rate (2 lbs/min). Another major problem was with the garnet delivery and metering system. Occasional flow would be interrupted or clogging would occur. Garnet starvation of course would cause the cutting jet stream to loose energy and the cut would degradate or stop entirely. Irregular metering of the abrasive would cause similar problems. Orifice failure would also cause catastrophic damage to the part material. These serious problems have been nearly rectified in the last two years through improvements in manufacturing and materials and also heightened supplier quality control standards. But still there remains minors areas such as nozzle wear that dictate that we add process tolerance to the machine tool's inherent accuracies. Minimally +/-.002" should be added to the machine's +/-.002" resulting in a finished part tolerance of approximately +/-.005". We are assuming that proper tooling will take care of part surface conformance and program indexing. It is possible on very small details to achieve tighter tolerances even in the range of +/-.001 - .002. Large, complex surfaced components can be waterjet machined to within +/-.010". The tolerance target for the near future will be +/-.001 for small and moderate envelopes and +/-,005 on large details.

V. Surface finish.

Roughness average in relation to waterjet machining should be examined by separating materials into two major groups: metals and composites. Metals breaks down into two subgroups: soft metals (aluminum, copper, brass) and hard metals (steel, stainless steel, nickel alloys, titanium). The soft abradable and usually the best surface finish is 125 to 250. The hard materials can attain finishes to the 63 to 125 range. The entry side of the jet produces the best finish. The exit is usually where striations occur and the finish roughens. The composite group also breaks down into two subgroups: solids (plastics like nylon and urethanes), solid-like laminates (graphite-epoxy) and kevlar laminates is the final group. Fine finishes are achievable with the solids 63 to 200 RA. The fibrous laminates such as aramid/phenolic do not allow for good finishes due to the stranding and fuzzing of the material, however waterjet is far more effective than mechanical machining in producing a finished surface. Factors that influence surface finish are: feed rates, pressures, garnet size and garnet flow.

VI. Allowable geometries.

Depending upon the type of machine tool employed, geometries of parts that are waterjet machinable are extensive. There are certain limitations. At the time of the writing of this article, the jet stream must pass through the materials cross section to achieve critical tolerances. There are advanced research systems that are accomplishing turning, drilling, and depth milling, however, these systems are not yet ready for the factory floor and it has not yet been determined to what level of precision these new capabilities will rise. Thus given the above stated condition, certain geometries present serious problems. When the exit stream can not be captured or properly deflected due to difficult part configuration (such as bosses or fold backs), then the danger of surface erosion or destruction is very great.

If you think of the abrasive (or pure) waterjet as a laser beam or a wire edm with 5 axis potential, you can see that it is a very versatile tool. Some of the existing motion systems can rotate +/- 90 degrees from vertical and rotate parallel to the "z" axis two or more full rotations (720 degrees). This flexibility of motion allows for a great variety of part surfaces. However, this puts extreme demands upon the cutting stream focusing mechanisms as well dictating nozzle and orifice technology that will keep the jet coherent and maintain a correct vector tool as one profiles through thick material controured at 45 degrees produces a cut length of 2.828" and at 60 degrees a 4.000" cut depth results. Other positive aspects of the waterjet process are as follows: omni-directional, small cutter diameters (.002 - .008 for pure water with a .001" diamond orifice is being considered and for abrasive jets exit diameters of .025 to .080.), minimal torque applied to material (usually between 2-15 ft/lb).

VII. Best materials for the process.

In section V, Surface finish, some of the materials best suited for waterjet machining were mentioned. Other materials include: glass (except for tempered which tend to fracture), laminates of differing thermal properties (the jet does not reach more than about 180 degrees F.), metallics and non-metallics bonded together, heat critical materials, fracture critical items, tool steels, foam, paper, rubber, and honeycomb materials of all types.

VIII. Cost factors.

This section will only be treated marginally. Systems, excluding off-line programming and installation will run from about $200,000 for two axis and between $500,000 to $1,000,000 and more for 5 axis sophisticated machine tools. Consumables such as garnet and spare parts and maintenance vary too widely to even give figures. Overhead and cost of money are dependent upon each companie's unique economic situation. Needless to state, the waterjet machining process is expensive, similar in many ways to other nontraditional methods such as laser and wire edm. However, the results that can be attained by using waterjet machining are often the most cost efficient ways to produce the needed components.

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APPLICATION OF ADVANCED ABRASIVE WATERJET MACHINING AT GE AIRCRAFT ENGINES

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ABSTRACT

For nearly four years GE Aircraft Engines (GEAE) has been taking advantage of the abrasive waterjet (AWJ) machining process. GEAE's introduction to AWJ machining was the development of a cooling hole drilling process for turbine components in an advanced engine application. This drilling process was demonstrated on a limited production basis in a laboratory environment and illustrated the potential offered by AWJ machining. Since that time, GEAE has invested in a State of the Art AWJ machining center and has applied the process to a wide variety of applications. These applications range from rough machining dovetail slots in nickel alloy turbine rotor components to drilling small diameter cooling holes. During the development of these applications the benefits of the AWJ process as well as its limitations were explored. This paper will discuss GEAE's application of the AWJ process as well as limitations discovered and areas of needed process and equipment research and development.

Organized and Sponsored by the Water Jet Technology Association.

1.0 INTRODUCTION

GE Aircraft Engine's (GEAE) experience with abrasive-waterjet (AWJ) machining began back in the mid-1980's. During this period GEAE, like many other manufacturing companies, was curious as to the capabilities of this new material working process called AWJ machining. This curiosity led to informal investigation of the AWJ process and several cutting trials were conducted in a variety of aircraft engine materials. Although there was some interest generated, and the benefits of this process for rough cutting two dimensional shapes was realized, the process was considered new and needed many refinements.

In late 1987, GE was manufacturing a component for an advanced engine which required the drilling of small diameter, 0.5 mm (.020 inch) cooling holes through a ceramic coated nickel alloy turbine component. These holes were being machined using a laser, and it was determined that the laser drilling process caused small cracks in the ceramic coating at the metal interface. This was an undesirable condition and an alternative process was needed to drill these holes with no ceramic cracking or chipping. AWJ was considered for this application and a development effort was undertaken to develop a robust AWJ drilling process for this component. This successful development activity spanned two years and established a process which was used to drill over 200 components (figure 1 and 2) over the life of the engine program. (Hashish, Whalen., 1991) This successful application of the AWJ process also launched GEAE as a AWJ process user .

Due to the success of this drilling project, GEAE decided in 1989 to invest in the AWJ process by purchasing an AWJ machining center. At this time GEAE realized that the AWJ process had tremendous potential in rough cutting as well as precise operations such as cooling hole drilling and tight tolerance finish machining. Since the full potential of the AWJ process was far from being realized, GEAE decided to specify the requirements for a state of the art AWJ machining center rather than a standard machine of that time. This decision started a six month effort to evaluate existing AWJ machine tools and process equipment, as well as define industry best practices. All of this data was combined with existing knowledge of advanced conventional machine tools to define the requirements of GE's AWJ machining center. During this time GEAE also conducted an extensive search of equipment manufacturers and integrators to select a team who would build this AWJ machining center.

QUEST Integrated, Progressive Technologies, and GEAE worked together to design and build this state of the art AWJ machining center based on the requirements established. This machine was designed and built in 9 months and installed at GEAE's facility in the spring of 1990 (figure 3). This machine possesses some unique features not normally integrated into a standard AWJ machine. These unique features included:

- An enclosed work environment for safety, noise reduction, and vapor containment
- A high tolerance , 0.08 mm (+/-.003 in.) accuracy five axis gantry manipulator
- Fixed precision fixturing points isolated from the vibrations of the process and manipulator
- Automatic waste removal system to circulate water within the catcher system and remove spent garnet and kerf waste
- Microprocessor controlled pressure profiling of the high pressure water system
- Built in vacuum system to support abrasive flow at low water pressures and a nozzle flushing system to keep internal surfaces clean and consistent.

- Complete integration of the manipulator and process equipment with monitoring feedback and control.

This AWJ machine tool with these features allowed GEAE to stretch the capabilities of the AWJ process and truly take advantage of the benefits offered by this process. It also allowed GEAE to determine some of the process limitations and areas for development.

Since this machine was originally installed, one significant enhancement has been made to further the capabilities of this AWJ machining center. In 1992, the standard abrasive-waterjet machining nozzle was replaced with the state of the art "Intelligent Nozzle" developed by QUEST under a National Center for Manufacturing Sciences (NCMS) contract. This nozzle offers many advantages over conventional AWJ nozzles especially the ability to rapidly change the mixing tube and orifice. In the "Intelligent Nozzle" the mixing tube and orifice are in a pre-alignable quick change cartridge. The use of the "Intelligent Nozzle" has improved GEAE's AWJ capabilities and reduce process setup times and cost.

2.0 GEAE's APPLICATION EXPERIENCE

Soon after GEAE's AWJ facility was installed and operational, a wide range of applications began to surface. The first real difficult application was the finish contour cutting of airfoil slots in a composite fan stator case (figure 4 and 5). AWJ machining was considered for this component because of several problems with the conventional milling process that was currently used. Conventional milling had a high process cost because of long cycle time and the use of expensive diamond tooling. In addition, because of the constraint of milling cutter size, conventional milling did not produce the small leading and trailing edge radius needed.

The development of an AWJ process for this application, was demanding from several viewpoints. First a complex four axis NC program needed to be developed. Complex programming alone was not that difficult of an issue, however, when coupled with the special considerations which are needed by the AWJ process, numerous trials were necessary. If a knowledge base for kerf shape, and process parameters existed, the development cycle for the NC programming of this component would have been reduced by 50%.

The second obstacle which needed to be overcome to develop a successful AWJ process was the space limitations and stream energy absorption. Because of the geometry of this component, accessibility was limited and a special right angle cutting head and catcher system was needed. Available technology in this area was quite limited and in this application like many others, if smaller more compact nozzles were available as well as efficient, long lasting stream catchers, the application base would be greatly expanded.

Overall this first complex application was successful and reduced process costs by 3 times while providing the airfoil shape desired. Along with this success, several limitations of the AWJ process were discovered.

Another application which tested the capabilities of the AWJ process was the rough machining of dovetail slots in a nickel based turbine rotor component (figure 6). This was a fairly straight forward application at first pass, however, after a few cutting trials, it became evident that this was a tough application for the AWJ process. The desired cutting geometry was a 5 mm (.200") wide slot by 25 mm (1.00") deep slot cut through the 45 mm (1.8 in) thick rim of the turbine disk. The initial problem encountered, was that as the corner was turned at the back of the slot, the stream trail back caused erosion and it was difficult to hold the geometric shape of the slot. Successful slots were machined, however, the cutting speed had to be slowed so much that the advantage of faster cutting speed was diminished. If the AWJ machine wrist and controller had the ability to cut with a lead angle and manipulate that lead angle as the nozzle rounded the 90 degree corner, this application would have been more successful. The ability to cut contour shapes with a lead angle to offset stream trailback would greatly enhance the tolerance capabilities of AWJ machining thicker components.

Since the AWJ process was unable to produce the wide slot in this component, the engineering requirement was altered to only require a 1 to 2 mm (.040 - .080") wide slot. Now this application was only making a cut in this disk at about 70 places. Another limitation was discovered when it came to actually machining these components. After cutting 20 or more of the cuts, the nozzle body mixing chamber would begin to clog altering the performance characteristics of the nozzle and effecting the kerf shape. The solution to this problem was to use an automatic mixing chamber flushing cycle to keep the mixing chamber free and clear of abrasive buildup.
The "Intelligent Nozzle" has this capability and improved the consistency of cutting the rough dovetail slot shapes.

This relatively simple cutting application uncovered two more significant limitations of the AWJ process, automatic, lead angle compensation and nozzle flushing for consistency. With these two limitations eliminated, the application base for this process is expanded.

Another application which shows both the benefits and limitations of the AWJ process is the manufacturing of composite tube clamps (figure 7 and 8) This application is a simple two dimensional cutting application. There are several benefits that are offered by using the AWJ process, first, since these clamps were for a development application and the geometry was not fully defined and verified, the AWJ offered the flexibility of machining several clamps rapidly, evaluating the geometry, altering the NC part program and repeating. In this application the AWJ process demonstrated it's strengths as a rapid prototyping tool. Additionally the AWJ process machined this composite material without delamination, chipping, and expensive diamond tools. The clamps were cut from a sheet of material and was very cost effective.

In addition to these benefits, several limitation were also realized. First, GEAE did not have built into the machine controller or programming system, software which automatically nested geometric shapes onto sheet material. This required manual nesting which was time consuming and not as efficient in material usage. If an internal automatic system existed, the programming time would have been reduced dramatically while increasing material utilization.. Another limitation discovered was the need for controlled pressure ramping. Without this option which was already built into GEAE's machine, the bolt hole would have had to been drilled conventionally causing increased costs. All AWJ systems that machine composite material systems should have this feature built in.

The last application which exhibits the benefits and limitations of the AWJ process is the drilling of cooling holes in a manifold component (figure 9 and 10). This application drilled over 1200 1 mm (.040 in) cooling holes through .8 mm (.032 in) titanium sheet metal. This application required very consistency hole size inorder to hold the engineering specified airflow requirements. In this application, the AWJ process offered cycle time benefits over conventional drilling and material property benefits over laser drilling. In addition to the benefits, several limitation were discovered which greatly effected the consistency of drilling these cooling holes. The first was real time monitoring of the orifice condition, any change in the orifice condition would greatly effect the consistency of the hole size. Another limitation was in the alignment of the orifice to the mixing tube. If the alignment was inconsistent from one alignment to another the resulting hole size would change dramatically. Finally the abrasive feed and mixing chamber conditions also need to be monitored and controlled to produce consistent hole size.

3.0 LIMITATIONS AND IMPROVEMENT AREAS

Although these are only a few of the applications which have been developed by GEAE over the past several years, these applications highlight the benefits and limitations of this versatile material working process. In these four applications, some of the AWJ process limitations were discussed, and numerous areas for improvement were identified. When these areas, listed below, are addressed and solved, the application base for the AWJ process will further expanded.

- Establishment of a computerized knowledge base for parameter setting and kerf shape determination.
- Reduce the physical size of the abrasive nozzle assembly, develop robust stream absorption systems for confined geometric shapes.
- Develop an AWJ process specific wrist manipulator and control software to allow lead angle cutting of complex geometric shapes and corners.
- Provide automatic nozzle body internal flushing and condition monitoring.
- Develop nesting software internal to the AWJ machine controller or programming system which is process specific.
- Institute computerized pressure ramping internal to pumping systems
- Provide and integrated process control systems to monitor and control the key process parameters of orifice condition, abrasive feedrate, and orifice/mixing tube alignment.

4.0 CONCLUSIONS

Through the review of several applications GEAE has made of the AWJ process to the manufacture of aircraft engine components the benefits and limitations of this process have been discussed. The AWJ process is very cost effective, has few detrimental effects on material properties, and has tremendous flexibility and versatility. But in addition there are several limitations and areas for improvement. AWJ processes will not replace all other manufacturing methods, but when applied to the right applications the benefits are substantial. GEAE has only begun to take advantage of this process, and as the process further matures, more applications will be developed and used to manufacture components for aircraft engines.

5.0 REFERENCES

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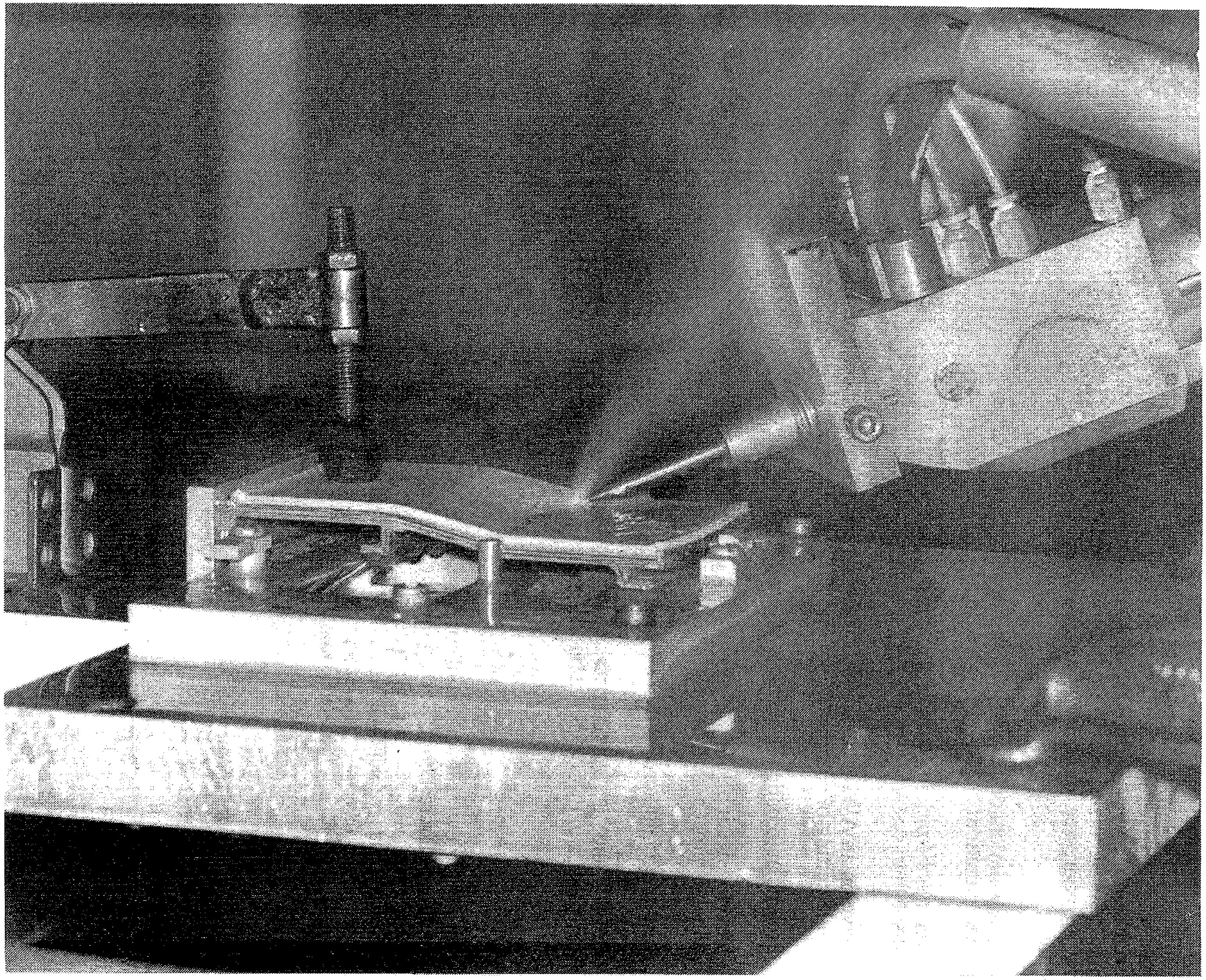

Figure 1: Cooling Hole Drilling in Ceramic Component

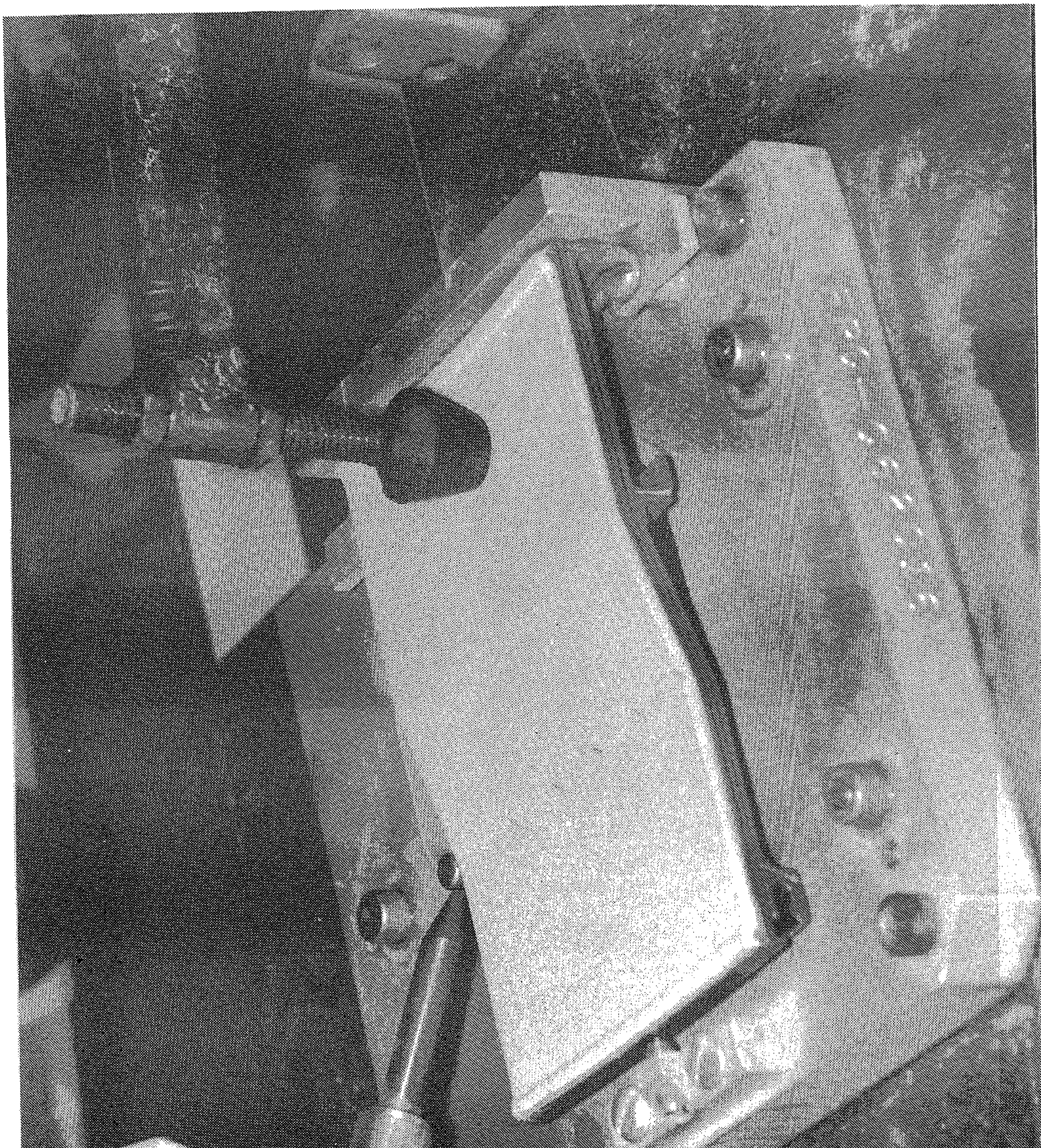

Figure 2: Set Up For Ceramic Shroud Drilling

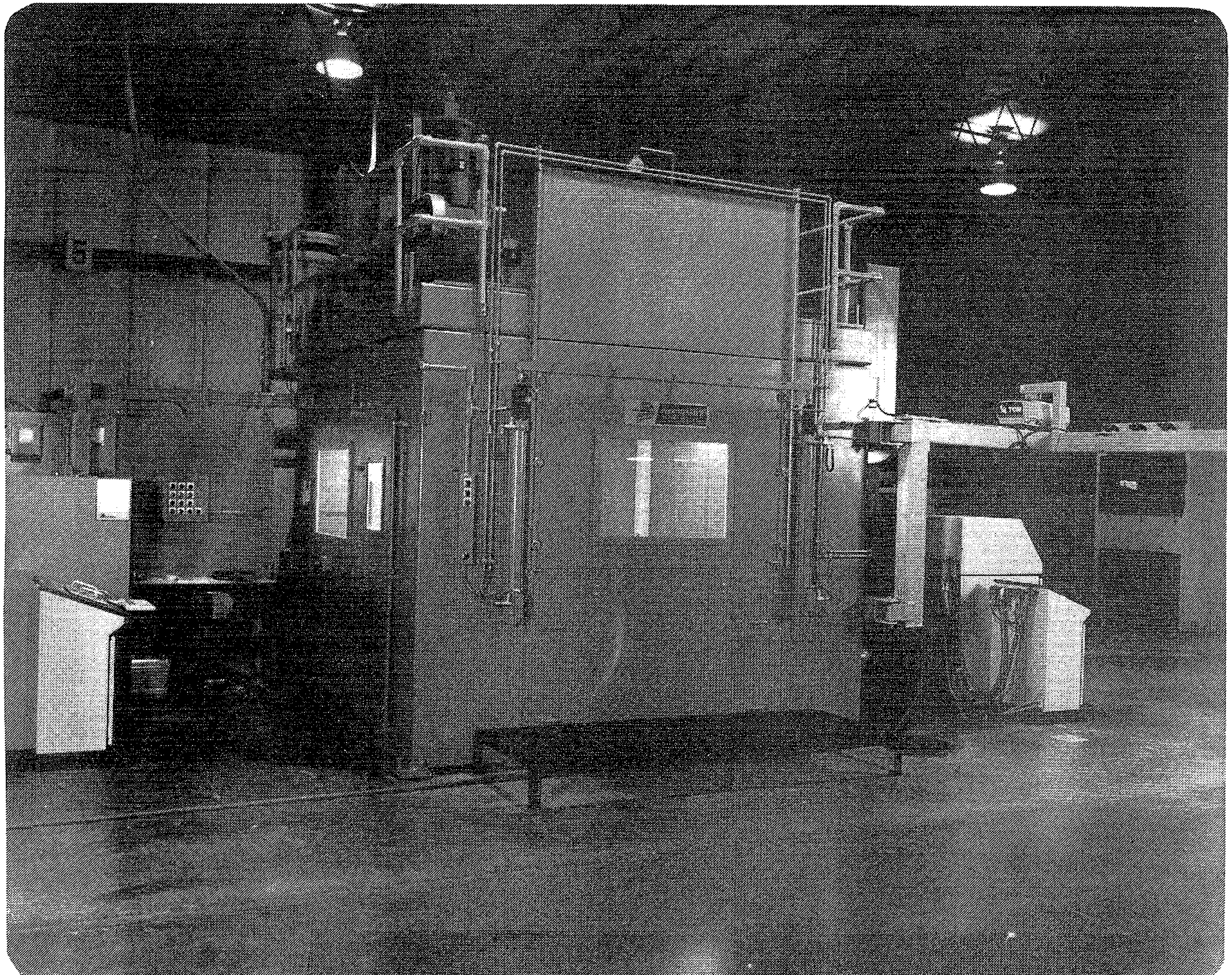

Figure 3: GEAE AWJ Machining Center

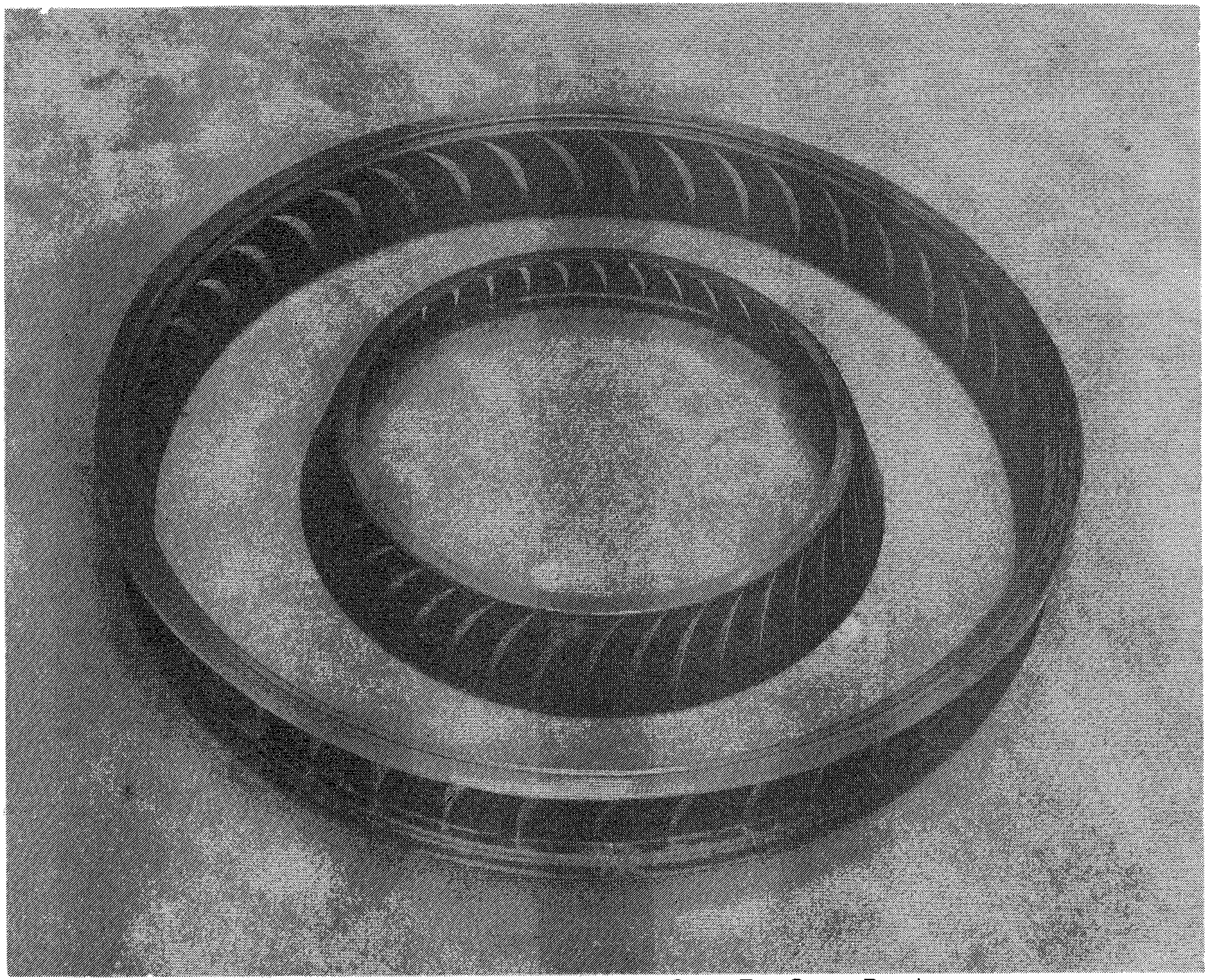

Figure 4: Composite Inner and Outer Fan Stator Bands

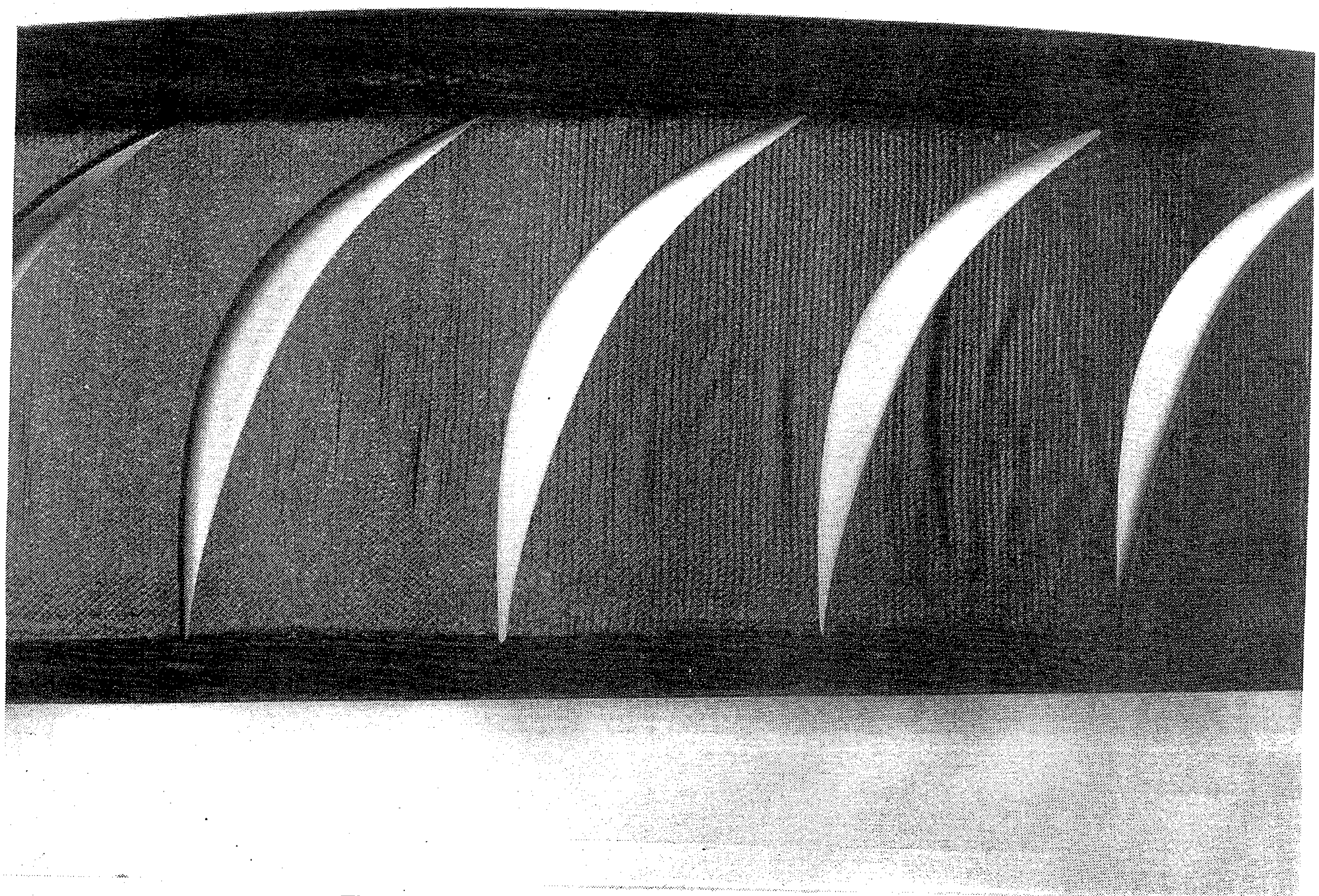

Figure 5: Detailed View of Airfoil Slots in Fan Stator

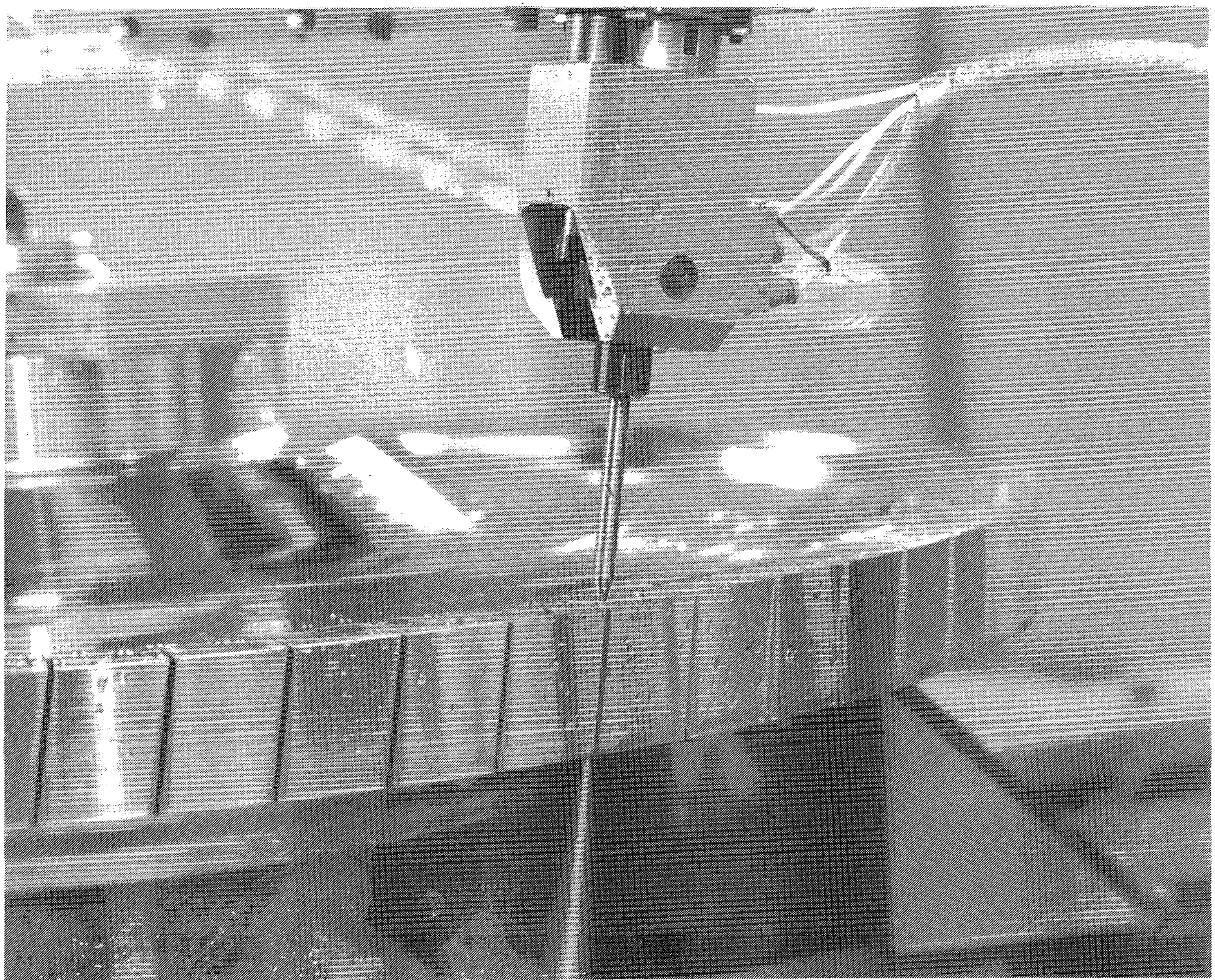

Figure 6: Turbine Disk Dovetail Slot Roughing

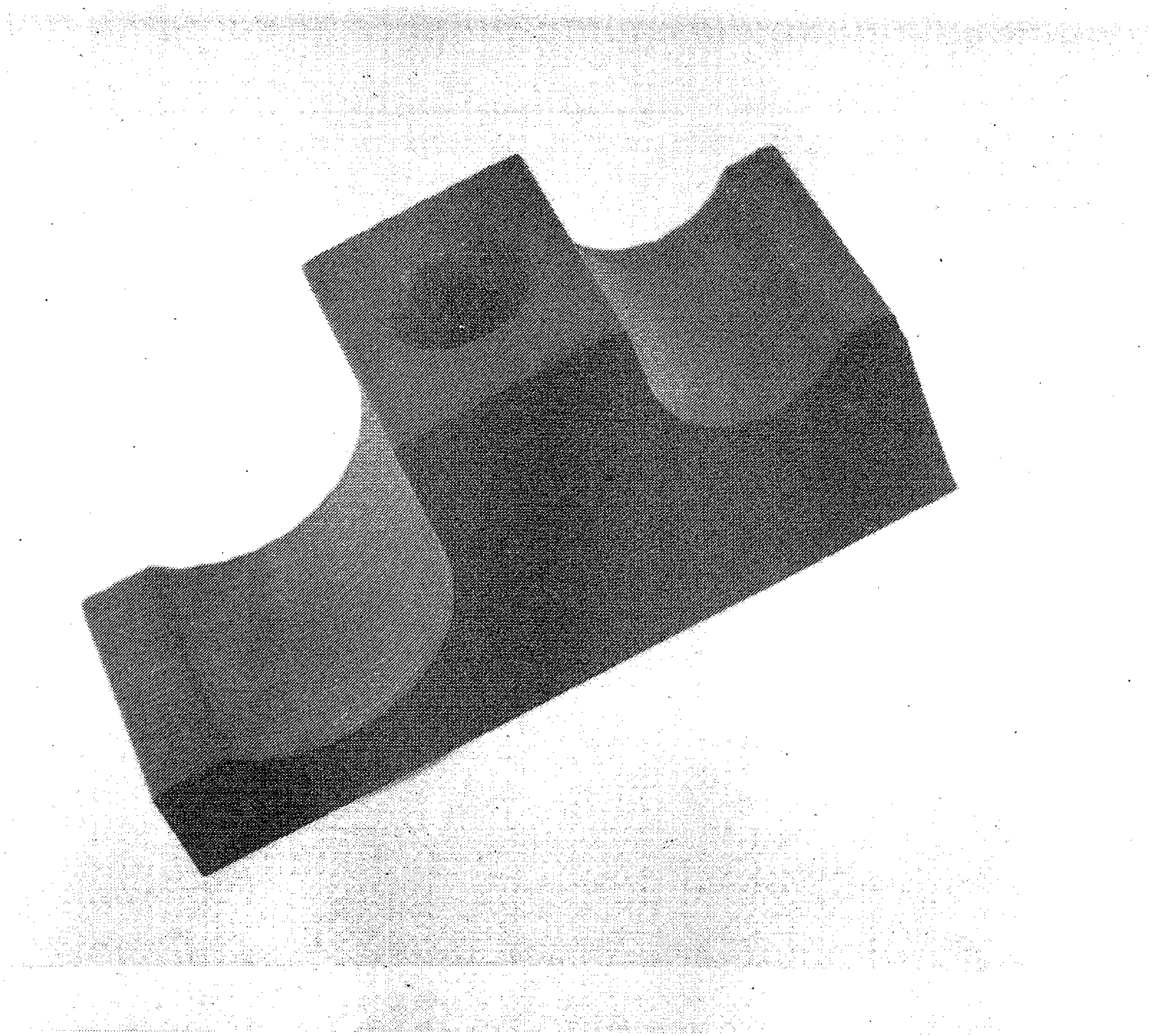

Figure 7: Machined Composite Tube Clamp

Figure 8: Composite Tube Clamp Machining

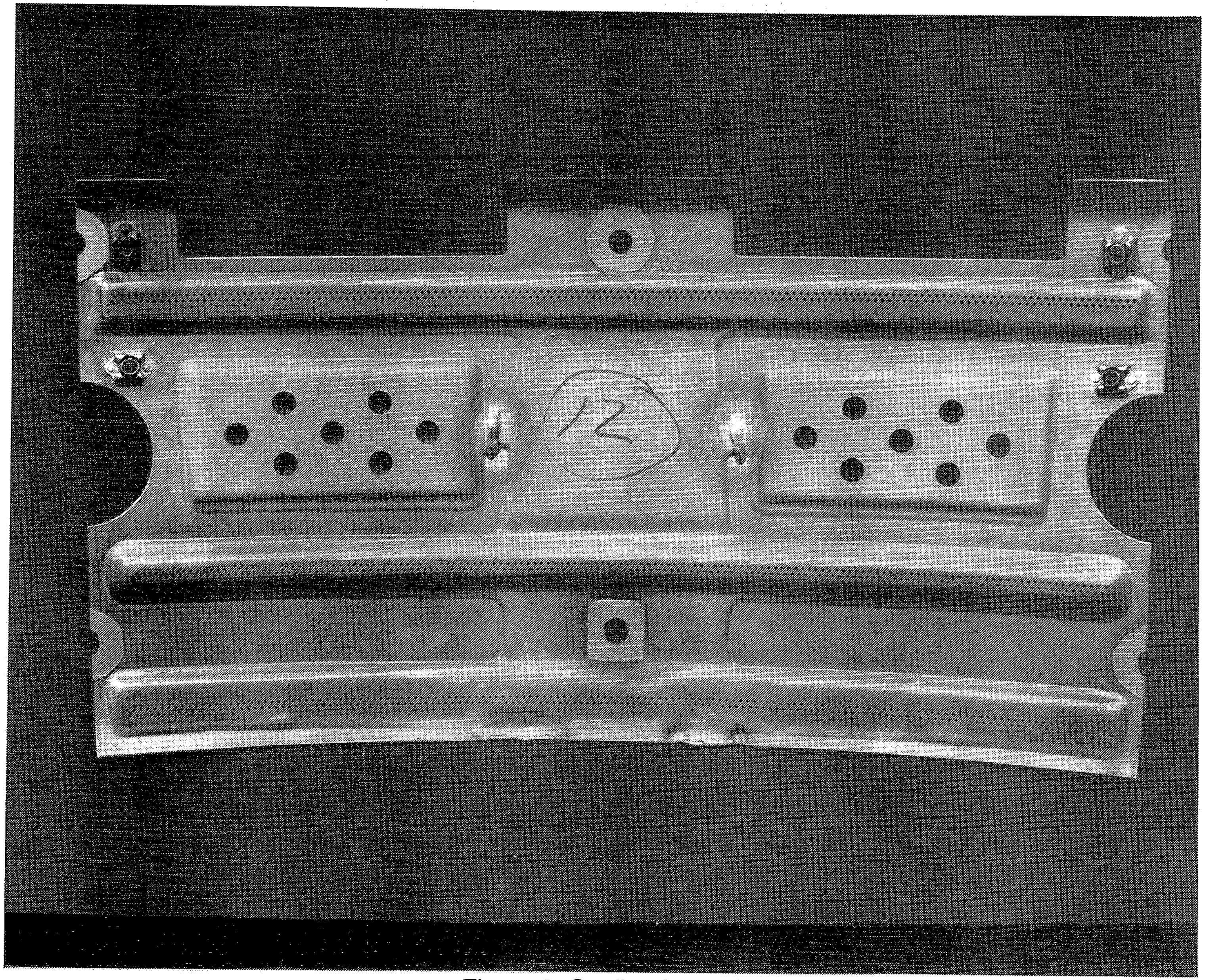

Figure 9: Cooling Manifold

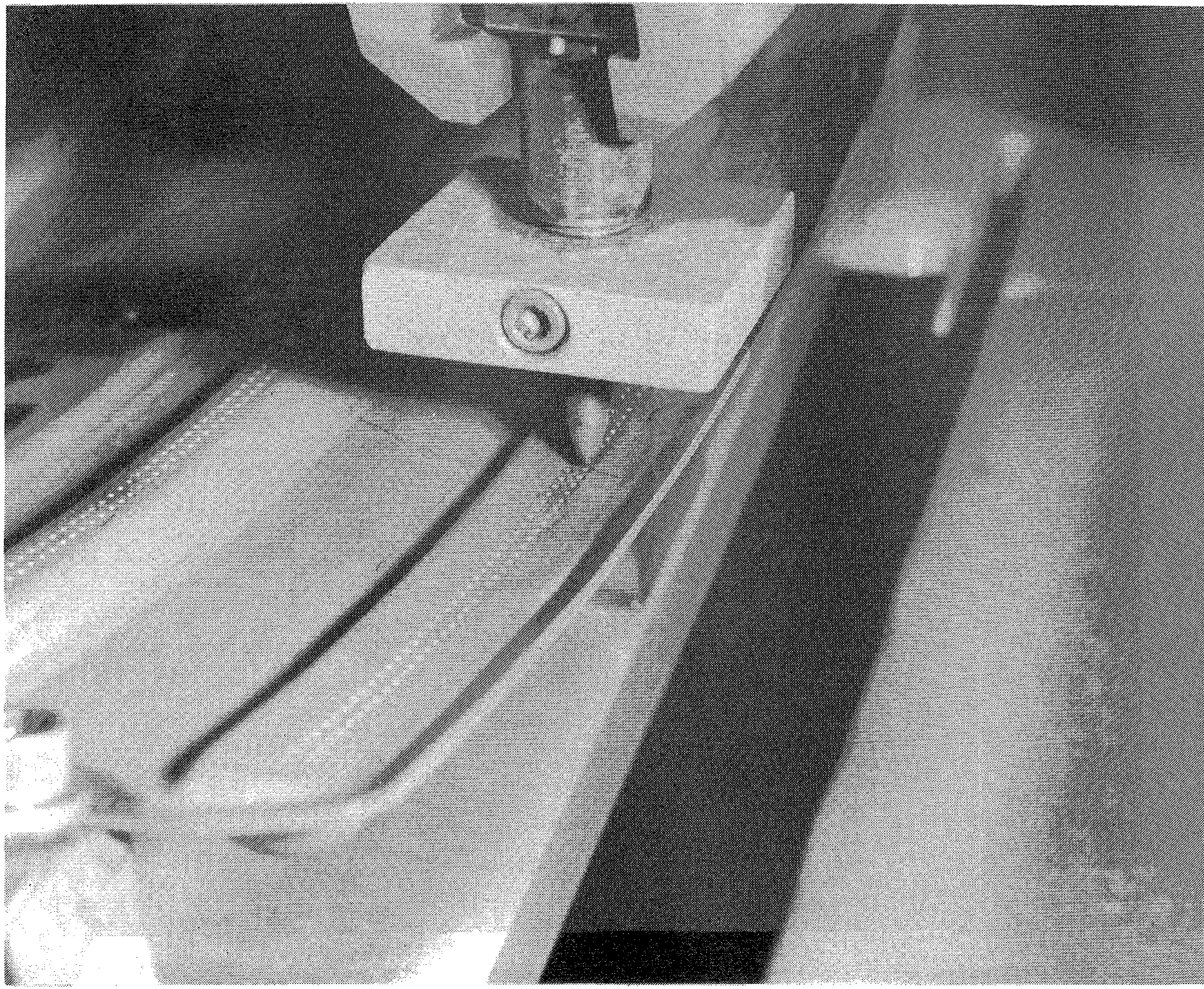

Figure 10: Cooling Manifold Drilling Setup

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Paper 68

EXPANDING THE MARKET FOR ABRASIVE JET CUTTING SYSTEMS

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ABSTRACT

The paper discusses actions that are needed to accelerate the exploitation of existing abrasive water jet technology. It outlines the technological improvements required to extend the markets for abrasive jet cutting technology and to retain markets in competition with advances in laser and plasma arc cutting systems. Details are given of the research and product developments necessary to open up new markets for abrasive jet cutting.

Organized and Sponsored by the Water Jet Technology Association.

1. INTRODUCTION

An estimated 700 to 1000 abrasive jet cutting installations have been sold in the 8 years since commercial exploitation of the technology began. About 80% of these installations are in manufacturing industries, 10% in Universities and research organisations, and 10% are used by contractors for repair and demolition work. The world market for abrasive jet cutting systems is probably 5 to 10 times the present user base. A substantial increase in cutting performance could double the potential market. A major threat to the market for abrasive jet cutting systems is the pace of developments in laser and plasma arc cutting systems. If lasers and plasma arc developments continue, without corresponding developments in abrasive water jets, then the total market for abrasive water jet cutting systems will shrink.

Recent surveys in Europe, supported by the EC under the Sprint Programme, have shown that industry in general is not well informed about the benefits and capabilities of abrasive water jet cutting. This lack of knowledge is restricting growth in sales. Studies carried out by BHR Group, into the needs of cutting system manufacturers and end users have provided information on the developments needed to expand the market for abrasive jet cutting systems. There are major new application areas for abrasive jets which involve integrating abrasive jets into a total solution. Innovative funding routes will have to be found to carry out the integration and to prove the systems in industry.

This paper outlines:

- A number of problems that are restricting the market for existing abrasive water jet technology.
- Improvements in abrasive jet cutting systems performance needed to extend the market and to compete against the higher performance laser and plasma systems entering the market.
- The research and product developments necessary to develop major new markets for abrasive jet cutting technology.

2. MARKETS

2.1 Market Developments in the Manufacturing Industry

Abrasive water jets, along with lasers and plasma arc, are classed as "power beam" cutting tools. The cutting heads of these machine tools make no physical contact with the material being cut and since cutting heads only weigh a few kilograms, they can be manipulated easily. Power beam machine tools can, therefore, be of relatively light construction compared to most machine tools which have to withstand large tool loads. CNC manipulation system for abrasive water jet cutting heads can be assembled from widely available components. As a result, many small engineering companies have been able to build "one-off" abrasive jet systems by fabricating an X-Y table and buying in the high pressure pumping equipment and abrasive entrainment cutting head. This practice is changing as awareness grows that a great deal of knowledge is required to design abrasive jet cutting systems that:

- Perform reliably in the severe environmental conditions generated by abrasive jets.
- Have sophisticated control software, that can take inputs from CAD systems and optimise cutting performance.
- Require an extensive data base of cutting performance, on a wide range of materials, in order to be able to rapidly set up and optimally cut different materials of varying thickness and shapes.

At present, the major market for abrasive jet cutting system is in the cutting of sheet materials on X-Y cutting tables. The market is dominated by a few international companies who can each offer a family of cutting tables. These companies either have, or are likely to acquire, the capabilities to produce a "total system" including manufacturing the high pressure water intensifiers and abrasive feed systems. Specialist cutting systems manufactures, who produce "total solutions", such as cutting cells for glasses, will continue to buy in the water pressurisation and abrasive feed systems.

An estimated 80% of abrasive jet cutting systems are used on X-Y cutting tables and 20% on multi-axis robots. With plain water jet cutting systems the proportions are reversed with 80% of jets manipulated by robots. A major reason for the small number of abrasive jets used with robots is the difficulty of catching the spent water and abrasive as it leaves the workpiece. The problems of catching jets are so severe that a large percentage increase in robotic applications is unlikely with existing abrasive jet systems.

2.2 Market Developments in the Contracting Industries

The first abrasive jet cutting tools for contractors were adaptations of the abrasive entrainment systems used in manufacturing industries. In these systems a high velocity water jet entrains dry abrasives which are carried in an air stream, to the cutting head. In general, entrainment systems were found to be too difficult for contractor's workers to operate reliably and to be too "fragile" for the harsh conditions existing on site. The alternative technology, of direct injection of abrasives before the cutting head (DIAJET), was developed to overcome many of the problems experienced by contractors with entrainment systems. A benefit of DIAJET was that it used existing contractors water jet cleaning pumps (350 bar) instead of the intensifiers needed by entrainment systems (2000 to 3500 bar).

The application of DIAJET systems, particularly for sub-sea operations, have gone way beyond what was originally envisaged. Recent developments in DIAJET technology to meet increasingly arduous applications have involved: operation at 700 bar to increase cutting power and allow operations down to 1000 m sub-sea; a move away from proprietary to purpose designed valves and components to achieve long operating periods under difficult conditions, with reduced maintenance.

2.3 Competition

The markets for power beam cutting technologies - laser, plasma arc, water jet, abrasive water jet -has grown rapidly over the past ten years. Market growth for laser and plasma arc systems has been sustained by increasing recognition of their potential, continuing improvements in cutting speed, in the thickness of materials that they can cut, in the quality of the cut surfaces, and national and EC programmes to promote the use of lasers. In the case of plain water jets, market growth has mainly been through the integration of water jets with multi-axis robotics to cut three dimensional "soft" parts in high volume manufacturing. New market applications exist for plain water jets but for the foreseeable future it is unlikely there will be major improvements in cutting performance. Market penetration by abrasive water jets has mainly been into industrial sectors who use materials on which lasers and plasma perform badly or not at all. Compared to laser and plasma arc cutting systems, abrasive jet cutting speed and cut surface quality improvements, over the past five years, have been small.

The major market for lasers, plasma arc and abrasive water jet cutting is in jobbing cutting, either within fabricators, such as aircraft manufacturers, or in specialist cutting job shops. Based on experience with lasers, specialist job shops will be the largest single market. A typical large job shop will have a number of lasers, plasma arc and other cutting systems. The initial case for buying an abrasive water jet can often be made on the basis that the job shop turns away two or more hours of machine time per day because the cutting required is not possible, or is uneconomic, on the shops existing cutting systems. There may also be an hour or two's work which could be cut as economically on an abrasive jet system as on their existing systems.

The fixed costs for a 200,000 to 300,000 pound sterling (dollars), 4m x 2m X-Y table, with its abrasive jet cutting system, can amount to 4 to 5 times the hourly running costs. Economics dictate that once a job shop has bought an abrasive jet cutting system they will try and achieve as high a load factor as possible, even though this means cutting materials that are more economically cut with laser or plasma arc. How a job shop allocates cutting jobs between different types of machines will vary greatly because of customers requirements, cutting system mix, experience, workload, etc.

Laser, plasma arc and abrasive water jet are seen as complementary techniques as well as competitive techniques. Programming requirements for the three systems are similar and skilled operators can easily transfer from one system to another. The abrasive water jet scores in being able to cut materials that the plasma arc and laser cannot cut or which they damage, or the material thickness is beyond laser or plasma arc capabilities. Whilst ultimately the type of system chosen is usually determined on the basis of comparative total operating cost, and is therefore very application dependant. A major drawback of abrasive jet cutting systems can be slow cutting speeds. A 3 to 5 fold increase in abrasive jet cutting speed would probably make the abrasive water jet the preferred cutting method for even those applications where it is currently uncompetitive, with lasers and plasma arc.

4. EXPANDING THE MARKET FOR EXISTING TECHNOLOGY

The major factors to be overcome in selling existing technology are:

- Potential users are unaware of the benefits of abrasive jet cutting to their business.
- The information provided by abrasive jet cutting system manufacturers does not support making a business case for purchasing an abrasive jet cutting system.
- The naturally conservative philosophy of many engineering companies in not buying new technology until not doing so damages their business.

Although there have been national programmes to promote the use of lasers in industry, similar programmes have not been funded for abrasive jets. In some European countries, national co-ordinating organisations to exploit abrasive jets have been set up, but they are experiencing difficulties in promoting abrasive jet cutting systems to the small to medium sized jobbing shops who are the largest potential market.

Abrasive jet cutting system vendors are losing sales because there is no agreed way of presenting cutting performance data. Potential purchasers of a cutting system will usually collect cutting performance data from a number of vendors. Each vendor has sets of performance figures and they all differ because they are not qualified as to what they relate to - straight line cutting speed, contouring, highest quality finish etc. Factors of 2 or 3 in quoted cutting speeds between different vendors are normal.

Since potential purchasers are usually conservative, they will use the lowest quoted cutting speeds in carrying out a cost justification for the purchase of an abrasive jet cutting system. Because cutting performance, in terms of cost per unit of area generated per minute, is application dependant, the use of inappropriate cutting data can lead to inappropriate rejections of abrasive water jet systems.

The major abrasive jet cutting system vendors need to co-operate to at least better define what their cutting performance data refers to - straight cuts at maximum speed, cutting speed for a defined edge finish, contour cutting, etc. Because entrainment based abrasive water jet cutting system vendors' cutting heads have approximately the same performance, for a given primary nozzle and mixing tube arrangement, it should be possible to agree definitive sets of cutting data.

An EC Brite-Euram project, co-ordinated by BHR Group, is carrying out tests on 6 cutting systems, under closely defined conditions, to provide the basis for presenting comparative cutting performance data. The project partners are willing to co-operate with vendors and users in achieving definitive data on which potential users can base their economic assessments.

4.1 Cutting Process Control

The most serious problem reported by entrainment abrasive jet cutting system manufacturers is lack of control over the processes involved in producing abrasive jets. The geometry and location in space of jets must be known throughout a cutting operation, or be predictable, or be continuously measurable to provide a feedback signal. Lack of control over the flow patterns and abrasive entrainment in the cutting head, along with unpredictable wear of nozzles, limits the accuracy and quality of the cutting process.

Unpredictable changes in jet characteristics, during cutting operations, cause serious problems. These changes occur due to damage to the primary nozzle or build up of deposits on the nozzle, wear or damage in the mixing tube. The use of diamond primary nozzles and composite carbide mixing tubes can reduce but not eliminate, process control problems. Direct injection cutting heads provide more control over the jet formation process but service experience with Direct Injection Systems is still limited.

4.2 Cutting Speed

In justifying the purchase of a cutting system, cutting speed is one of the important considerations. As mentioned previously, abrasive jet cutting performance, for some bulk applications, is slower than lasers and plasma arc systems. To improve the economics of cutting installations in these applications, some X-Y cutting system vendors sell systems with twin cutting heads. Experience shows that to take full advantage of twin cutting heads, in a jobbing environment, two standard 1.2 x 2.4m sheets of material need to be cut side by side. This leads to table sizes and capital costs which are difficult to justify. If cutting speeds could be increased by about two over current values these bulk markets for abrasive jet cutting could more than double. In particular, job shops operating a mixture of systems - punches, lasers, plasma, gas cutting etc, could make a strong case to purchase an abrasive jet cutting system. In a mixed cutting system environment an abrasive jet system provides enormous flexibility in scheduling jobs within the shop and extends the range of materials that a shop can economically cut.

For the foreseeable future, it is impractical to operate abrasive water jets at pressures above 4000 bar. This means that significant improvements in cutting performance will not be achieved from existing entrainment cutting technology.

Suspension jets performance given by Hashish (1993) and direct abrasive injection by Bloomfield (1991), shows that passing the abrasive/water slurry through the primary nozzle, can provide significantly higher cut surface areas per minute than with entrainment systems. However, before such systems can be developed commercially for some high precision cutting applications, an enormous amount of research and testing of components and systems is required.

4.3 Abrasive consumption and disposal

With all the 'power beam' technologies there are potential pollution problems from the by product of each process. In the case of AWJ, whilst the pollutant, grit, is basically non-toxic, there is still the remaining problem of disposal.

Consumption of abrasives is one of the main operating costs. The abrasive has to be caught, removed from the catcher or tank, treated and disposed of. Legislation is imposing tighter controls on waste disposal. Because of the possibility of more legislation some uncertainty is introduced into the cost of future operations, and as a result many users are prudently looking at environmentally sensitive disposal requirements now. Such uncertainties however complicate making the case for purchasing an abrasive jet cutting system. If the number of abrasive systems, in a particular location, is sufficient it may pay to centrally treat spent abrasive and use it in non-critical abrasive applications. This is also an area where future research and development is required.

5. NEW MARKETS FOR ABRASIVE WATER JETS

5.1 Foundries - fettling of castings.

One of the earliest proposed applications of abrasive water jets was to the fettling of castings. The majority of castings are fettled by hand to remove flash and surface defects and to separate castings from gates, runners and feeders. Fettling is a physically demanding, tedious, repetitive task, that is often carried out in a particularly unpleasant and health damaging environment.

World wide there is probably 10 millions tonnes of castings per year that could potentially be fettled by abrasive water jets. The major reason why automated abrasive jet fettling has not been achieved is the high cost of developing a "total robotic solution" and the inherent flexibility of human labour. Work in Europe, supported by the EC under the SPRINT programme and co-ordinated by BHR, involves the building of two pilot robotic cells to carry out foundry trials of abrasive jet fettling. The trials will generate data to allow financial, technical, social, safety and environmental justification to be made for automated abrasive jet fettling systems. If successful the trials will identify those sectors in the fettling market which could economically be addressed by abrasive water jets.

5.2 Demilitarisation - Cutting of shells and bombs

The end of the cold war has led to a minimum of 5 million tonnes of surplus or obsolete munitions - bombs, shells, rockets, etc, of which 40% are in Europe. These munitions contain valuable, recyclable materials but de-commissioning of munitions presents extreme safety, health and environmental problems. These problems have to be overcome because munitions have a finite shelf life and international agreements now prohibit dumping of munitions at sea.

Before munitions can be rendered safe they have to be cut open or their casings punctured in order to remove explosives and chemicals or to prevent explosions during incineration. Investigative tests on live munitions have shown that abrasive water jets and in particular direct abrasive jets (DIAJET), are potentially the most cost effective way of disassembling an estimated 30% of munitions. A number of studies are being carried out to determine the munitions that can be safely and economically disassembled using abrasive water jets.

5.3 Mining, Quarrying, Civil Engineering and Oil and Gas Industries

In the mining, quarrying, civil engineering and oil and gas industries, a wide variety of applications for abrasive water jets have been identified that involve downhole cutting operations to reduce exploration and production costs or to make possible new production methods. These operations typically involve: cutting notches and slots to better control rock blasting or to control mechanical rock splitting; remotely cutting through piles and casings to remove off-shore structures or subsea well heads; cutting slots or holes in casings to improve oil and gas production or to carry out side track drilling.

Because of the difficult and restricted operating conditions, only direct abrasive jet cutting systems are suitable for down hole operations. At present DIAJET is being used commercially for cutting piles and casings off-shore and experimentally for rock notching and slotting in controlled blasting experiments. Projects are being developed for deep hole operations with a longer term aim of compact, steerable down hole drilling and cutting tools.

6. CONCLUSIONS

Cutting systems based on entraining abrasive into a high velocity water jet is a mature technology. Unfortunately, there are unlikely to be any great improvements in performance because of limitations on pumping equipment. Even so, there is a sufficiently large market to maintain a few large manufacturers of complete systems - pumping and abrasive feeding equipment, plus cutting tables and robotic installations, as well as cutting system assemblers for niche applications.

Recent development work on the current generation of low pressure direct abrasive injection system (DIAJET) has been aimed at improving reliability and robustness in order to operate under difficult site and sub-sea conditions. For the future the need is to develop direct abrasive injection/suspension systems to compete economically with other technologies over a wider range of applications.

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STUDYING THE MOVEMENT PARAMETERS OF SPACE TYPE ROTARY WATERJET HEAD

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ABSTRACT

The space type rotary waterjet head is an equipment which can be widely used in the petrochemical and other industry to clean tanks, sinks and other vessels. This paper described that the author study the movement parameters of a space type rotary waterjet head. On the basis of simulating the movement condition of rotary head with computer and analysing its movement regularity, this paper explained that how movement parameters effect the movement regularity and moving trace at emphasis, and gave a basic method of determining movement parameters which the waterjet effecting the property of the rotary head.

1. INTRODUCTION

The space type rotary waterjet head (SRH) can clean any space type object and clean over all surface of this object. So, it has been used in the petrochemical and other industries widely, to clean the inner surface of storage tanks, sinks and other vessels.

2. THE BASIC CONSTRUCTION OF SRH

SRH has two circuition shafts which vertical each other. When the waterjet circuits an axle, this axle circuits another axle too (see Fig. 1). When the section area of waterjet is not recognized and the distance of target forms a spherical surface which radius is R (where R =distance of target), the waterjet plane on the target surface is defined by parameter functions:

$$x = x(t)$$
$$y = y(t)$$
$$z = z(t)$$

We call the shaft driving shaft which the waterjet circuits and another driven shaft which vertical with that in SRH. The driving shaft and driven shaft are combined with such as circular cone gear, circular cylinder gear, worm and gear, etc. (see Fig. 2). According as mechanical theory, we can see:

$$i = \omega_1/\omega_2 = n_1/n_2 = Z_2/Z_1$$

in this equation,

i is transmission rate
ω_1 is angular velocity of driving shaft, rad/s
ω_2 is angular velocity of driven shaft, rad/s
n_1 is rotational speed of driving shaft, RPS
n_2 is rotational speed of driven shaft, RPS
Z_1 is gear numbers of driving shaft
Z_2 is gear numbers of driven shaft

The driving shaft is circuited not only in angular velocity ω_1 by the opposite acting force which the nozzle take place, but also the nozzle is circuited around driven shaft in angular velocity ω_2 by mesh module at the same time.

3. ANALOGUE THE TRACE OF SRH WITH COMPUTER

In order to observe the movement of SRH, analysing how the parameters effect the movement of SRH, knowing the movement regularity of SRH, we used a computer to analogue the movement of SRH.

In the figure 3, the tri-dimension right angle coordinate system is defined. We can define a spherical surface which radius is R, and let the focal point at the coordinate origin O which the driving shaft axle focus with driven shaft axle of SRH at it, and let the driven shaft axle in the Z axis. In order to study simply and conveniently, we can let SRH has one nozzle and the eccentricity $e = 0$, that is the waterjet injects from coordinate origin O along X axis positive, and circuits around driving shaft and driven shaft. Assume M (x, y, z) is the point which the waterjet inject at in some time, then we can obtain:

$$x = R\cos(\alpha)\cos(\beta)$$
$$y = R\cos(\alpha)\sin(\beta)$$
$$z = R\sin(\alpha)$$

When the time $T = t$, then

$$\alpha = \omega_1 t$$
$$\beta = \omega_2 t$$

because, $i = \omega_1 / \omega_2$, so $\omega_2 = \omega_1 / i$

therefor: $\beta = \omega_1 t / i$

so, we can obtain:

$$x = R\cos(\omega_1 t)\cos(\omega_1 t / i)$$
$$y = R\cos(\omega_1 t)\sin(\omega_1 t / i)$$
$$z = R\sin(\omega_1 t)$$

According to the above equations, we can obtain the position which is the waterjet on the spherical surface. Let $Z = 0$, we can obtain the projection drawing which is the waterjet on the spherical surface points along Z axis. Using a computer, trace drawing of jet's points was made which along Z axis.

In fact, SRH has a eccentricity e , so:

$$x = \sqrt{R^2 - e^2}\cos(\alpha)\cos(\beta) + e\sin(\beta)$$
$$y = \sqrt{R^2 - e^2}\cos(\alpha)\sin(\beta) - e\sin(\beta)$$
$$z = \sqrt{R^2 - e^2}\sin(\alpha)$$

Involve the x, y, z to the second power and add up as follows:

$$x^2 + y^2 + z^2 = R^2$$

This proves that M (x, y, z) is a point on the spherical surface. According above equation, when the eccentricity $e \neq 0$, the trace of the waterjet can be obtained by a computer.

4. THE MOVEMENT TRACE AND PARAMETERS OF SRH

In order to study simply, we assume that the movement trace and parameters of SRH as follows:

I) The eccentricity $e = 0$;

II) The SRH has one nozzle only (in fact, the SRH has two nozzles which are opposite each other in position);

III) The trace of waterjet has one point on the equator when it circuits one round.

Because the revolution shaft (driven shaft) of SRH circuits around Z axis, the interval distance which the moving trace on the equator (XOY plane) by waterjet hits is maximum and the density is minimum. While, at two poles, the moving trace are all through them, overlamps many times, and the density is maximum. In between the equator and poles, the jet's density is greater along with the latitude increase. So, it is necessary that study the frequency and distrilution which the waterjet hits on the equator.

In many moving parameters, the transmission rate i is an important effect parameter for moving trace. We know:

$$i = n_1/n_2$$

So, at some time t, the revolution numbers of driving shaft and driven shaft are:

$$N_1 = n_1 t$$
$$N_2 = n_2 t$$

thus: $i = N_1/N_2$

When N_1 is an integer and N_2 is an integer too, the moving trace of waterjet will circulate. On the other hand, the finishing point of the moving trace coincide with the starting point. At this time, if SRH circuits continually, the moving trace of waterjet will repeat as last cycle only, and can not take place any new trace. If N_1 and N_2 always are not integers at the same time, the trace will not circulate always.

Because i is a rational and a rational can be expressed with a fraction p/q (p and q are integers, q is not equale zero) always, and we know:

$$N_1 = (p/q)N_2$$

so, an integer q can be finted and let $N_2 = q$, to make $N_1 = p$. Therefore, when i is a rational, the moving trace is circulate always at no longer.

When i is an irrational, because an irrational can not be expressed with a fraction p/q, the two integers N_1 and N_2 can not be finded always to make $N_1/N_2 = i$. On the other hand, i is determinated by Z_1 and Z_2, $i = Z_2/Z_1$ (Z_1 and Z_2 are integers), it is impossible that i is an irrational. That is the moving trace of SRH is circulate always.

Because Z_1 and Z_2 determine i, they effect on the movement trace. Z_2/Z_1 is a simple fraction, that is Z_1 and Z_2 are primes each other, and they are all not zero:

$$i = N_1/N_2 = Z_2/Z_1$$

so, $N_2 = (Z_1/Z_2)N_1$

When $n_1=Z_2$, N_2 equals Z_1, that is when the driving shaft circuited Z_2 rounds, the driven shaft circuits Z_1 rounds. For example, $Z_2/Z_1=181/17$ means that when the driving shaft circuits 181 rounds, the driven shaft is circuited 17 rounds. We call N_1 is "the circulate cycle" at which N_1 and N_2 are all integers.

When Z_2/Z_1 is not simple fraction, it must be changed to simple fraction. Then we can find the circulate cycle. For example, the circulate cycle is 308 rounds for 308/17. But the circulate cycle is not 306 rounds for 306/17, it is 18 rounds, that is because 306/17=18/1. For example again, the circulate cycle is not 616 rounds for 616/54, it is 308 rounds.

When $Z_1=1$, the waterjet hits Z_2 points on the equator, that is it divides the equator into Z_2 parts which are equal each other. When $Z_1 \neq 1$ (assume Z_1 is a constant C), the driving shaft circuits one round, the driven shaft circuits Z_1/Z_2 rounds. It may be seen that the angular which the driven shaft circuits is C times at which $Z_1=1$. It can be proved that when $Z_1 \neq 1$, the waterjet hits the points which are same with $Z_1=1$, and it can divides the equator into same Z_2 parts too in the circulate cycle.

Exactly, SRH has an eccentricity e, so, on the equator we can obtain:

$$x = R\cos(\alpha)\cos(\beta + \arcsin(e/R))$$
$$y = R\cos(\alpha)\sin(\beta + \arcsin(e/R))$$

In fact, because the place which the waterjet hits the spherical surface on is moving toward the front or moving toward the back an angular $\theta=\arcsin(e/R)$ only (see Fig. 4), the simplicity above has no affectation for the cleaning effect.

It is complex, in fact, comparing with assume conditions as follows:

I) A real nozzle hits two points on the equator when it circuits one round. These two points are not at starting point only, but their moving regularity are same.

II) A real SRH has two opposite nozzles. Their moving trace are not coincide exactly when the eccentricity e is not equales 0, but their moving regularity are same.

III) Because eccentricity e is not equales 0, the moving trace of waterjet are not through the poles. The moving trace contacts the circles which centres are at the poles and the radius is e. So, the poles are dead areas where can not be cleaned.

5. THE PARAMETERS SELECTION OF SRH

The chemical containers which were cleaned by SRH are various, such as vessles, still, etc., and their shape, specifications and the cleaned foulings are various too. So, the demands are not same each other for SRH. According as the kinds of foulings, some are hard but very fragile. At this time, the interval distance of the waterjet moving trace not need so density enough. This kind foulings will be broken and fall down from the container. But some are tenacity or has very adherent. It needs the interval distance very density to clean them from container all and no remain. Thus, we can see, the cleaning head which was designed according to the first state will can not clean all, because its cover rate is not enough.

While the cleaning head which was designed according to the second state will make the efficiency decrease using at the first state.

Therefore, when we select the parameters of SRH, it should be accorded with the demands as follows:

I) Can obtain the higher cover rate.
II) Can obtain the maximum of the cleaning efficiency.

The ideal SRH should be that the cleaning head has some cover rate at starting. The cover rate and the density are increasing with the time going on, and obtain a limited value at last. On the other hand, if the foulings are cleaned easy, the used time are fewer and increase the efficiency. If the foulings are cleaned difficult, the used time will be longer. In these time, the cleaning head do not clean the place where the cleaning head has been cleaned before, but the cleaning head cleans the place where it has not been cleaned. That is the cover rate has been increased. We think, the moving parameters can be selected as follows:

I) Select a proper Z_2. Selecting a proper Z_2 is selecting a proper circulate cycle. In order to that SRH can break the harder foulings, the target distance of the generally:

$$L / d_0 <= 200$$

where, L is the target distance

d_0 is the diameter of the nozzle

When the diameter of the nozzle is d_0 and $L=200d_0$, the diameter d of the waterjet can be obtained by calculating or experimenting. Then the circulate cycle can be calculated by the formula:

$$N_1 = Z_2 = 2\pi L / d$$

This is the maximum of the cover rate that the cleaning head can make.

II) Select a proper i. Selecting a proper i is that the integer part of the i is selected. The integer part of the i defines the shares which SRH shares the equator in a round. Therefore, the integer part must satisfies the need at least which the density of the moving trace demands. The decimal part of the i is determined by Z_1 and Z_2 where Z_1 and Z_2 are prime numbers each other. In the first place, the integer part of the i should be changed at a little. The values of Z_1 and Z_2 is adjusted properly and let them are prime each other.

It is tentative that we studied the moving states of SRH. There are some problems to be studied further.

Acknowledgments
The authors would like to express their thanks to Mr. Zhao Chunyang, Mr. Li Guochang and so on who have helped this work.

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Figures

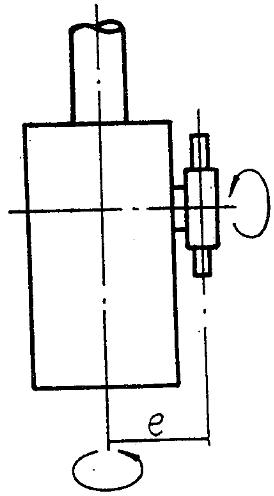

Fig. 1

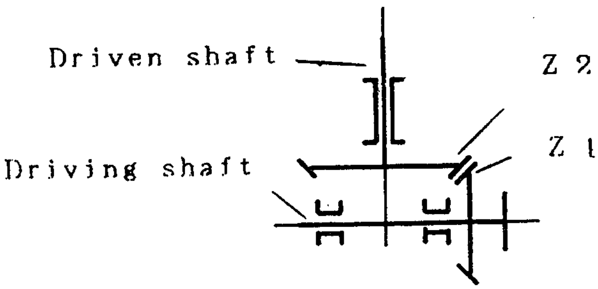

Fig. 2

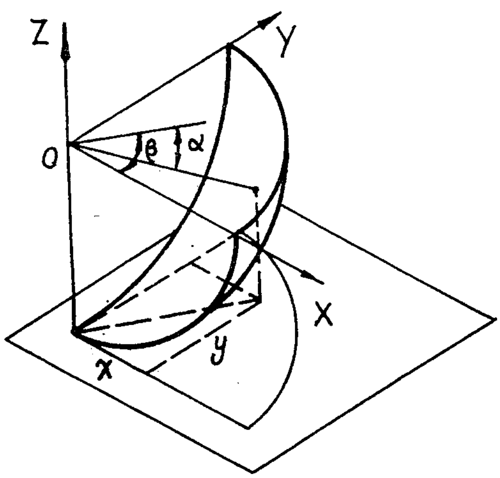

Fig. 3

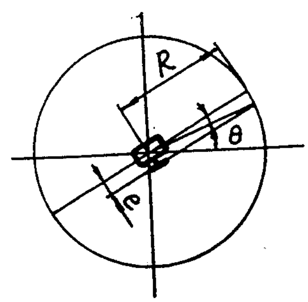

Fig. 4

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Paper 70

THE CLEANING TECHNOLOGY OF HIGH PRESSURE WATER JET FOR THE FOULING OF HEAT EXCHANGER

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ABSTRACT

Heat exchanger is an equipment which is used widely in the petrochemical operation and has to be needed to clean because of fouling formed. So, it is important to study and to clean for having fouling of heat exchanger.

Combining Beijing Yanshan Petrochemical Corporation -- a jumbo-sized joint petrochemical enterprise in China, using high pressure water jet technology to clean the heat exchanger with practice, this report expounds the study and application of high pressure water jet cleaning for the heat exchanger under different kinds of heat exchanger, various working conditions and petrochemical materials for the forming fouling. In the report, we introduced how to check and determine for the clean quality, and put forward to decide methods of high pressure water jet for cleaning heat exchanger in the technical achievements and economic efficiency.

Organized and Sponsored by the Water Jet Technology Association.

1. Intruduction

1.1 Heat exchanger is an equipment which is used by petrochemical industry widely. Various kinds of the heat exchangers cover about 20 -- 70 percent of all petrochemical process equipments; 20 -- 50 percent of the weight of equipments and about 12 -- 30 percent of investe in the process equipments, sometimes, even 50 percent.

In Beijing Yanshan Petrochemical Corporation there are several thousands of heat exchangers in more ten petrochemical production plants of the Corporation.

1.2 The heat transfer equipments play an important role in the petrochemical production and operation. The heat exchanger has direct effect on the safe production; the production capacity and products quality of petrochemical unit.

In the operation process, because of various reasons, such as, operation condition, petrochemical materials and the construction of heat exchanger and so on, they make the heat exchanger fouling, disturb the operation, even bring shutdown or accident.

1.3 Although various kinds of heat exchanger's construction and the form of heat transfer are not same, they have the same working principl, for example, the tube - heat exchanger, its heat flow is shown in figure 1 - 1, the heat flow (t_1) transfer the other side of the tube's wall (t_2), the amount of heat:

$$Q_1 = \alpha_1 A(t_1 - t_2) \qquad \text{K cal/h}$$

as the conduction of heat , the heat turn to tube's wall (t_3), the amount of heat :

$$Q_2 = \lambda / \delta_0 A(t_2 - t_3) \qquad \text{K cal/h}$$

On the other side of tube's wall (t_3) the heat quantity get to cool flow, as the heat convection the amount of heat :

$$Q_3 = \alpha_2 A(t_3 - t_4) \qquad \text{K cal/h}$$

where:

A —— heat transfer surface area of the tube's wall m^2

t_1, t_2, t_3, t_4 -- the temperature of every point (to see Fig. 1 - 1) ℃

α_1 -- The coefficient of convection of hot flow K cal/$M^2 \cdot h \cdot$ ℃

α_2 -- The coefficient of convection of cool flow K cal/$M^2 \cdot h \cdot$ ℃

λ -- conduction coefficient of tube's wall K cal/$M^2 \cdot h \cdot$ ℃

δ -- the chickness of tube's wall m

For the constant heat transfer , the heat from hot flow transfer to tube's wall, then to transfer cool flow , their quantity of heat should be equal. this is:

$$Q_1=Q_2=Q_3=Q_0$$

Through calculate, we could get the amount of heat from hot heat to cool heat by the formula:

$$Qc=A\cdot(t_1-t_2)/[(1/\alpha_1)+(\delta/\lambda)+(1/\alpha_2)] = A\cdot K(t_1-t_2)\ldots\ldots\ldots\ldots(1)$$

where:

$\alpha_1, \alpha_2, \lambda$ —— constants (for using heat exchanger in on-the spot)

t_1, t_4 —— operation control index

δ_0—— this is also constant, for cleaned the heat exchanger or the new heat exchanger. So this, we could get the design amount of heat Q_0. But in production process, because of every reasons, the inside and outside of heat exchanger's tube will be fouled (see figure 1 - 2). Meanwhile,

$Q_1=\alpha_1 A(t_1-t_2)$ K cal/h

$Q_2=(\lambda_1/\delta_1)A(t_2-t_3)$ K cal/h

$Q_3=(\lambda_0/\delta_0)A(t_3-t_4)$ K cal/h

$Q_4=(\lambda_2/\delta_2)A(t_4-t_5)$ K cal/h

$Q_5=\alpha_2 A(t_5-t_6)$ K cal/h

$$Q_f=1/(1/\alpha_1+\lambda_1/\delta_1+\lambda_0/\delta_0+\lambda_2/\delta_2+1/\alpha_2)=K_f A(t_1-t_6)\ldots\ldots\ldots\ldots(2)$$

δ_1 δ_2 —— the thickness of inside and outside of the tube fouled, m between (1) and (2) we can know, $Q_f<Qc$ in case of condition, heat transfer is effected by the fouled tube.

According some report, after using heat exchanger, the heat transfer area is not change,if heat load is constant,the fouling will make the temperature go up.

$$\Delta T_f/\Delta Tc=1+UcRf\ldots\ldots\ldots\ldots(3)$$

where:

ΔT_f —— temp diff after fouling.

ΔTc —— no fouling's temp diff after fouling.

Uc —— total heat transfer coefficient at cleaing.

R_f —— fouling coefficient.

Assume the operation is in the conatant tempreture differentiation codition, the heat load decrease with the fouling increasing. The quantity of decreasing as follows:

$$1-[(q/A)_f/(q/A)_c]=(UcRt)/(1+UcRf)\ldots\ldots\ldots\ldots(4)$$

where,

$(q/A)_f$ ---- compare with the amount of heat after fouling

$(q/A)_c$ ---- compare with the amount of heat when no fouling

Cleaing purpose should be to clean fouling and to make reaseach design capicity to meen to need of operation.

2. Beijing Yanshan Petrochemical Corporation, a jumbo-sized joint petrochemical enterprise in China, has successfully fulfilled cleaning a mumber of heat exchangers with different media and under various working conditions with the high pressure water jet cleaning technique for over ten years. This meets the demand of service and production.

2.1 Comparing the cleaning methods:

Many methods can be used to clean the fouling of the heat exchangers. Compared with the other methods, the high pressure water jet cleaning has the following advantages:

2.1.1 Fast cleaning speed:

The high pressure water jet has a very high energy density and can be easily automated or mechanized to do cleaning , so its cleaning speed and cleaning efficiency are very high. Eg, It takes only 30-120 seconds to clean a six -meter long tube bundle. The average speed is 0.13 m/s which is ten times faster than human cleaning's.

2.1.2 Good cleaning quality:

As long as suitable parameters such as the pressure and flow etc and correct cleaning way, including excellent ambitus equipments,are chosen, the high pressure water jet cleaning can make the cleaned heat exchanger look just like the new one.

2.1.3 Suitable for cleaning the complex surface:

The mechanical cleaning can only clean the surface to which the tools can touch directly and the chemical cleaning can't clean the complex inside and outside surfaces. Beijing Yan Shan Petrochemical Corporation once succeeded in using the high pressure water jet to clean the round cooling coil of Φ33X3 , R400mm with fast speed and good quality. The coil which was fully plugged by fresh water foulings has nine cycles and the total length is 66 meters. It is not impossible to clean it with the other methods.

2.1.4 Having no damage to the heat exchanger

In the mechanical cleaning, the hard metal tools can produce heavy mechanical force resulting in easily damaging the heat exchanger's tube bundle. In the chemical cleaning, acid and base can probably corrode the equipment.But the high pressure water jet cleaning can avoid fully all the above . It only cleans the fouling inside and outside the tube bundle , while not damaging the equipment.

2.1.5 Well protecting the enviroment

Comparing with the chemical cleaning, the high pressure water jet cleaning can protect efficiently the environment. As is known to all, the direct draining of the waste liquids after the chemical cleaning can bring about serious pollution to the environment, while taking measures to dispose them will increase the cost and the amount of work. The foulings which drop down after the high pressure water jet cleaning are usually solids which are easy to be seperated with water and then disposed, and the remained water can be directly drained or used circularly. What's more, as a result of wet operation, a large amount of powder can be reduced and the cleaning personal and environment can get good protection.

2.1.6 Suitable for the condition of flame-proof and explosion-proof

During the cleaning with the pure water, no spark is produced. So it is suibable for the condition of flame proof and explosion-proof which often occurs in the petrochemical enterprises.

2.1.7 Able to be used easily , and able to save lots of mam power and shorten the cleaning time

Compared with the human chemical cleaning and mechanical cleaning, the high pressure water jet cleaning can be used easily, and save lots of man power and shorten the cleaning time. It needs only one - fifth man power of human cleaning, and decreases largly the labour intersity.

2.1.8 Low cost

Compared with the chemical or the other cleaning, the cost of high pressure water jet cleaning is very low . Eg, when cleaning a heat exchanger, its cost is only one - tenth of the chemical cleaning's.

2.2 Setting the cleaning equipments.

2.2.1 The high pressure water jet cleaning syatem of the tube heat exchanger consists of the following parts (see figure 2 - 1).

1).the high pressure pump;
2).the hose;
3).the pedal valve;
4).the elastic jet lever(hose);
5).the rigid jet lever;
6).the heat exchanger ;

According to the cleaning requirements, choose the suitable driving method and operation parameters such as the pressure and the flow for the high pressure pump. Through the high pressure hose ,the high pressure water generator— the high pressure pump can transport the high pressure water to the pedal valve which controls the ON/OFF of the water . Corresponding to the different construction, fitting position , scale specifications and foulings of the heat exchanger, the different nozzle and actuator - the ambitus equipments such as the hand elastic and rigid jet lever and cleaninger with kinds of type are chosen.

2.2.2 The high pressure water jet cleaning system of shell heat exchanger consissts of the following parts (see figure 2 -2).The ambitus equipment shown in this figure is the special-purpose cleaner developed by Beijing Yanshan High Pressure Water Jet Cleaning Technical Center.

2.2.3 Cleaning hard jet to clean the surface of the head cover and tube sheet.

2.3 Choosing suitable cleaning process

Choosing different cleaning process under different condition can get twice the result with half the effort.

2.3.1 First of all, according to the foulings' state ,choose high pressure water generator with suitable capacity (i.e, the pressure and flow of water jet). For the hard foulings,choose high pressure and low flow ; for the porous foulings such as the foulings on the air cooler's external fins, choose low pressure and high flow; for genernal foulings, choose the medium pressure and flow.

2.3.2 When cleaning the tube bundle fully plugged by hard foulings, choose nozzle with the holes forward and rigid jet lever (see figure 2 - 3)

2.3.3 When cleaning the tube bundle partly plugged or fully plugged by the porous foulings , choose the hose with nozzles which have both forward and backward holes can have a good efficiency. (see figure 2 -4)

2.3.4 According to the physicaland chemical properties of the foulings, sometimes , it's possible to clean those fooulings which are very difficult to be cleaned or even can't be cleaned when high pressure water jet cleaning is used with physical, chemical or mechanical cleaning . Such technology can increase the efficiency by tens of times.

2.3.5 A better cleaning result can be obtained when choosing the rotary jet , abrasive jet or spade jet according to the construction of the heat exchanger and the foulings . Now,Yanshan Petrochemical Corporation has developed the technology of "single spade" and "wide spade" with 600 — 1000 mm jet width .

2.3.6 Usually the heat exchanger is mounted in different field and by different style, so sometimes it's necessary to design the suitable clothing used when cleaning.

2.4 Precantions for safe cleaning

Consummate safe meatuses play an important role in cleaning .

2.4.1 First of all , the high pressure water generator must be in a good state

That is to say , it can generate the pressure and flow required by operation and can run stationarily for a long time.

2.4.2 Various kinds of spare parts must all be in readiness and in good state , so the actuator, the ambitus equipments.

2.4.3 Disconnet completely the cleaned heat exchanger with the process syste.

Thorough cleaning should be done for the heat exchanger to eliminate the remained water or foulings resulting in explosion or giving off the harmful gas.

2.4.4 The ball strade with obvions marks must be set around the work area to ensure the safe distance.

2.4.5 The cleaning workers must wear protection clothing, esp, the full eye protection to ensure his safety.

2.4.6 The related regulations of the government and factory for the safe operation must be observed .

2.5 Assessing the cleaning quality

2.5.1 Usually the check of the cleaning quality of the visual parts , such as, the head cover , the tube sheet , the tube mouth and the outside surface of the tube is through observation.

2.5.2 For the straight tube such as the U - tube or coil tube, usually watering them is used to check the cleaning quality, according to the water flow.

2.5.3 Beijing Yanshan Petrochemical Corporation usually uses the industrial sight glass to check the cleaning quality of those invisible parts such as the depth of the tube and the core of the shell. This can be done in the following two ways:

Ⅰ). taking the picture both before and after the cleaning to do the comparison

Ⅱ). com paring the cleaned heat exchanger with the new one.

2.5.4 The methods described in the 2.6.item of this manual can quantitivelly appraise the cleaning quality

2.6 Quantitive appraisal of cleaning benifit

2.6.1 It is sure to qualitively appraise the efficient and quality.Untill now there is no instruction about how to quantitively analyze and appraise the cleaning effect. In general situation, according to the need of factory, metric instruments can be installed in the system to control the plant running. For the quantitively appraising the cleaning effect of every heat exchanger, it can be settled by using portable uncontract flow meter.

2.6.2 The transfer heat quantity of the heat exchanger is:

$$Q=W_1Cp_1(T_1-T_2)=W_2Cp_2(t_2-t_1) \text{ K cal/h} \qquad (5)$$

where:

W_1,W_2---the flow of cold and hot flow (kg/h)

Cp_1,Cp_2---the average specific heat of cold and hot flow (K cal/kg.℃)

T_1,T_2---inlet and outlet temperature of hot flow (℃)

t_1,t_2---inlet and outlet temperature of cold flow (℃)

(5) Cp_1Cp_2 are known characteristic constant of fluid, the value of T_1,T_2, t_1 and $t_2$can be got from field metric instrument. If W_1,W_2 have been measured, then the cleaning effect can be quantitively appraised.

2.6.2a If running system can stablize the temperature difference, that is the T_1,T_2,t_1 and t_2 maintain unchanged, and if the flow W_1,W_2in clean status (new or completely cleaned heat exchanger) have been measured cleaned heat exchanger) have been measured cleaned heat exchanger) have been measured and the W_1',W_2' in foulings status have been measured, then the direct quantitive comparison can be operated, that is the hot fluid decreasing ratio:

$n_1=(W_1-W_1')/W_1 \cdot 100\%$

cool flow increasing ratio:

$n_2= [(W_2'-W_2)/W_2'] \ 100\%$

As above indicated, under the conditions of temperature unchanged, only reduce production(for example W_1 is petrochemical materials) or increase the cool flow can the system need be satisfied. Otherwise increase the consuming (for example W_2 is cooled water) to satify the need of system.

The loss caused by foulings-formation is: product unit price (W_1-W_1') running time (hour);

The loss caused by increasing cold water is: cold water unit price $(W_2'-W_2)$running time (hour)

2.6.2b In running system, during the time before and after foulings-formation, W_1, W_2, T_1, T_2, t_1, t_2 are variables. If these datas have been measured, quantitive appraisal can be operated, that is from the above formula, the transfer heat per hour after foulings-formation Q_1 and the transfer heat in clean status c new or completely cleaned heat exchanger) Q_0 can be got.(the heat loading decreasing rate $[(Q_0-Q_1)/Q_0]$ 100% is the energy increasing rate which guarantee the normal running. The cost caused by increasing energy consuming is:
energy consuming unit price(Q_0-Q_1)running time (hour).

2.6.3 The benifit resulting from using high preaure water jet cleaning heat exchanger can be accurately calculated. For example:benifit resulting from the shortining of overhaul period, from the increasing of running period, from the reusing of rejected heat exchangers by various reasons,from the enlonging of the foulings rebuilding period that after completely high presure water jet cleaning, respectively enlong the plant running period.

3.conclusion

3.1 For cleaning the heat exchanger, the high pressure water jet is an effective technology in practice.Because it has special performance and function, the high pressure water jet is more better than the other methods.

3.2 Because of various reasons, so it is necessary to clean foul and to full. The foulings must be cleaned in time to ensure the normal running of the plant, and the economil efficiency of the factory and social efficiency.

3.3 There are lot of heat exchangers in refinery; chemical engineering , petrochemical and other industry,especially China. So the using high pressure water jet cleaning technique has a great market.

3.4 The personnals who research the high pressure water jet cleaning technology must do their best to improve insistently the high pressure water jet cleaning technology and the cleaning equipments to meat the needs of production.

4. The Concluding Remarks

Beijing Yanshan Petrochemical Corportion has successfully fulfilled cleaning lots of heat exchangers with the high pressure water jet cleaning technology, and rich experiments have been accumulated. Still there are lost of work to be done. We'd like to work together with the our counterpants in China and abroad to improve incensistently the high pressure water jet cleaning technology.

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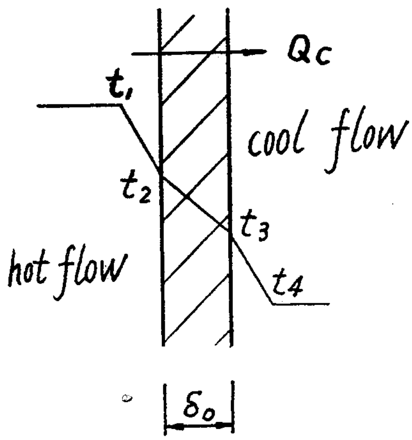

Fig. 1-1

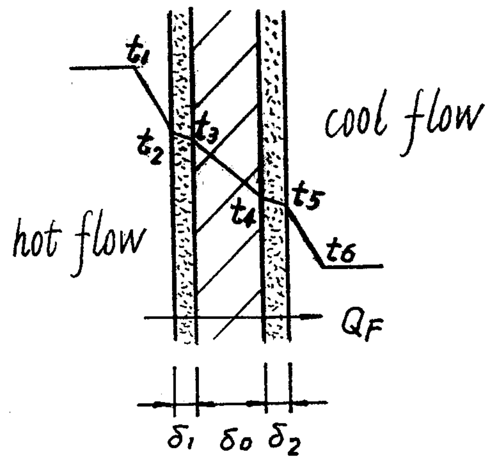

Fig. 1-2

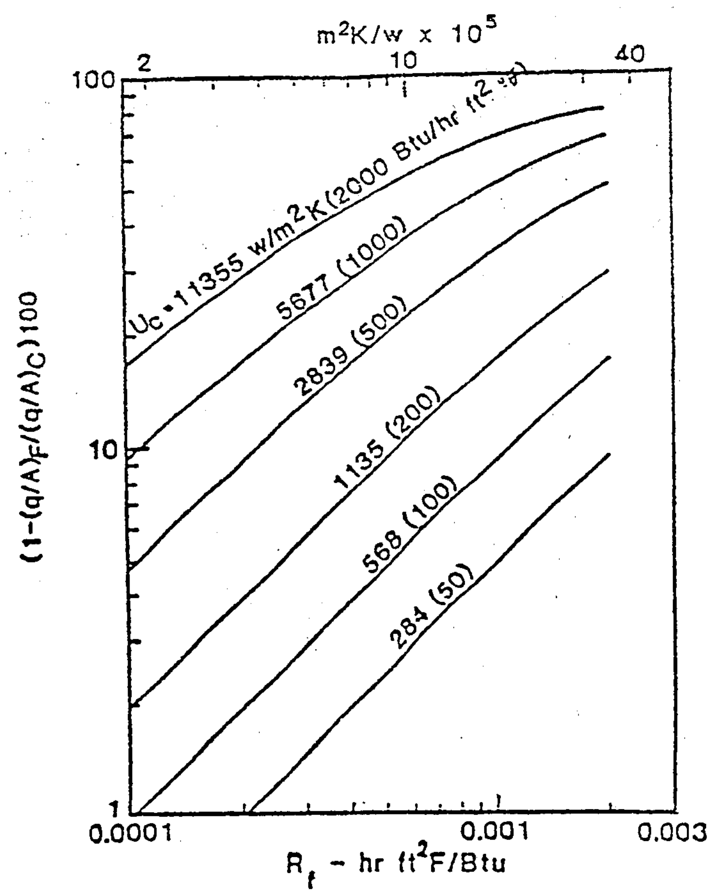

Fig. 1-3

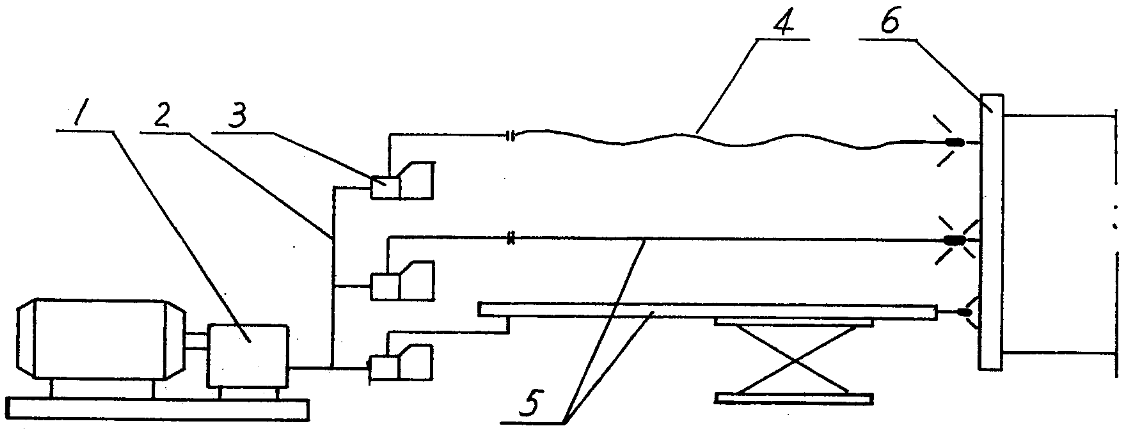

Fig. 2-1

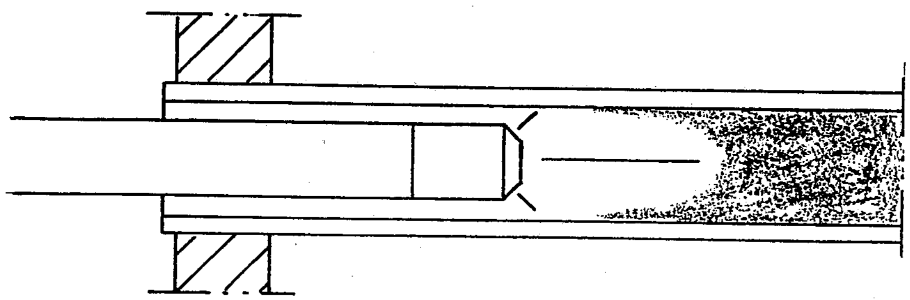

Fig. 2-2

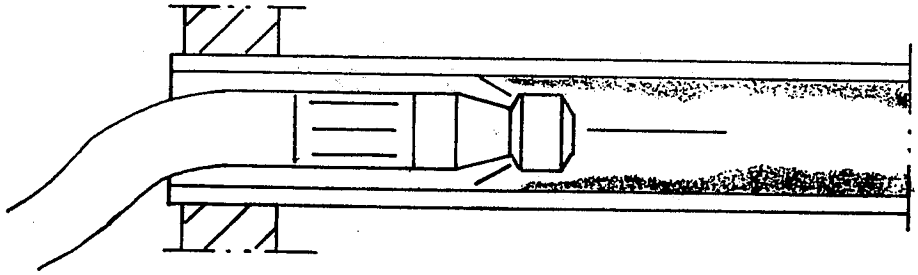

Fig. 2-3

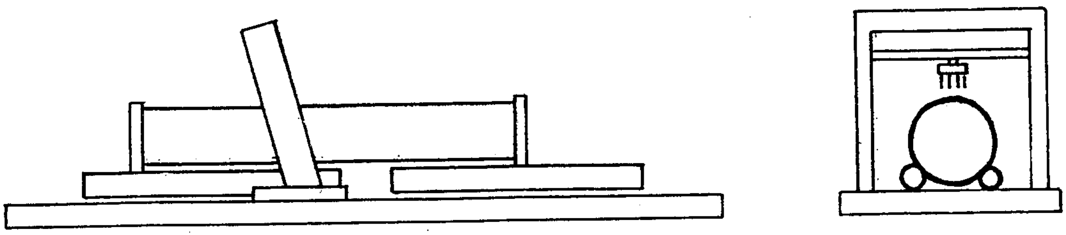

Fig. 2-4

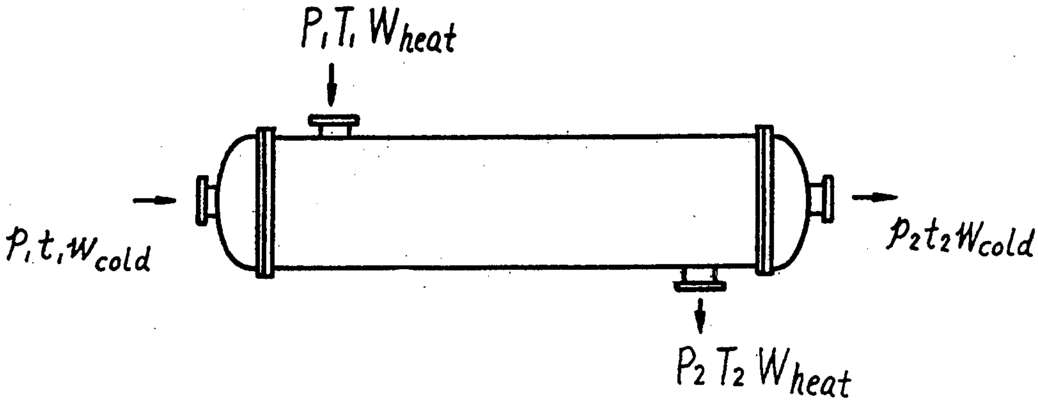

Fig. 2-5

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Paper 71

HIGH EFFICIENT CUTTING EXPERIMENTAL STUDY ON DEEP SLOTTING WITH PARALLEL SWINGING - OSCILLATING WATERJET (PSOWJ)

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ABSTRACT

In this paper, the PSOWJ and its application are studied. Based on the results of cutting tests with bricks and coal, the paper establishes a cutting model and analyzes the characteristics of PSOWJ. At the same time, the stability of cutting and the fluctuation of cutting depth are studied.

Organized and Sponsored by the Water Jet Technology Association.

1.0 BASIC CUTTING CHARACTERISTICS OF PSOWJ

1.1 Multiple - Cutting With Certain Energy

To realize multiple cutting, we set the traveling (oscillating) speed U larger than the swinging speed V_n. The average cutting number is

$$n = U/V_n = 2Af/V_n \quad (1)$$

Where, A - the swinging amplitude
f - the swinging frequency

1.2 Uneven Cutting

Because of the traveling direction being the same as the swinging direction, the cutting depth is not even. The cutting time at each point is

$$t_0 = d/U_0 = d_0/(wl + V_n\cos\varphi) \quad (2)$$

For n times cutting, the total time is

$$T = d_0\sum_{i=1}^{n}\left[1/U(\frac{i-1}{n}\cdot\frac{1}{f}+t+1/U(\frac{n-i+1}{n}\cdot\frac{1}{f}-t)\right] \quad (3)$$

Where, d_0 - the diameter of the nozzle
w - the swinging angular velocity of the lance
l - the length of the lance
φ - the swinging angle of the lance

1.3 Collapsing

The former two characteristics make a curved surface in the cutting area, which will create free faces for collapsing. When the direction of swinging is opposite to the direction of traveling, the jet component acts on the protruding parts of the curved surface and removes these parts. The energy consumed is equal to $(h + \Delta r)$.

1.4 High Frequent Impacting

When V is small, A large and f high enough, the strength of the material is inversely proportional to the loading speed $d\sigma/dt$. According to Bingham's model, the penetration rate dh/dt is

$$dh/dt = \sigma/\xi + d_0/E \cdot d\sigma/dt \quad (4)$$

Where, σ - the loading strength
ξ - the damping coefficient
E - elastic modulus

1.5 Fatigue Breaking

Before the ith impacting, the material has been jetted for (i-l) times. Therefore, its resistant strength is lowered due to partial fatigue breaking.

1.6 Cutting Periodicity

The swinging periodicity results in the periodicity of jetting. In turn, the shape of the slot bottom is of periodicity. When the lance swings forwards, the curved surface is uneven. When it swings backward, the curved surface becomes even due to collapsing. After one cycle, the slot is deepened by V_n/f. Hence, the study on the cutting process can be simplified on one cycle.

2.0 CUTTING MODEL

A smooth curve is used to describe the slot bottom, as the curve b shown in Figure 1. Because of the periodicity of cutting, such a curve is existing.

The oscillating coordinator is XOY, representing the macro - cutting process, the swinging coordinator is $or\varphi$, representing the micro - cutting process. The cutting areas corresponding to both processes must be equal. Therefore

$$\frac{dy}{dt} = \frac{w \cdot f}{2V_n}[2(1 + S + y)(h + h' + \triangle r)/\cos\Phi + (h' + \triangle r)^2 - h^2] \quad (5)$$

$$x = (1 + s + y)tg\Phi - V_n \cdot t \quad (6)$$

Where,
S - the off - distance
h - the cutting depth in forward swinging
h - the cutting depth in backward swinging
Δr - the collapsing depth

3. THEORY OF MULTIPLE - CUTTING WITH CERTAIN ENERGY

The fading of cutting depth results from friction, damping and off-distance, and so on. Assuming the cutting damping is equal to the depth ratio of two cuts

$$Z(j) = h_j/h_{j-1} \quad (7)$$

Then, the increasing rate of the slot is

$$K = \frac{H_N}{H_0} - 1 = N^{-\alpha}\Phi(N) - 1 \quad (8)$$

Where,
H - single cutting depth
H - multiple cutting depth
N - cutting number
α - the fading factor of cutting

The fading function is

$$\Phi(N) = \sum_{i=j=1}^{N\,i-1}\prod(Z(j) + 1)^{-1} \quad (9)$$

Only when $\alpha<1$, then $K>0$, which is the essential condition for multiple cutting.

3.1 Uniform Fading

When fading is only decided by the property of materials, then Z(j) is constant, we have

$$K = N^{-\alpha} \cdot \frac{1 - e^{-N\lambda}}{1 - e^{-\lambda}} - 1 \tag{10}$$

Where, λ - the fading factor

3.2 Uneven Fading

When fading is related with the jet parameters, we have

$$k = N^{-\alpha} \cdot \sum_{i=1}^{N} \exp\left[-\frac{\lambda}{W}\sum_{j=1}^{i=1}(i-j)h_j\right] - 1 \tag{11}$$

Where, w - the width of the slot

4. CUTTING EXPERIMENTS

Using the binary linear regression method to deal with the test results, we get a cutting equation

$$\triangle h = 5.35(P_0/\sigma_c - 1)U^{-0.335} \tag{12}$$

At the same time, the fading factor is $\lambda = 0.0155$.

In Figure 2, the heavy line is the test results, while the dotted line is the calculated results. Compared with swinging waterjet, PSOWJ consumes less energy, it is only about 2/3 of the former.

The effect of swinging and oscillating is equal to the raising of cutting pressure. The pressure increased is

$$\triangle P = (P_0 - \sigma_c)K_{max} \tag{13}$$

Where, P - the jetting pressure
σ - the compression resistance of material
K - the maximum increasing rate

5.0 THE FLUCTUATION OF CUTTING DEPTH

On the whole cutting process, the cutting depth increases stably. However, it is not uniform within one cycle. The reason is

a. the swinging speed is not even.
b. the cuts are different from each other.
c. the friction varies with the cutting depth.
d. the cutting depth in forward swing and backward swing are different.

Therefore, the cutting depth is of fluctuation.

6.0 CONCLUSION

(1) Only when $\alpha < 1$, can the cutting efficiency be raised. The increasing rate of cutting depth is $K = N^{-\alpha}\Phi(N) - 1$.
The fading function $\Phi(N)$ is decided by the jet parameters.

(2) PSOWJ has six basic characteristics multiple cutting with certain energy, uneven cutting, collapsing, high frequent impacting, fatigue breaking and cutting periodicity.

(3) PSOWJ can raise the jetting pressure

$$\triangle P = (P_0 - \sigma_c)K_{max}$$

(4) The calculated results (f=23. 07 1/s, k_{max}=82. 35%)
and the testing results (f=23. 5 1/s, K_{max}=93%)
are basically the same.

(5) The collapsing depth Δr is related with the depth h. This relation obtained from the experiments is $\Delta r = 3.15(h + 1)$.

7.0 ACKNOWLEDGEMENTS

This work is finished under the direction of Prof. Cheng Dazhong.

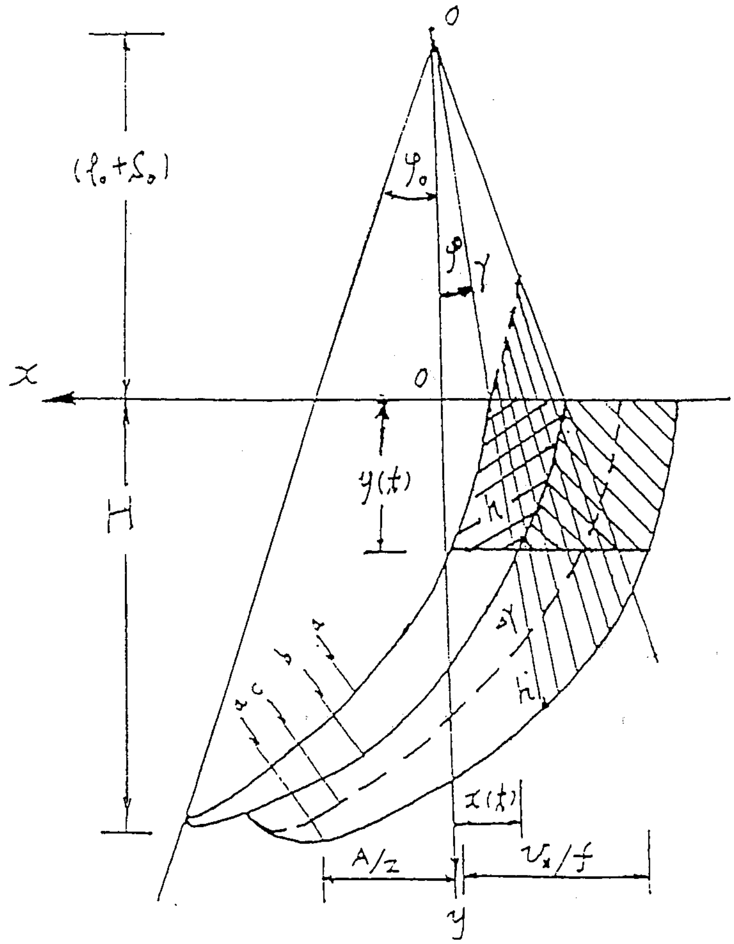

Fig. 1 The Cutting Model

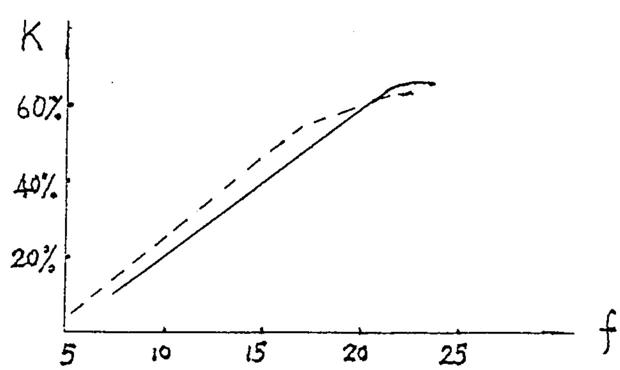

Fig. 2 Effect of Frequency on The Cutting Depth

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Paper **72**

THE APPLICATION OF SENSORS FOR PROCESS MONITORING IN HIGH PRESSURE WATER JET TECHNOLOGY

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ABSTRACT

In production technology, high-pressure jetcutting is considered to be the best separation method for cutting various materials today. Paper, textiles, food, plastics and ceramics are frequently cut this way. For the separation of metals, ceramics and compound materials, such as metal plastics, abrasives have generally to be added. Permanently increasing demands in the branch of product engineering concerning exactitude, quality, security, flexibility and economic efficiency have led in jetcutting technology to the development of modern NC- or CNC- controlled high-pressure jetcutting systems. Besides, the water jet is applied as a device in flexible production systems.

Increasing demands concerning the manufacturing of products or components necessitate an optimal conception of the manufacturing processes. In order to meet the requirements of given work tolerances, a detailed process of monitoring and controlling is necessary for the quality control of the finished product.

Today, "online" monitoring and controlling systems are increasingly applied in manufacturing, engineering, and processing. Comparable process controlling systems have not been common in jetcutting technology up to now, since process-specific sensor systems have not been available.

High demands, regarding the sensitivity, threshold, resolution and of course, solidity in rough shift to shift operation, have to be met by these sensors. The tolerances of modern production lines necitate the use of monitoring systems far in advance of quality control of the finished component, to recognize and correct fabrication spread as early as possible in the process to minimize the reject rate. Another goal is the improvement of the surface finish in order to reduce or skip secondary treatment.

The FHG-IPA therefore is occupied with the development of a sensor system which permits control of cutting power (jet convergence, flowthrough), positioning (jet), attrition (cutting nozzle), collision "on-line." The advantage of such a system is the improvement of quality and manufacturing security, making the use of high pressure jetting profitable for wider industrial applications.

1 Introduction

Water jet cutting is a cutting process that is very suitable to cut various materials. Nowadays paper, cardboard, fabrics, food and plastics are often industrially cut with high-pressure jets. Generally abrasives have to be added when separating metals, ceramics and compounds (fig.1)

The increasing interest of industry in the application of new materials with newly generated material properties leads to results that with the high-pressure jet are achieved with much more flexibility, more economy and less ecological damage than with conventional cutting systems. As with the conventional production technologies the water jet as a tool can be guided and managed with flexible production centres.

With today's international competition production engineering is permanently confronted with the increasing deman for better quality, more flexibility, safety and economy, and therefore means and ways have to be found to optimize, monitor and controll the process of water jet cutting. The recognition of process drifts minimizes the production ofrejects and increase the economy. The consistent linking of machine and technology by means of microelectronics and dataprocessing may stabilize production processes and help eliminate faults.

In production and process engineering today intelligent processing systems, that means "online" monitoring and controlling of systems, are used more and more often to ensure a better process stability. As faults caused by tools here very often occur, systems to measure the cutting power and the recognition of fractures are of greater importance. For milling, drilling and thrilling a number ofsolutions have become known which detected failures in the cutting operations and thus allow conclusions of the wear condition of the tools (fig. 2). To recognize these changes caused by wear or fraction the cutting tool itself is also to be scanned.

Adapted to the need of the water jet as tool, monitoring and controlling systems are also applicable with water jet cutting processes, using sensors and systems that reliably detect disruptive factors and whose application strive for better cutting qualities and smaller size tolerances (fig. 3).

Therefore high standards are demanded of the sensors regarding their sensitivity, their threshold, resolution and not least their solidity. To meet set production datas, such as tolerances, systems could be used, for example, which would already during production processes - that is long before the quality control of the finished part - recognize production trends and are able to intervene by means of monitoring strategies. The aim of this measure is a better machine exploitation by reducing production faults, a better processing quality by smaller measurement tolerances with good surface qualities and therewith the improvement of the economy.

2 Analysis of Malfunctions and Malfunction Factors

Effort was put on the improvement of machine availability and production safety in our work at the Fraunhofer Institute for Production Engineering and Automation. The main attention was payed to the monitoring of the cutting tool and its influential parameters.

Following the malfunction analysis in chipping production systems, with high-pressure cutting machines organisatory and technical malfunctions can be distinguished (fig. 4). Technical malfunctions may again be subdivided into machine and processing troubles. The results of the tests were obtained with a special machine, however, they are also applicable to other similar machines. The cutting machine consists of a water cooled high-pressure pump, 20 m pipe system, 2 cutting stations with 3 axes each, cutting heads for water as well as abrasive jet cutting, and an abrasive supply unit.

Because many parameters exist with water jet cutting the linking of several signals out of the process are necessary to ensure a reliable tool monitoring. The most important of these signals are summarized in figure 5. The jet of a jet cutting nozzle consists of the core region, the compact and droplet jet as well as the droplet cone. Quantity and Quality of the jet flow are at last responsible for the achieved jet efficiency and therefore of the cutting effectiveness. This is why monitoring the process is the aim of our work. Faults of the machine, such as wear of the globe valve, wear of the high-pressure valve, wear of the high-pressure seal of the plunger, filter life, exceed of the oil temperature in the hydraulic system, are statistically registered, but are not relevant for these studies.

3 Description of the Tool - Jet Form per Jet Effectiveness

The tool of a water jet cutting machine is the high-speed jet - either "pure" or "with the rocks" with abrasive supply. In comparison to a mechanical cutting tool the fluid jet is not geometrically determined, but its form and effectiveness results from the cooperation or conflict of a multitude of influences, amongst which "chaos" is not the last to be found. Everybody, who ever drilled holes with the water jet, must have wondered about their shape. This, however, seems less incomprehensible, when one observes the jet of a cutting nozzle at a constant pressure. Its shape is round sometimes and the next moment it flows in a helix - "Mr. Reynolds sends his regards".

To sum up: For the effect of a jet it can be said that, analogous to the laser jet, the energy density of the jet, this means energy per area, ranks in first place. This means that the relation between the form and the effect of the jet is designed by the flow dynamic of a high-speed jet. Or more practically spoken: There is an area of the jet which is particularly suitable for cutting tasks as the relation between cut depth and cut width is optimal. F igure 6 shows a cut notch in aluminium in relation of the distance of the nozzle to the workpiece surface.

The flow dynamic of a high-speed jet was examined by the Japanese YANAIDA and OHASHI and presented at the "5th Jet Cutting Conference" in Hanover in 1980 (fig. 7). Along the jet axis the jet can be subdivided into different sections, which differ in size and form of the jet flow speed. The beginning of the jet has a homogenous speed area, whose total can be calculated as follows:

$$v = v_0 = \sqrt{\frac{2 \cdot p}{\rho}}$$

v velocity [m/s]
p pressure [bar]
ρ density

Caused by the correlation between the flowing fluid and the static surroundings the jet is slowed down at its contact areas. The approximation of the speedprofil as function of the jet distance is optained by the following equation:

$$v(r) = \frac{Q}{\sqrt{2 \cdot \tau \cdot \sigma}} \cdot e^{-\frac{1}{n}\left(\frac{x-x}{\sigma}\right)^n}$$

Q flow rate [l/min]
σ standard

Therefore, with a constant fluid volume the jet has to expand, this is to say the processed area becomes larger and the energy density diminishes.

4 Tool Monitoring at the Cutting Jet

Of all parameters responsible for the formation of a jet only the pump pressure respectively the pressure occuring at the nozzle can be monitored and analysed "online". Instationary flow processes, comprehensibility of the medium water, pulsation of the high-pressure pump as well as the difficult conditions of the surroundings are a great challenge to the sensor receptors and amplifiers regarding the monitoring of the concentration and cutting capability. Contact-free signal reception is a demand, insensitivity against moist, dust and heat are requirements that limit the choice. Nevertheless it is possible to find systems that provide useable data for the guidance. At the moment sensors for monitoring jet concentrations and turbulances, cutting effectiveness, and abrasive flow are tested.

Apart from the pressure the geometry of the nozzle drilling is responsible for the shape of the water jet. This means a resistance ot the high-pressure water jet whose size is determined by the hydraulically effective cross section area as well as length, inlet and outlet angle, who again is responsible for the quality of the jet concentration. The flow cross section resp. the hydraulic diameter of a profile is calculated by the relation of the cross section to its perimeter.

$$D_h = 4 \cdot \frac{A}{U}$$

Consequently for water jet cutting a round nozzle drilling possesses the favourable hydraulic cross section or the smallest possible resistance.

$$D = D_{hK} = 4 \cdot \frac{A_K}{U_K}$$

$$\text{with } A_K = \frac{\pi \cdot D^2}{4} \text{ and } U_K = \pi \cdot D$$

with D nozzlediameter
D_h effectiv nozzel diameter
A_k circle area
U_k perimeter

A change in the nozzle drilling through which the fluid flows mainly shows in a worsening of the jet concentration. The increasing flow resistance is equal to a larger friction, which causes higher flow turbulences. In figure 8 this behaviour is shown in a comparison of two jets, recorded with a video camera.

The observation of the brightened-up jets with a video camera produces a shadowgraph. An analysis of the distribution of the grey areas may supply information - without any direct contact - on the jet concentration as well as the jet position of the cutting jet before the cutting procedure starts (fig. 9). Corresponding data are also available in the jet catcher system and, with an adequat analysis, supply "online" conclusions about the jet concentration or the obtained cut quality.

5 "Online" Cut Quality Monitoring of the Cutting Jet in Testing

The best information about the cuttting process can be obtained near the working area. But there are a couple of different problems which prevent the use of sensors in the working area:
The danger of mechanical destruction, the risk of electrical damage caused by humidity, difficult carrying of the sensors, contactless measurement acquisition and transmission necessary. That are the reasons why process signals from the working area are not continuous and only used in labaratories. For industrial aplication we need continuous process information. Therefore process signals had to be found that would allow an indirect observation of the cutting process. The technological background is the the relationship between jet forming and jet effect, or the physical dependence of the jet forming from hydrodynamic proportions, e.g. pressure and flow rate.

The measurement signals at the entrance of the cutting machine, namely efficiency resp. current and speed of the high-pressure pump, are easily to be determined, but the distance between the monitoring and cutting process is too long, this is to say too many distrubance factors are registered integrally, such as pressure loss, leakage and temperature of the oil hydraulic, and prevent a reliable analysis of the process. Porcess information which refer to the correlation of the water jet tool and its environment, such as temperature, sound emission or body sound vibrations. To register process data sensors are applied that monitor the pressure and flow rate, the flow characteristics of the jet, the abrasive amount and the jet concentration. The measurement signals are analysed with a 12-channel measurement amplifier. The lead computer is a personal computer. This PC controls the registration and analysis of the measured data and is responsible for the data exchange between the components, this means it sends commands to the high-pressure pump for abrasive amount and cutting jet guidance. For controlling and monitoring the cutting jet as tool the IPA (Fraunhofer-Institute of Production Engineering and Automation) uses an Apple Macintosh II. This online cutting jet monitoring is set up resp. extended for a DFG (translation: German Research Community) research study. To communicate with the cutting system the computer is equipped with an IEEE-488 interface (plugged card NI-488 of National Instruments). The sensor signals are amplified and digitalized by a meter amplifier, make Hottinger Baldwin Messtechnik. They can be called up via a parallel bus (IEEE-488) from the control and monitoring computer.

The parameter within a cutting process that is the most simple and immediate to be measured is the working pressure. DMS pressure sensors, type EBM 6051, range 0 - 5000 bar, were used for the high-pressure measurement.

A further parameter which is essential for the cutting process is the volume flow or mass flow that runs through a cutting nozzle. As no device is available on the market that is able to measure flow amounts of 4 l/min at a pressure of 4000 bar within the high-pressure area, the flow can only be measured in the low-pressure area of a machine, this is to say before the high-pressure pump. A Pelton-Turbine make *Kobold-Messring* is used. The diagramm of figure 11 shows clearly that, in comparison to weighed measuring datas, the results of the turbine are good. As the sensor provides information on the momentary flow of water to the pump the measuring datas have to be averaged over a certain period of time.

The aim of the developement of underpressure measurement at the water jet tool is to obtain contact-free, tool-relevant inormation about e.g. jet concentration and jet impulses. The concept of measurement uses the water jet pump principle. The according to Bernoulli theoretically established values are well approached by the measurements (fig. 11). The second diagramm in fig. 11 shows the course of the underpressure signal at the cutting head and in the catcher when drilling into high-quality steel sheet. After the break-through of the jet an underpressure signal can be measured in the catcher as well. The larger signal fluctuation is due to the consideringly more turbulent cutting jet in this area.

Figure 12 shows the test construction for body sound measurements at the cutting head. To sum up is may be said that the body sound measurement for the monitoring of the water jet as tool is successfully applied. Malfunctions in the nozzle drilling impair the jet quality and manifest themselves in the intensification of the flow turbulences that cause larger viabrations in the cutting head. The malfunction caused may therefore be recognized with the increase of the single level of the frequency spectrum and therewith in the change of the averaged total sound level of the body sound signal.

Figure 13 shows process signals of the cutting process. During this period a leaking check valve of the high-pressure pump disturbed the function of the cutting system. The recording of signals, pump pressure, nozzle pressure, flow rate and below atmosphere pressure in the cutting head was made online. As the check valve is formed as ball with taper seat that turns when operated these malfunctions did not always occure when pressure was generated. All sensor signals detect the malfunction of the high-pressure production. The effect of this malfunction is shown in the cutting result, the cutting quality becomes considerably worse. Significant pressure variations cause a turbulent inhomogeneous jet flow. The discontinuous jet flow results in increased but also uncontrolled material removal, where material particels are spasmodically knocked off.

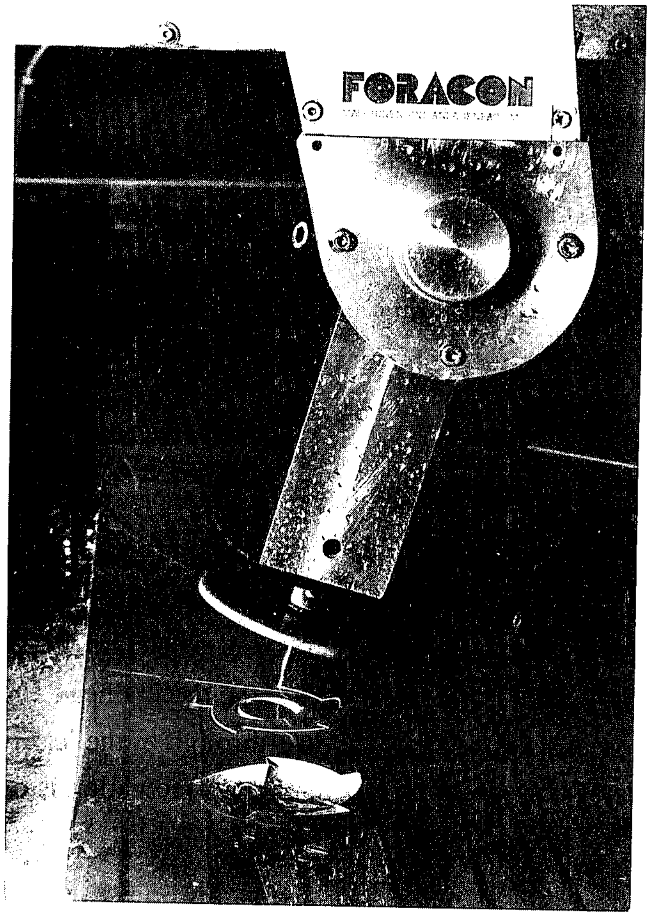


Figure 1: Abrasive water jet cutting with a high precision 5-axes machine

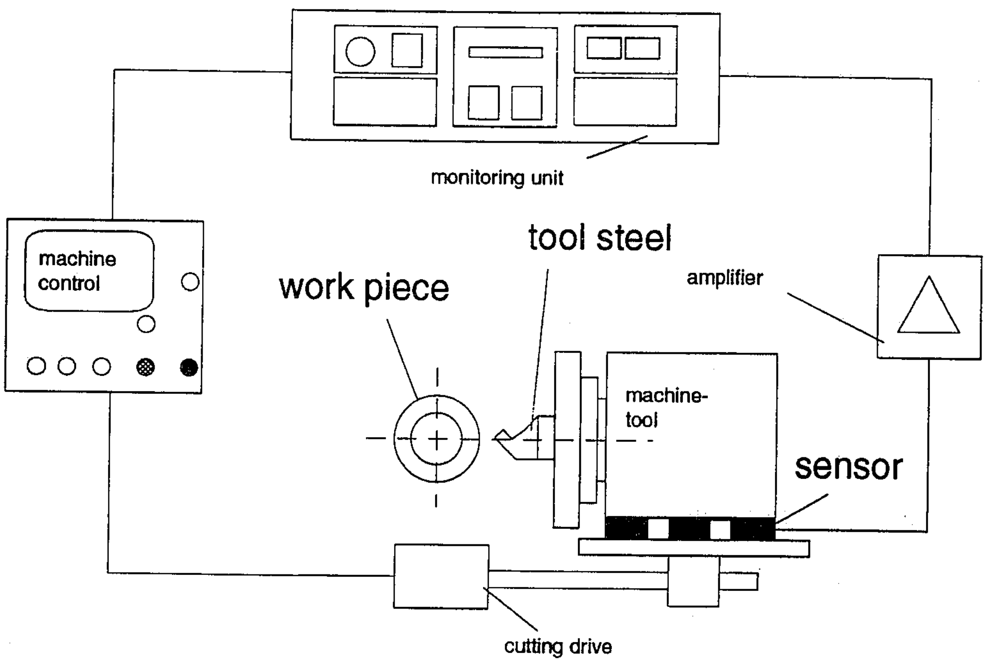


Figure 2: Monitoring systems in the drilling process

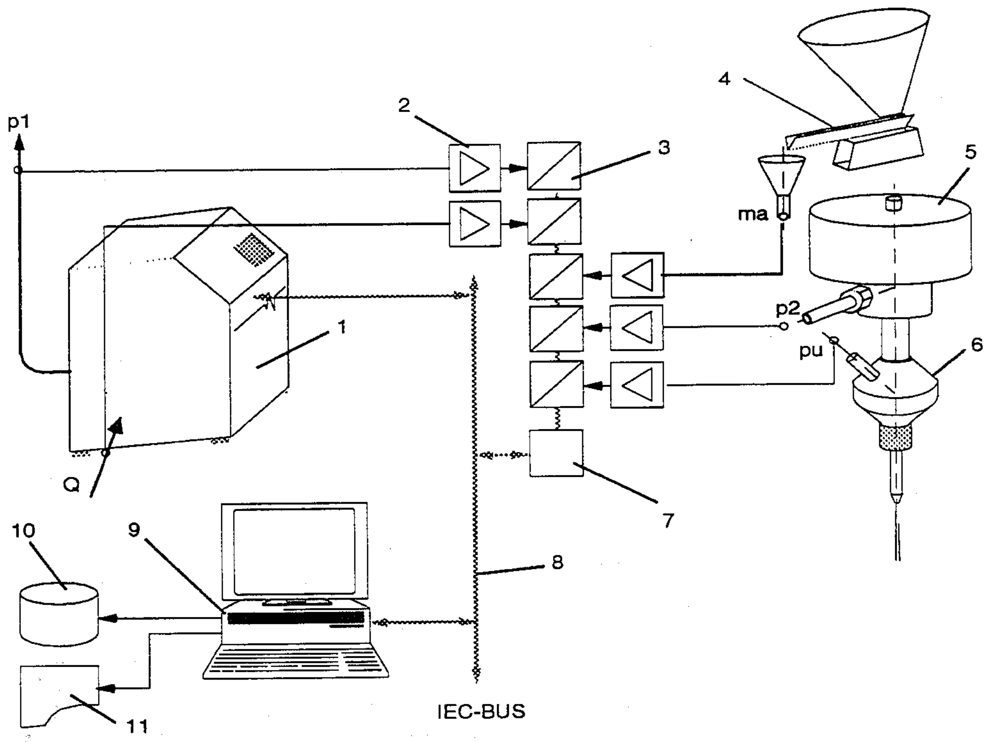


Figure 3: Diagram of cutting process monitoring Structur for acquisition of pressure, flow rate, below atmosphere pressure and amount of abrasive high pressure pump (1), measuring amplifier (2), A/D-transformer (3), abrasive dosing system (4), high pressure valve (5), cutting head (6),measuring processor (7), IEEE-Bus (8), computer for measuring acquistion and interpretation (9), data storage (10) and data output (11)

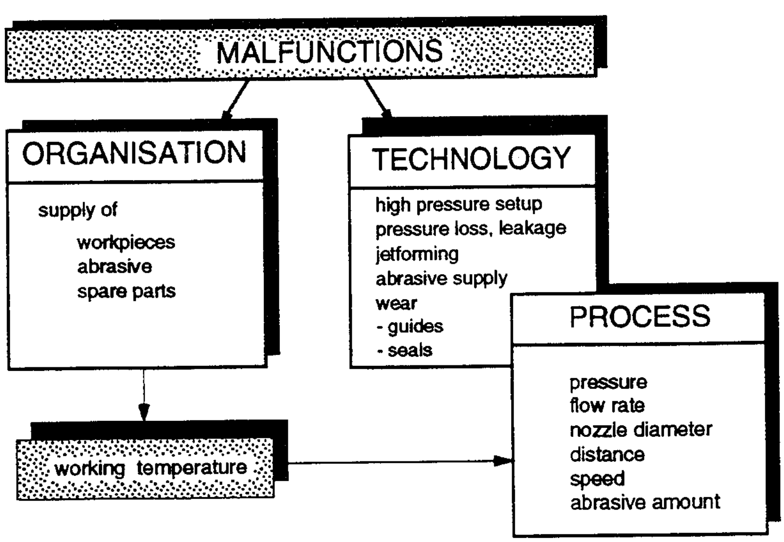


Figure 4: Malfunctions in the jet cutting process

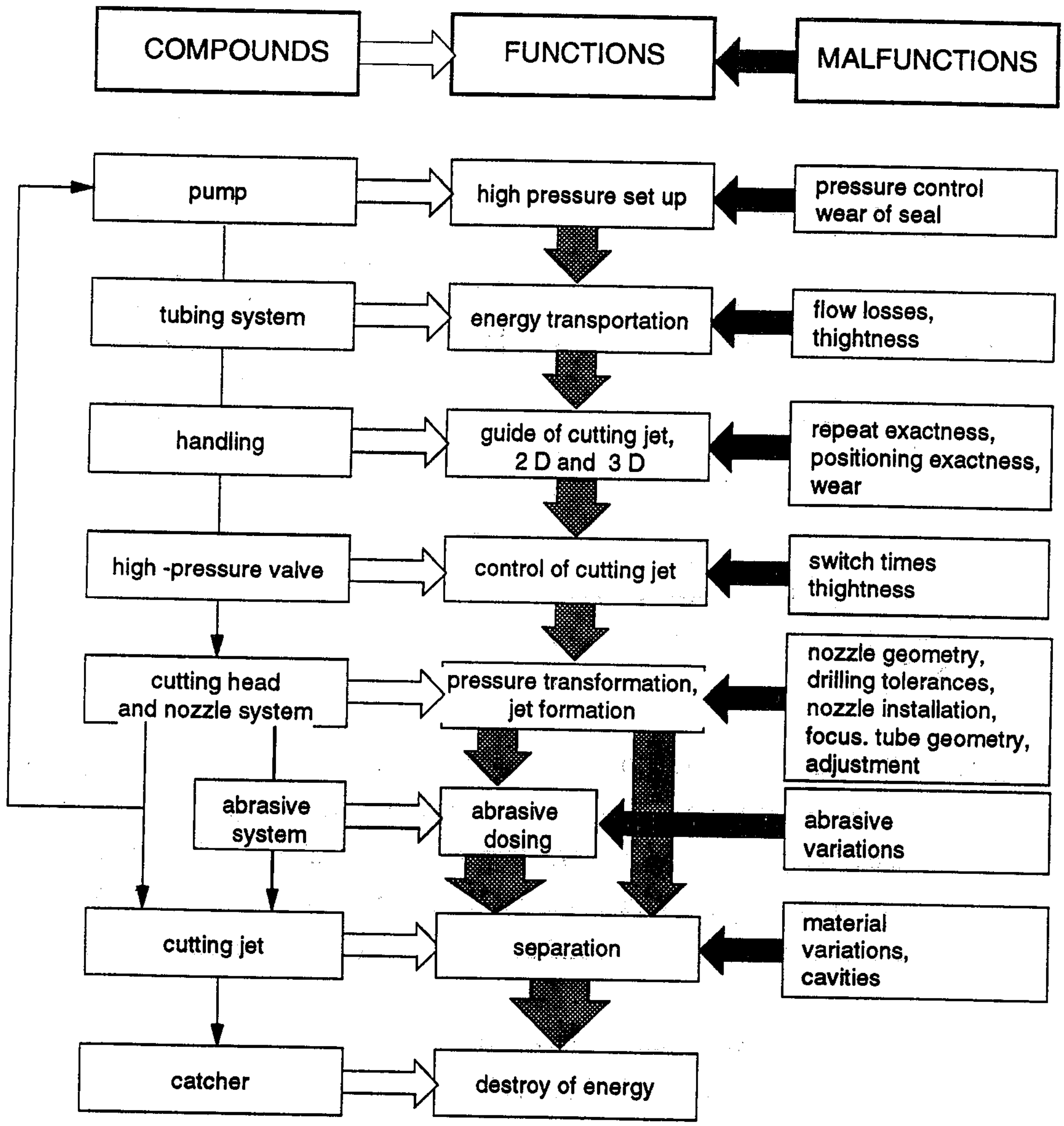


Figure 5: Components, functions and malfunctions of a water jet cutting system

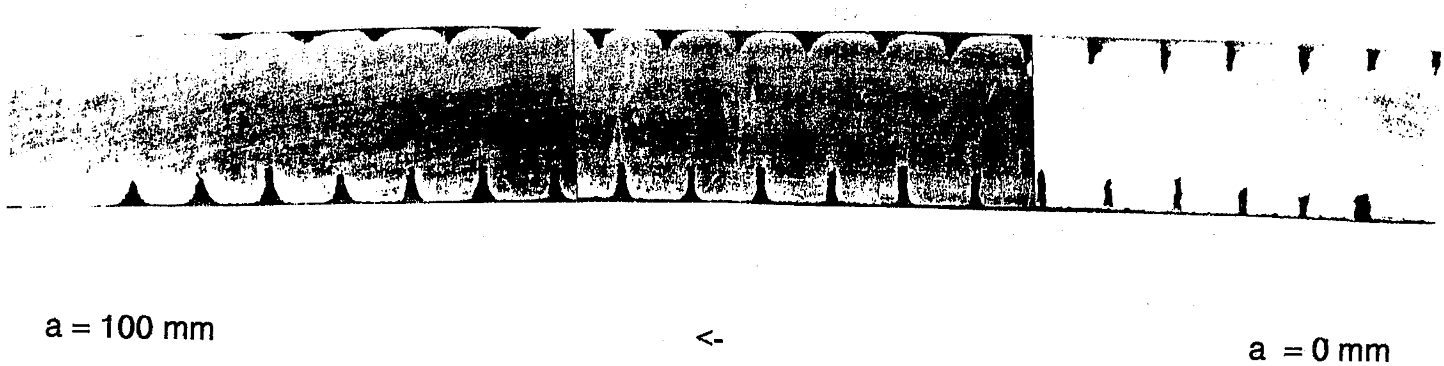


Figure 6: Cut notch in aluminium in relation of the distance of the nozzle to the workpiece

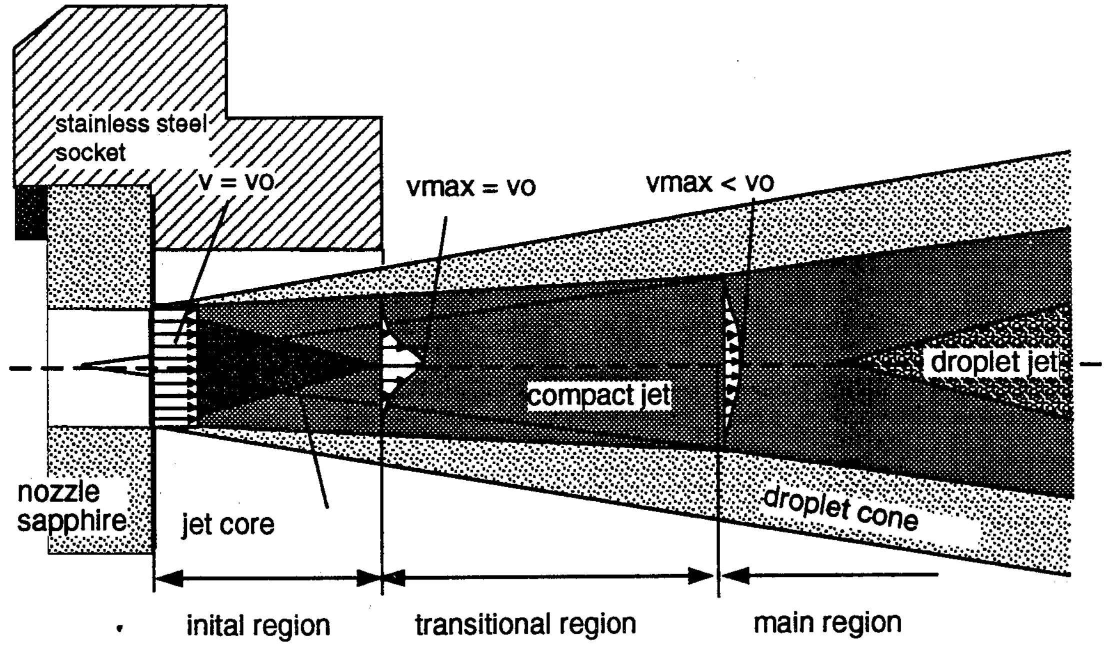


Figure 7: Scheme of the waterjet in air

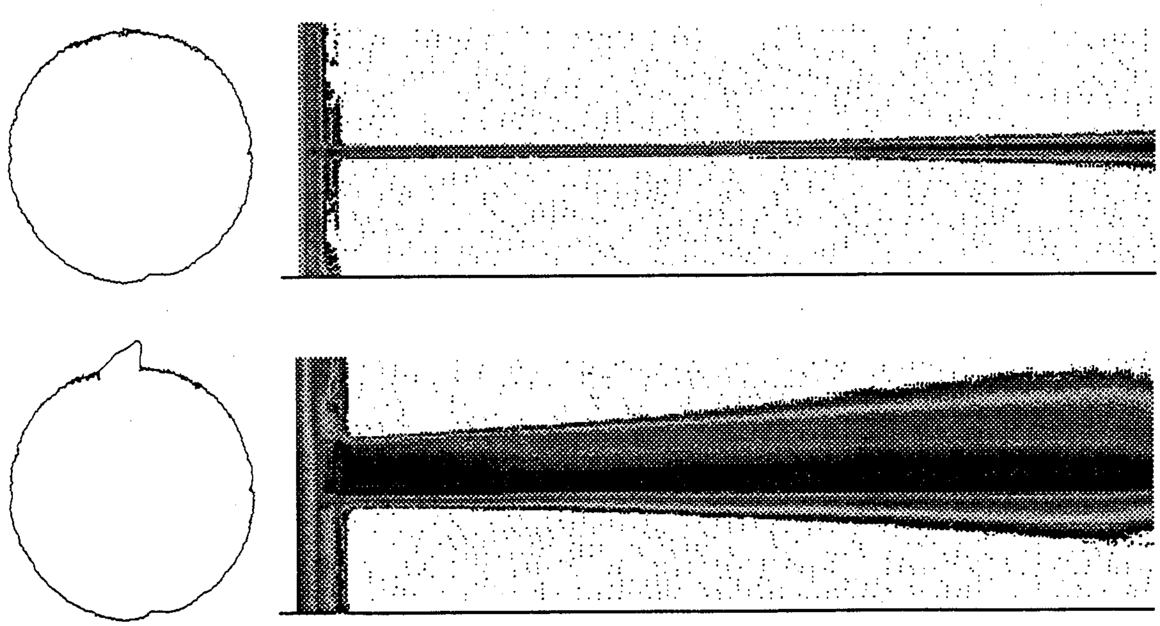


Figure 8: The influence of the nozzle bore hole on jet forming, pressure 3500 bar, diameter 0.25

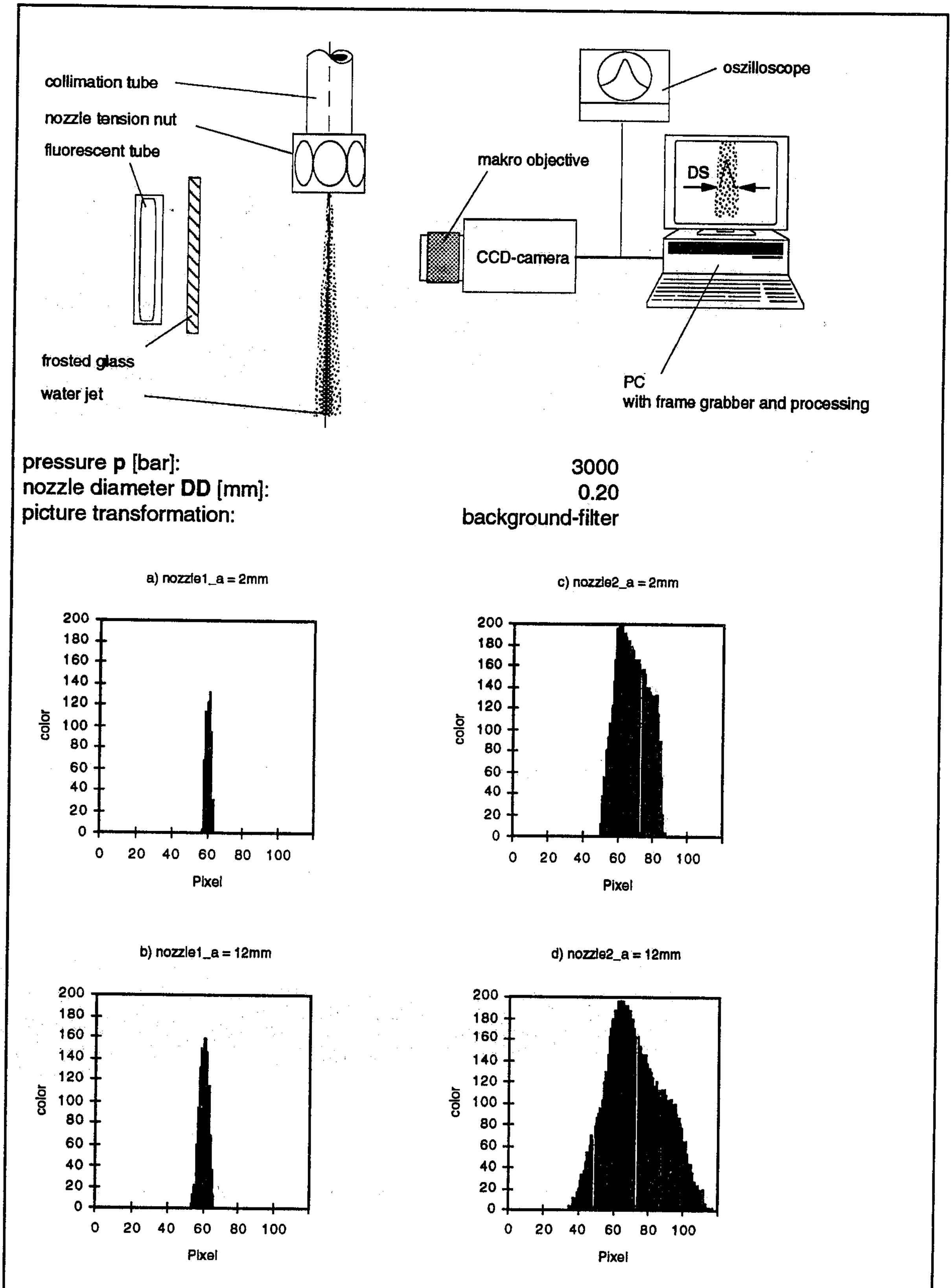


Figure 9: Analysis of the shadowgraph of water jets

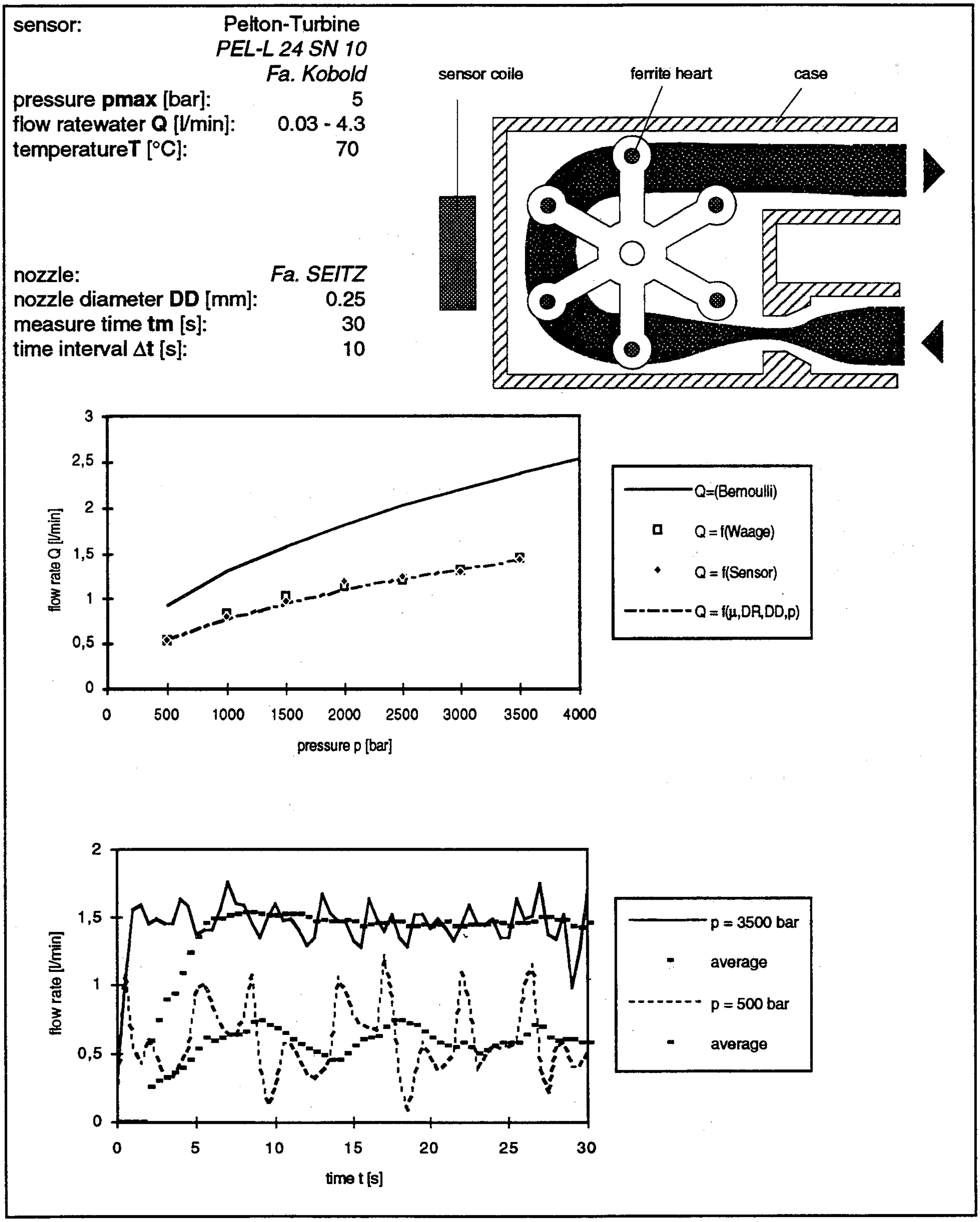
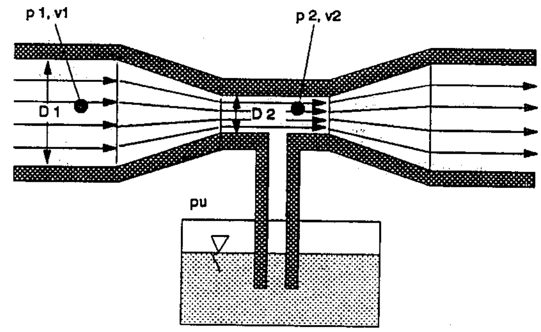
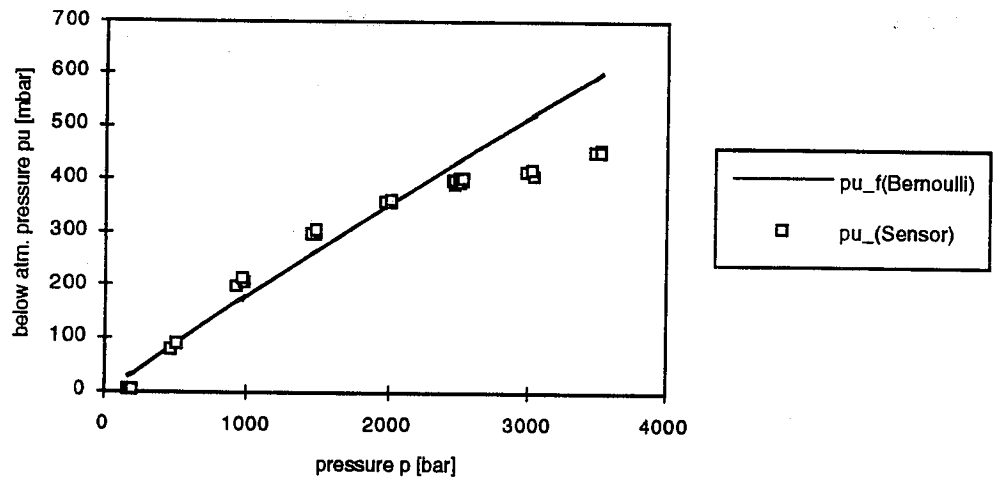


Figure 10: Measuring of the flow rate with a Pelton-Turbine

collimation tube diameter **D1** [mm]: 5
nozzle diameter **D2** [mm]: 0.25
nozzle factor μ: 0.66

$$p_2 = \rho_2 \cdot \left(\frac{p_1}{\rho_1} + \frac{1}{2} \cdot v_1^{2} \cdot \left(1 - \frac{d_1^{4}}{d_2^{4}}\right)\right)$$





pressure **p** [bar] 2500
working distance**a** [mm]: 10
nozzle diameter **DD** [mm]: 0.25
nozzle factor μ: 0.66
material: V2A, 1.5 mm

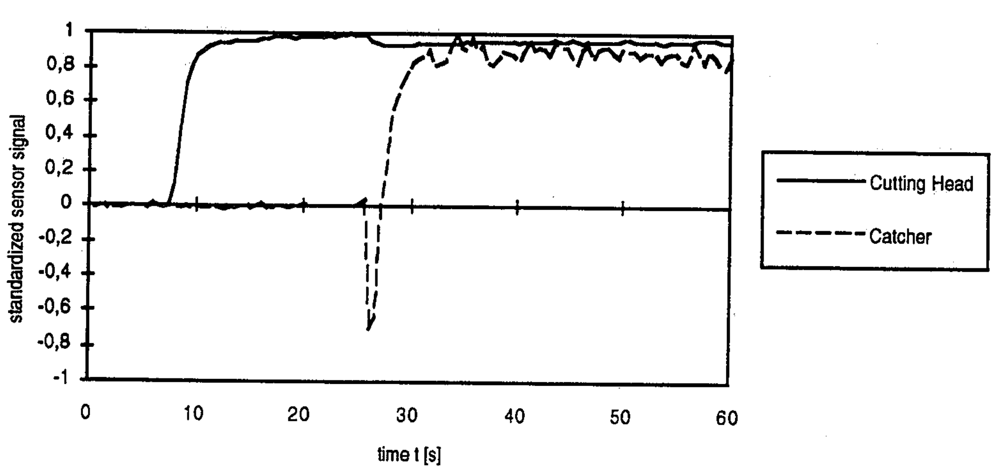
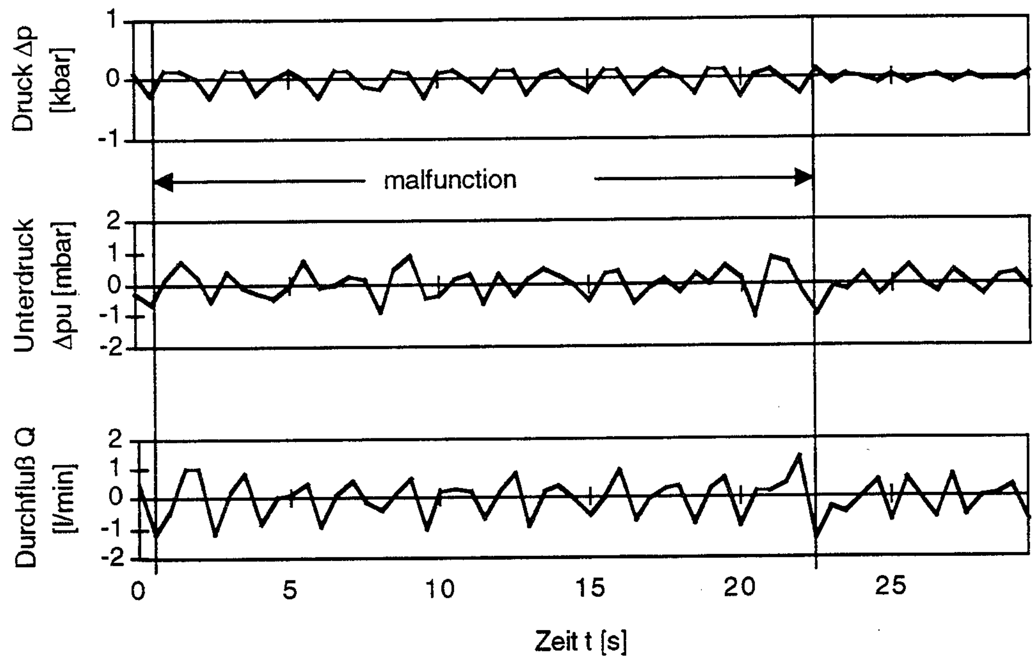


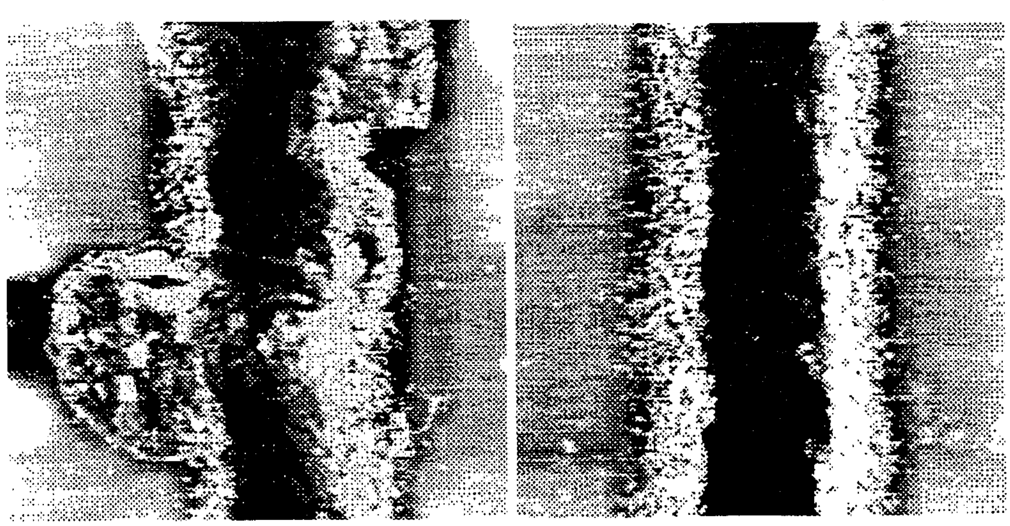
Figure 11: Process controlling with the below atmosphere pressure

pressure **p** [bar]: 3500
nozzle diameter **DD** [mm]: 0.25

malfunction: leaking high-pressure check valve of the high-pressure pump

measurement system underpressure **pu** [mbar]: absolute pressure sensor, *Fa. HBM*
measurement system flow rate **Q** [l/min]: Pelton-Turbine, *Fa. Kobold-Messring*





a) malfunction b) normal

Figure 13: process signals during a malfunction

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Paper 73

INNOVATIVE DESIGNS FOR X-Y CUTTING SYSTEMS

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ABSTRACT

The application of waterjets and abrasivejets to close tolerance CNC X-Y systems pose some challenging design problems. These challenges include but are not limited to operation in an extremely hostile environment, the minimizing of X-Y service costs and applying the correct control systems.

Designs addressing these and other challenges have been implemented and are operational in various manufacturing applications.

Organized and Sponsored by the Water Jet Technology Association.

1.0 THE EARLY YEARS

1.1 The application of waterjets and abrasivejets to coordinate cutting equipment has been practiced since the mid 1970's. Early applications were prior to the advent of the abrasivejet. Therefore, they were subjected to a humid environment. But nothing as damaging to the machinery as the atmosphere created by abrasivejets. Some examples of the early applications are:

A. Cutting shoe parts

B. Cutting prepregs

1.2 These and other early applications required fairly loose positioning tolerances, (ie +/- 0.020), X-Y systems from M.G. systems, Heath, ESAB, and others were set up with waterjets. Most of these systems were designed for torch or plasma cutting. The first systems employed tracing "eyes" to control machine movements. They did not offer high speeds. Positioning tolerance capabilities were often in the +/- 0.030 range. Some were capable of tighter tolerances at much higher costs. A good example was the M.G. Systems Model 4500. It was CNC controlled and capable of +/- 0.005 positioning tolerances.

1.3 In the mid 1980's waterjets employing abrasives became available. Abrasivejet cutting presented sales with opportunities beyond their wildest dreams. Overnight the applications went from cutting non-metallic fairly weak materials to cutting anything. Examples of items that Abrasivejets cut are:

Aluminum alloys, brass, carbon steel, ceramics, dies, Frp's, glass, hastelloy, hardened carbon steel, kevlar, magnets, marble, mirrors, plastics, plexiglass, rubber, stainless steel, tantung, titanium.

And of course sales were made and so were promises.

1.4 Many X-Y cutting systems were sold that could not hold tolerances required by these new applications. Some manufactures began to list tolerances in creative ways in order to sell machines, (table 1.4-1). An example was the tolerance modifier used by one X-Y manufacturer. The modifier was: "over any 4 foot X 4 foot cutting area with the Z-Carriage in it's full up position". This type of modifier tends to be overlooked. You know, it's kind of like "fine print".

1.5 Cutting speeds for abrasivejet applications are slow. The majority are less than 100 inches per minute;

CUTTING SPEED CHART

MATERIAL (ALL AT 1/2 INCH THICK)	PRODUCTION CUTTING SPEED (IPM)
ALUMINUM ALLOYS	12
BRASS	9
CARBON STEEL	6
STAINLESS STEEL	4
TITANIUM	7
TOOL STEEL, (HARDENED)	2

Thus, existing X-Y's could perform the coordinate manipulation of the cutting head. But other obstacles were soon apparent. The most obvious being the extremely hostile environment created by the abrasivejet. The results were:

1.5.1 Unhappy customers due to down time and parts out of tolerance.

1.5.2 A stunting of sales growth due to unhappy customers, (the word gets around).

1.5.3 Gun shy sales personnel, (the commissions weren't enough to heal the wounds inflicted by unhappy, irate customers).

1.5.4 A need for equipment designed specifically for the application of abrasivejets and waterjets.

2.0 THE NEW AGE OF WATERJET MANIPULATION.

2.1 To undo the damage and expand the application of waterjets new manipulator designs were needed. Positioning accuracies, rigidity, smooth speed control and protection of mechanical systems were problems that needed to be addressed. CHUKAR INDUSTRIES was formed specifically to create X-Y systems for applications of waterjets. A prime design goal was the elimination of these earlier problems.

2.2 CHUKAR INDUSTRIES was formed October, 1989. The first X-Y system became operational in July, 1990. Today the first system is used in a job shop application and does abrasivejet cutting five and six days a week. Service requirements on the machine have been limited to one loose encoder to motor coupling and normal cleaning and lubrication. Lubrication is done once every six months and involves one mechanic for two hours.

2.3 The problem was addressed by the following: The abrasive environment was successfully challenged with a creative sealing mechanism employing labyrinths, lip seals, sheet metal covers and positive pressure ventilation, (table 2.3-1). This type of closure protects against the abrasive environment without costly bellows that wear out due to abrasive dust in their folds, (table 2.3-2). A set of <u>fully closed</u> bellows will cost from $4,000.00 to $10,000.00 for a machine set. A new machine set of Lip Seals is $600.00. Less expensive "U" shaped bellows are easier to replace but don't provide proper sealing. Bellows tend to cause positioning problems. The varying drag created by the bellows as they are compressed and extended causes loads on the servo system to vary. The lip seals apply a constant load to the servo system. Bellows also require extended beam length for the accumulated bellows. Lip seals do not.

2.4 High rail gantry design is beneficial in preventing foreign material from contaminating the mechanisms. It also allows the operator closer access to the work table.

2.5 To apply abrasivejet in many industries, machine positioning accuracy must be +/- 0.005 inch maximum. To attain and maintain these accuracies one must remember from basic design; you get out what you put into a machine. Therefore, it's not just high powered electronics that will yield a close tolerance machine. First you need a rigid, stable machine frame, (table 2.5-1). Second, the initial positioning of the components that hold machine tolerance must be dead on. Third, don't rely on "gadgets" such as controller back lash compensation if you expect consistent parts without adjustment for years to come. Fourth, the speed range of the machine, say 0 to 500 inches per minute, should be available without any mechanical changes (ie gearing). And last but not least, the equipment should employ state-of-the-art control systems as a standard and be capable of adapting the controller of your choice without costing you an arm and a leg.

2.6 A word of warning, abrasivejet cutting versus traditional milling requires much less control power or ability. Don't spend money on a control just for the name. Most controls are similar not only in operation but service as well. Be certain the machine uses a closed loop control system. The control company has a good service record. And let the X-Y manufacturer help you in your choice of controls, that's part of his expertise.

2.7 We have addressed the accuracy requirement with:

2.7.1 Special structural design of the X and Y beams.

2.7.2 Mass in the support structure using steel not aluminum to prevent vibration.

2.7.3 Lead screw drives with anti-backlash lead nuts and support bearings, (table 2.7.3-1).

2.7.4 Close tolerance, expensive, machining of the structure to provide "dead on" positioning of the critical components.

2.7.5 The use of ALLAN BRADLEY 9/230 control as a standard, which incorporates the following features:

- USA Manufactured
- 32 bit processor
- High speed digital or analog servo interface
- Fiber optic I/O ring
- Advance flash memory & shadow RAM
- Surface mount technology
- 3 Axis plus 1 spindle
- Single board design
- 1 millisecond servo update
- Analog servos
- I/O capacity 1,000 points
- PAL capacity 10,000 elements

However the machine design allows for "plug in" adaption of other machine tool controls.

2.7.6 Wide contouring speed range, 0 to 500 IPM thru proper control, servo, mechanism integral design. (some Model 106X-Y's are operation in this range with Y-beam assemblies of greater than 1800 pounds), (table 2.7.6-1).

2.8 In conclusion, there are a large number of X-Y manufactures that build systems capable of manipulating a waterjet or abrasivejet cutting head. However, you must ask, "was this equipment designed for this task?". If "yes", then will it perform as specified for years to come? Cost vary widely but are normally the first indicator of machine quality and or ability. A quality 10 foot by 6 foot cutting area X-Y will cost $100,000.00 to $120,000.00 without the high pressure water and abrasivejet systems. Money in excess of this may well be thrown away. Lower costs will indicate a design with no factor of safety, structure too light, designed with an objective to cut costs rather than produce the highest quality machine.

2.9 CHUKAR INDUSTRIES X-Y systems are designed specifically for abrasivejet cutting and have successfully demonstrated their ability to address the above related design and operational concerns.

ESAB Waterjet Machine
GXB Lobo 12/17/87

MODEL	GXB 600	GXB 800	GXB 1000	GXB 1200	GXB 1600
Net Cutting Width	72"	96"	120"	144"	192"

Rail Length: 10'0", 16'0", 20'0", 26'0"

Master Carriage Length: 5'8"

Net Cutting Length:
10'0" Rail System, 66.0" Net Cutting Length
16'0" Rail System, 126.0" Net Cutting Length
20'0" Rail System, 168.0" Net Cutting Length
26'0" Rail System, 242.0" Net Cutting Length

Recommended Work Height: 28" from floor

One (1) Motorized Lift Station:
6" Vertical travel, motorized
6" Vertical travel, mechanical

Machine Control: See separate specification

Drives: Rack and pinion, closed loop servo motors with encoders and non-backlash gear boxes

Speed Range:
.25-50 or 2-250 ipm (Auto-Path)
.5-50 or 2-250 ipm (Compu-Path)
(up to 600 ipm available upon request)

Machine Rails: Stainless Steel

Machine Accuracy:

GXB 600	GXB 800	GXB 1000	GXB 1200	GXB 1600
± .010"	± .010"	± .010"	± .010"	± .014"

As measured on each axis with the tool station in the upper most position within a 4' x 4' work area
NOTE: The above accuracies assume a part is programmed. Digitized parts using a photo-optic tracer will add ± .010 to the above chart.

NOTE: ACCURACY LIMITATIONS

Machine Repeatability: ± .003" as measured on each axis with the tool station in the upper most position within a 4' x 4' work area.

Waterjet Machine Package: Includes: Operator's pedestal mounted control, rack axis rail and master rail, way covers, plated rack, drive covers and pen tracing tool. One station.*

ESAB Mechanized Cutting Division

Figure 1.4-1

SEALING SYSTEM DIAGRAM

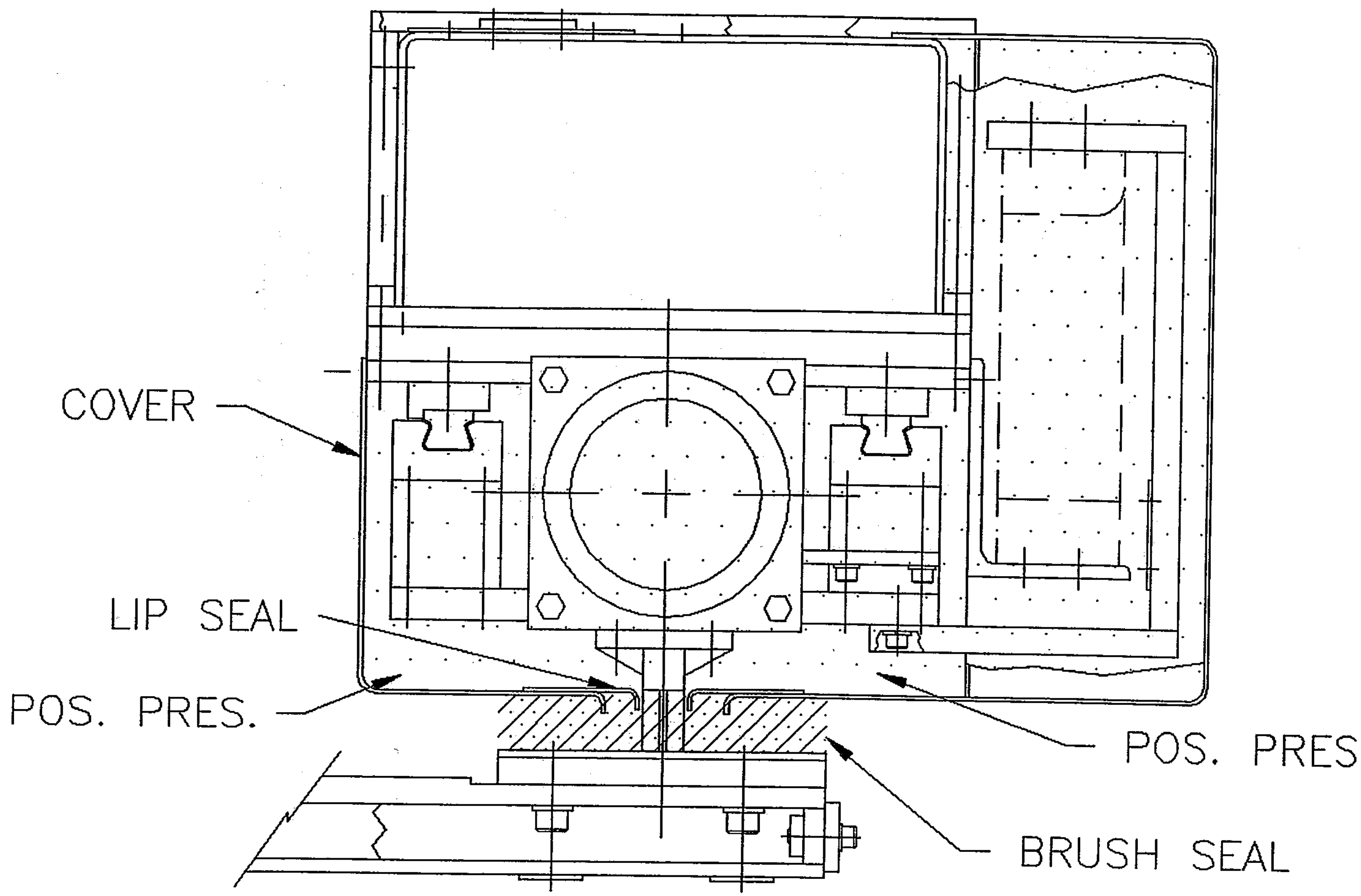

Figure 2.3-1

BELLOWS TYPE PROTECTION

Figure 2.3-2

CHUKAR INDUSTRIES MODEL 106X-Y

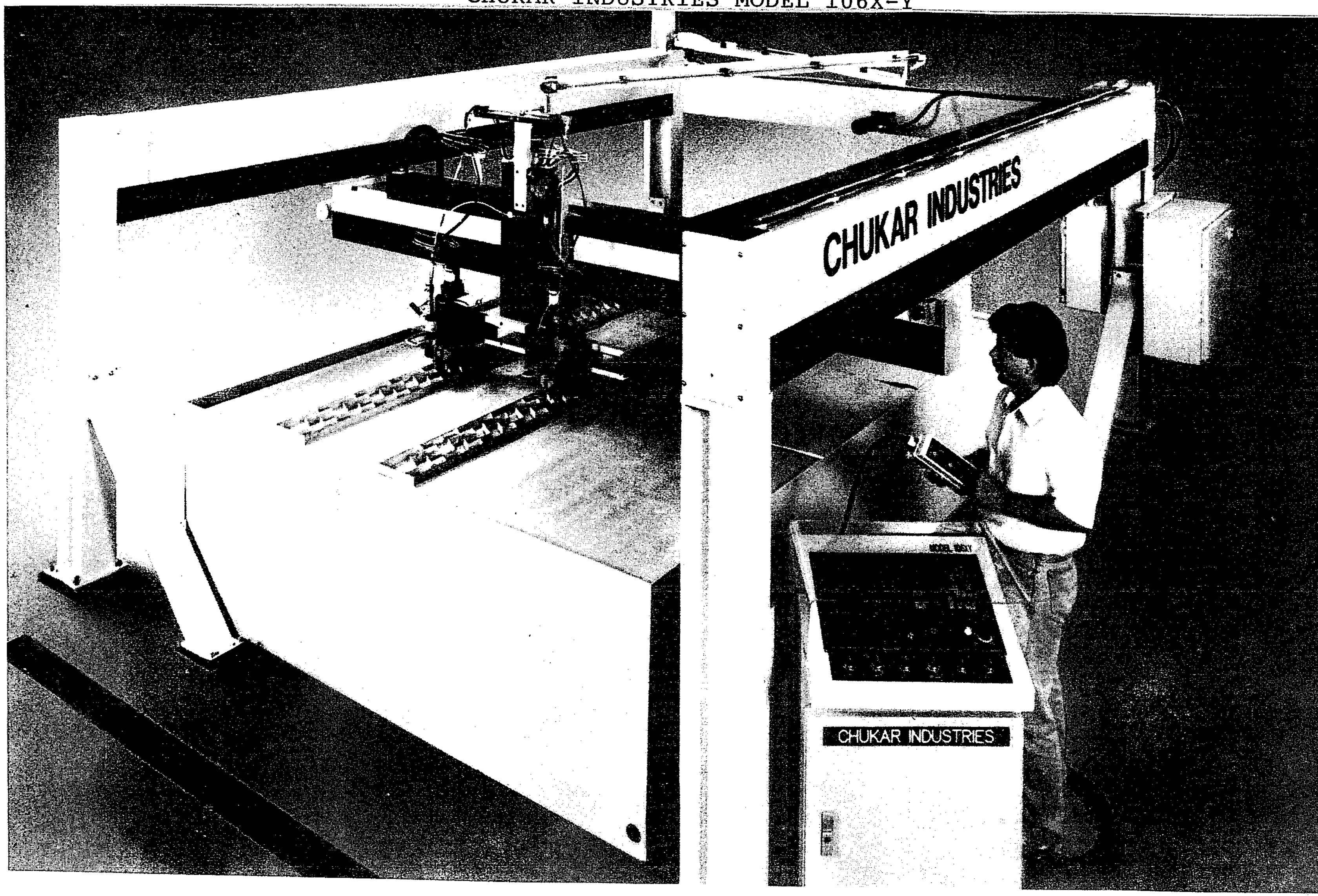

Figure 2.5-1

DUAL PRELOADED BALL MOUNT

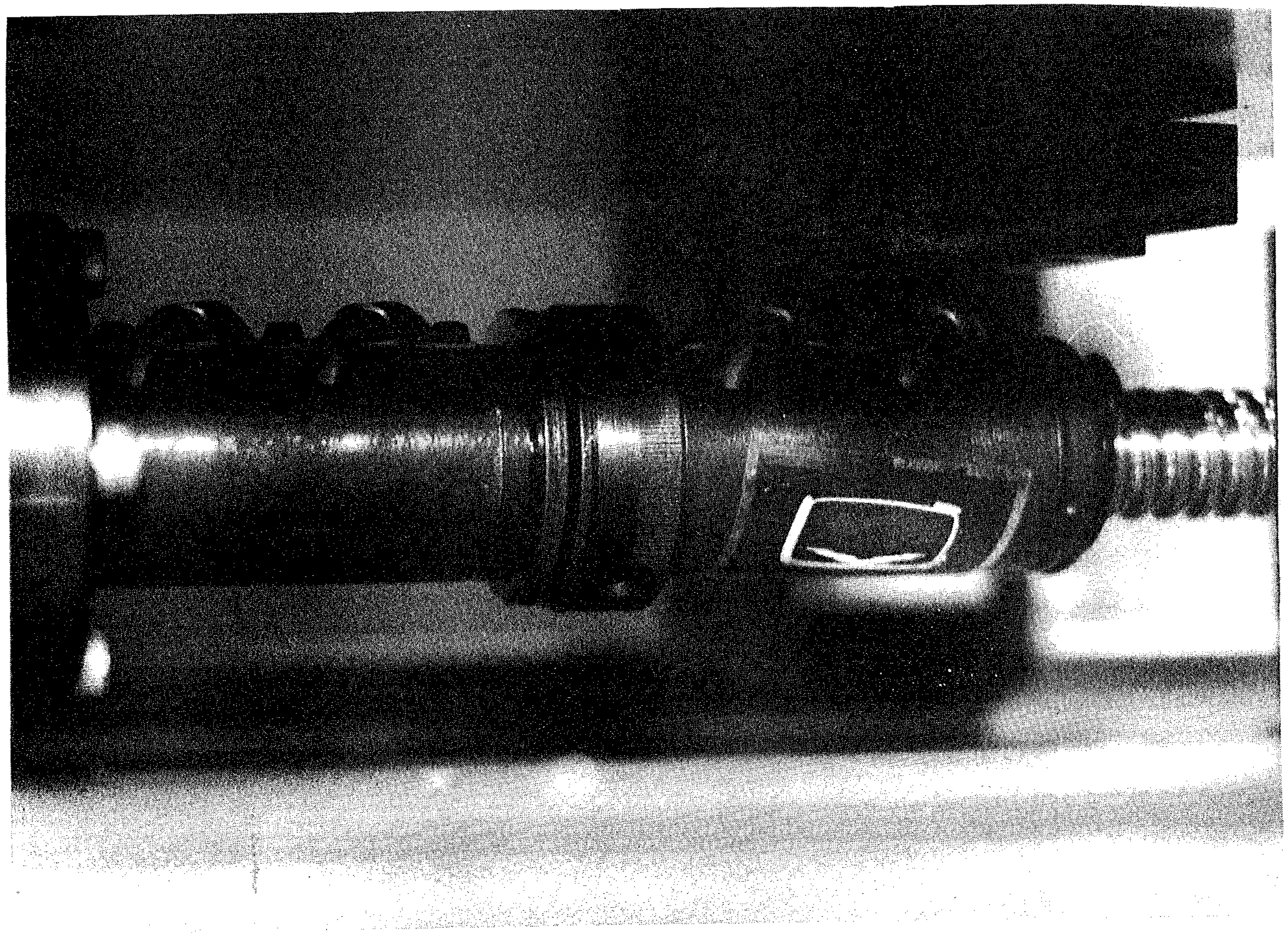

Figure 2.7.3-1

6 HEAD WORDENGLASS MODEL 106X-Y

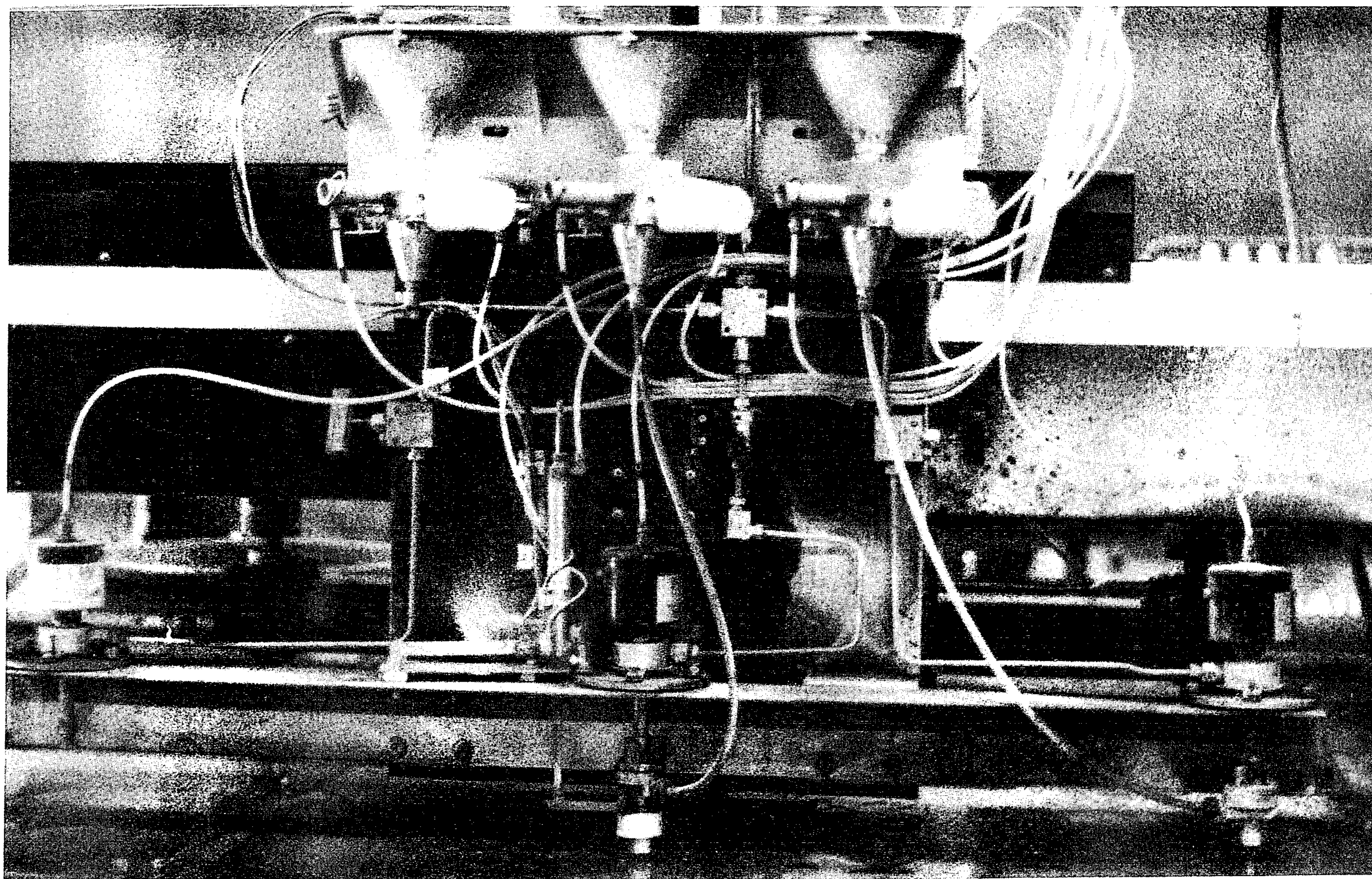

Figure 2.7.6-1

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