THE U. S. WATERJET TECHNOLOGY ASSOCIATION

NEWSLETTER

SUMMER / 1986 265 HARMON AVE., LEBANON, OHIO 45036 VOL. 2

40.000 PSI ?
(YES!)

The Membership
Water Jet Technology Association

Dear Member,

Many of you have recently received a copy of a letter sent to me by Mr Mondy of Job Master. Because of the statements in that letter, I believe it important that you be aware of certain facts,

The Water Jet Technology Association was formed in May of 1983, during the course of a waterjet meeting at the University of Missouri-Rolla. Following that initial meeting, a Standards Committee was designated at the Board of Directors meeting held in Golden, CO on August 5, 1983.

The first meeting of the Standards Committee was held at the Henry VIII motel in St. Louis on March 9th 1984. At that meeting it was unanimously voted that "The Committee act, as a whole, in developing the standards for nomenclature and operational standards, based on the British Code of Practice." This referred to the Code of Practice for the Use of High Pressure Water Jetting Equipment, which had been published by the Association of High Pressure Water Jetting Contractors in the UK, and which was discussed at the meeting.

A draft document was then prepared, based not only on the UK document but also incorporating suggested practices adopted from as many sources as could be identified during the summer of 1984. This was then circulated for discussion. As a result of comments which were returned, some 10 pages of suggested changes were brought to an open meeting, held in Denver on October 23, 1984. Each of these suggestions was separately discussed, and a final draft approved.

This draft was included in the preprints issued to each attendee at the 3rd US Waterjet Conference held in Pittsburg, and reviewed in a presentation to that conference on May 29, 1985. At the subsequent meeting of the Waterjet Technology Association held at that meeting the Recommendations were adopted. They are now available.

It is stated, in the preface to the document that "As identified in this document, this set of recommendations is subject to review and bi-annual modification." At the present time suggested changes to this document have been received from several sources, and will provide a basis for document review during the course of the next year. No such recommendation has been received from Mr. Mondy at this time. The document has, in general, received favorable comment from both industrial and government sources, including officials of various OSHA who have commented that no existing documents are available in this line from those groups.

It has been the intent of those who have put in a considerable effort in order to develop this series of recommendations, that an advisory document be made available on the use of high pressure equipment. That is what the Association has developed. It is a series of recommendations, which individuals may or may not wish to follow. We are anxious, however, that it reflect the best advice to those who would seek to use it, and thus I encourage comments on any aspect which readers might wish to see changed.

Because of the legal action which Mr Mondy has outlined, a copy of his letter has been referred to legal council, who has re-assured us of the validity of our position. A copy of my reply to Mr Mondy is available to anyone interested.

On a final note, you should be aware that, following conversations with cognizant personnel, we were unable to define activity at ASTM, or the National Safety Council which would indicate any chance of standards being issued by either organization in the near future.

Should you have any further questions on this matter please do not hesitate to contact me, and I will be glad to respond to you.

Respectfully I remain,

Yours sincerely,

David A. Summers
President

SUBCOMMITTEE FORMED.

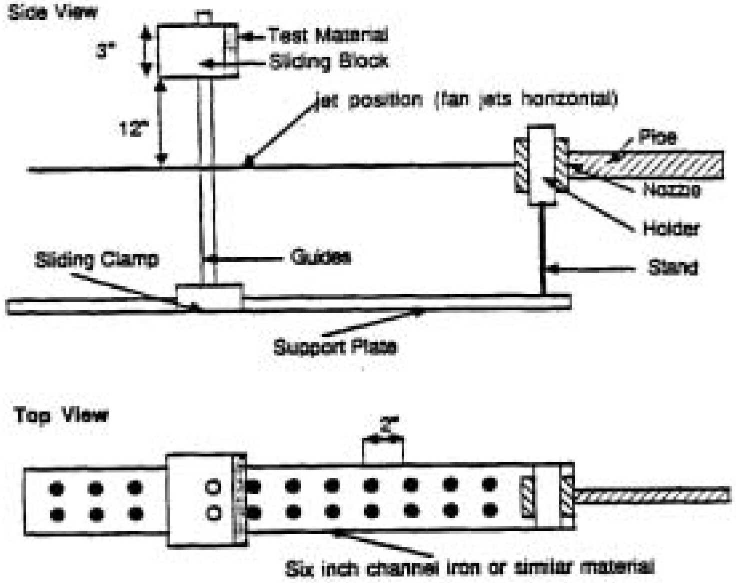
Dick Passman; J.D. Frye; Chuck Mondy and his son; Sid Taylor; Milt Anderson; George Rankin and Dave Summers attended a meeting held in the Houston Hilton in Texas on January 30, 1986.

Following general discussion on the role of the WJTA in standard development, as opposed to the effort being put forward by a subcommittee of ASTM Committee E-34, it was agreed to form a subcommittee of the WJTA Standards Committee. The initial members of this committee were Sid Taylor (Chair) of Weatherford; Milt Anderson of Butterworth; George Ranken of Aquadyne; and J.D. Frye of HydreServices. The initial charge to the committee was to collect together and coordinate a set of existing standards which cover the equipment which is used by the waterjet community. Following construction of that database it is intended to define additional working safety standards for equipment use in high pressure applications. (These would be of th type such as "To what pressure can one use ¼" NPT thread in fittings?")

Consequent to this agreement, the meeting discussed common insurance problems and other problems of a political nature before agreeing to examine a newly propose method for evaluating the effectiveness of cutting nozzles. (See Diagram)

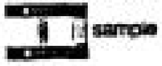
Anyone interested in joining that subcommittee, or having input to it, is asked to contact Mr. Sid Taylor of Weatherford at (713) 439-9400.

Standard Method of Test Equipment for Nozzle Evaluation



For Testing Fan jets the test material would be polystyrene sheet
For testing conventional round/pin/zero degree jets the material would be sandstone
For testing abrasive jets the material would be aluminum.

To run a test the block is raised, the jet switched on and the block dropped so that the test material passes through the jet, at the same speed each time. The test sample will then have a slot in it approximating the structure of the jet.



Possible Sliding Block Shape

David A. Summers
University of Missouri-Rolla
January 30, 1986

ANNOUNCEMENT'S

WATER JET TECHNOLOGY ASSOCIATION ANNUAL MEETING.

WHEN: July 16, 1986
WHERE: Henry Vlll Hotel and Conference
Centre
4690 N. Lindbergh
Bridgeton, Missouri
(St Louis County)
63044
TIME: 9:00 to 5:00 P.M. (Wednesday)

***BOARD OF DIRECTORS MEETING.**

WHEN: Will be held on Tuesday evening the 15th. of July, 1986.

For Reservations at the Hotel, please call.... (314) 731-3040

For more information on the meeting you can call Dave Summers at (314) 341-4311 or Evette Steele at (513) 932-4560.

PLEASE "R.S.V.P. PLEASE
(513) 932-4560

UPCOMING EVENT'S:

***27th. U.S. Symposium on Rock Mechanics.**

WHEN: June 23-25, 1986
WHERE: University of Alabama
P.O. Box 2967
University, Alabama 35486

For more information phone (205) 348-3025

***8th, International Symposium on Jet Cutting Technology.**

WHEN: September 9-11, 1986
WHERE: Durham, England

For more information please contact:
Jane Stanbury
Conference Organizer
8th Jet Cutting Symposium
BHRA, The Fluid Engineering Centre
Cranfield, Bedford MK43 OAJ,
England

International Water Jet Symposium.

***International Water Jet Symposium.**

WHEN: September 9-11, 1987
WHERE: Bijing China

For more information please contact:

Dr. Fun-Den Wang
Water Jet Technology Assn.
390 Union Boulevard
Suite 540
Lakewood Colorado 80228
U.S.A.
Phone: (303) 980-1353

HIGH PRESSURE WATER BLASTING: OVERCOMING THREE COMMON DEFICIENCIES

By W. Glen Howells, Ph.D.
Berkeley Chemical Research
Berkeley, CA

There are at least three deficiencies in high pressure water blasting. They are:

1. The inability to obtain nozzle pressure more closely matching pump pressure.
2. The lack of focussing of the water jet emerging from nozzles and
3. The limitation of pressure available from a specific pump which in turn limits performance.

All of these problems are related to the chemical structure of water and each one can be ameliorated by modifying the basic physical chemistry of water. Except in ice (or as is more commonly recognized in snowflakes) water does not have sufficient structure for the maximum effectiveness one would wish for the ideal fluid that is to be used in high pressure blasting.

Water has the composition H_2O. It consists of a molecule in which one oxygen atom is individually attached to two hydrogen atoms. As in many materials, different electrical charges. In water the hydrogen atoms carry a partial negative charge. These positive and negative charges give rise to electrostatic interactions. As a consequence individual water molecules are attracted to one another. This attraction results in a limited structure and because of this, water is a liquid. Other approximately equivalent compounds, such as hydrogen sulfide (H_2S), are gases at normal temperatures and pressures since they do not possess even this limited structure.

However, by dissolving a particular chemical in water it is possible to take advantage of the electrical charges and impart more structure tot he water by modifying its physical chemistry.

This specific approach has been successfully employed in high pressure water blasting for the last eleven years. The "structure inducer" is called SUPER-WATER® concentrated industrial water blasting additive. This additive is soluble in water and is capable of attracting and binding water molecules in such a way that a more extensive and well defined structure is obtained. Each individual (or in chemical terms, "monomeric") unit of SUPER-WATER® is capable of attaching to itself 13 to 14 water molecules. If the backbone of each SUPER-WATER® is regarded as linear, This results in sets of intertwined longitudinal structures with cylindrically oriented water sheaths.

SUPER-WATER® has a high molecular weight so each of its molecules gives rise to a very extended structure within the water. Such extended structures stabilize laminar flow and decrease turbulence or the formation of vortices in boundary layers. This brings about socalled drag reduction and effectively takes care of the first deficiency mentioned in the opening paragraph. Now pressure obtained at the nozzle more nearly approaches pump pressure because friction losses are reduced by approximately 50%.

The second deficiency is that water diverges when emerging from even the best designed nozzle. This too, obviously is a direct consequence of the general lack of structure of water. The molecules have an inherent desire to "part company" in rapidly flowing jets. However, with the SUPER-WATER®-induced structure present in the water the integrity of the jet is maintained. When SUPER-WATER® solutions emerge from either cylindrical or fan jets, a remarkable difference in appearance is immediately observable. In cylindrical jets, where usually a cone of water is produced, SUPER-WATER® gives a cylindrical jet. With such a cylindrical jet, energy is not dissipated prior to reaching the target and also the effective stand-off distance is greatly increased. Additionally, water vapor pockets that lead to random damage by cavitation are not so readily formed.

Thirdly, when a jet of SUPER-WATER® impacts a target (at speeds which are usually supersonic) the extended structures act as though they were solid particles. This is because they have insufficient opportunity to relax: they behave as though they were molecular chains bombarding the surface. This "solid behavior" greatly enhanses the effectiveness of the water jet and has been judged by many users to be equivalent to several thousand more pounds of pressure.

These are the three steps used to explain the markedly increased efficiency of SUPER-WATER® solutions over plain water. Users claim that increases in effectiveness of 2-50 times are obtained depending upon the task.

Finally, SUPER-WATER® solutions are slippery and many users are convinced that by imparting lubricity to the moving parts of pumps, the product extends pump life time and extends nozzle life.

**Above article has been reprinted from the Dec./Jan. issue of THE MAINTENANCE JOURNAL.

SHIP HULL CLEANING WITH SELF-RESONATING PULSED WATER JETS

by

Andrew F. Conn and Georges L. Chahine
Tracor Hydronautics, Inc.
Laurel, Maryland, U.S.A.

ABSTRACT

Cleaning trials on ship hulls in drydock have shown that white metal finishes can be achieved with pulsed, self-resonating water jets, using no grit or other additives. Under an ongoing program, these preliminary field trials were conducted in the shipyard at Tracor Marine, Fort Lauderdale, Florida. These tests have demonstrated potential of achieving the desired surface finishes at economically viable rates of cleaning. The success of these trials has motivated the continuation of this program to develop a prototype device for commercial use in shipyards.

INTRODUCTION

Grit blasting of steel ship hulls in drydock is an established and successful method. An operator can easily produce a wide range of results—varying from a gentle and rapid removal of marine growth and loose paint patches to an excellent "white metal" finish suitable for immediate application of a primer coating—by changing where he stands relative to the hull, and how he sweeps the air-borne particles across the surface. With such a procedure already in place in shipyards all over the world, why then did our company decide to embark on this examination of whether or not water jets—containing neither additives nor abrasive particles—could be a competitive replacement for the existing technology? The primary reason is pollution, the major drawback to grit blasting.

The most commonly used material for shipyard blasting of steel is known as "Black Beauty," a slag by-product from the smelting of copper. Although ideal for this use—in terms of the hardness and sharpness of the particles—the finer grit particles can be carried for large distances if even a gentle breeze is blowing. Nearby waterways are inevitably polluted by this grit; and cleaning costs in and around the drydock must be added to the significant contribution that the grit adds to the cost per unit area of cleaned hull. Accumulations of grit under floating drydocks may eventually lead to a major dredging effort. And the protective suits required for the grit blasting operator, to protect his eyes, skin, and lungs, can become infernos on even a moderately warm day.

A number of shipyards have begun to acquire some type of water blasting equipment because of the problems listed above. None of the existing water jet systems, however, are capable of economically creating the kinds of white metal finishes (SA-2.5 or SA-3; see the definitions of these surface finishes in Table 1) that many ship owners and the U.S. Navy require. Although the existing water jet systems can rapidly create an SA-1 surface, the white metal requirement cannot be effectively achieved with conventional water jet nozzles when operated within the pressure limitations of even non-standard, positive-displacement pump units, namely, up to 138 MPa (20,000 psi). Since the costs associated with hoses and other components rise rapidly with pressure; and there is a rapid decrease in the lifetime of all components as pressure increases, it is very desirable to keep the system pressure within the rating of what we would term a standard pumping unit, i.e., 68.9 MPa have been available (10,000 psi). Pumps and associated hardware which operate at or below 68.9 MPa have been available for many years from numerous suppliers and are now developed to a level of high reliability and safety. This is particularly important in what can only be described as the extremely rugged environment of most shipyards.

The conflicting objectives of minimizing system pressure and yet achieving a rapid and thorough removal of fouling, paint, and rest from a steel hull were partially resolved in an earlier study our company conducted for the U.S. Maritime Administration (1,2). Using the CAVIJET cavitating fluid jet technology, it was demonstrated that pressures of only 13.8 MPa (2000 psi) were sufficient to economically create an SA-1 surface. As discussed in References 2 and 3, a six-nozzle experimental system requiring only 66.3 kW (89 hp), cleaned at a rate of over 500 m^2/hr (5,400 ft^2/hr). At the time of this study (1975), the CAVIJET system power costs per unit area cleaned were only one-fifteenth of the grit costs for a comparable grit-blasted surface. Experiments, however for achieving a white metal surface showed that although CAVIJET nozzles operating below 68.9 MPa (10,000 psi) could indeed remove all of the required surface adherents, the cleaning rates per unit of power were far too low to be practical with that type of cavitating water jet.

A new invention--which, although using entirely different principles, also creates an effective "amplification" of the erosive capabilities of a water jet--has recently shown itself capable of providing white metal surfaces within the 68.9 MPa (10,000 psi) constraint and at rates that are potentially competitive with grit blasting. This invention, the "SERVO-JET tm" self-resonating pulsed water jet, and the results of some preliminary cleaning trials on ship hulls in drydock, are discussed in the following sections of this paper.

THE SERVOJET SELF-RESONATING PULSED WATER JET TECHNOLOGY

The advantages of pulsing to improve the erosive action of a jet--by either modulating or interrupting the flow, and hence using the waterhammer stress created by a series of individual slug impacts--have long been appreciated by the users of water jets for cutting and cleaning applications. Such interrupted or pulsed jets provide an enhanced erosivity, compared with steady-flowing jets, for either cleaning a substance from a substrate or cutting into a bulk material, because of several interacting physical phenomena. These include: a larger initial impact stress, due to the waterhammer effect; larger outflow velocities, which aid the material removal processes; an increased area of impact, thus allowing delivery of the impact to a greater surface; and short duration, cyclic loadings which serve to more efficiently interact with naturally occurring material flaws and enhance debonding of surface adherents.

enhancement can readily be created, without the excessive internal component wear and pressure losses associated with mechanically pulsed water jets.

THE EQUIPMENT

Since the objective of these field trials was merely to determine the feasibility of obtaining white or near-white metal finishes on actual ship hulls, the equipment used was selected on the basis of availability and minimal cost. Although this decision resulted in some interesting challenges during the testing, it proved correct since we did achieve our goals for this part of the project. The natural site for these trials was at TMI (Tracor Marine, Inc.), Fort Lauderdale, Florida, since TMI and Tracor Hydronautics are both subsidiaries of Tracor, Inc. A TMI-owned WOMA pump, with 68.9 MPa (10,000 psi) capability at flow rates up to 100 l/m (26.5 gpm) was used, along with another portable diesel-powered unit, rented for the occasion. The rental pump was laso rated for up to 68.9 MPa with flow rates up to 114 l/m (30 gpm).

The multi-nozzle SERVOJET array is seen schematically in Figure 2. A total of 15 nozzles were available, eight in one manifold and seven in the other. High pressure, 12.7 mm (½ in.) ID hoses were run independently from the rental pump and the WOMA to the eight-nozzle and seven-nozzle manifolds, respectively. The support plate for the relative positionings of the two sets of nozzles, as seen in Figure 2b. The support plate was mounted to a 51 mm (2 in.) diameter steel pipe, which in turn was clamped (see Figure 3) to the basket of the machine chosen to provide motion for the SERVOJET nozzle array.

This machine, as seen in Figure 4, was a "High Reach," (Model 50F Aerial Work Platform manufactured by JLG Industries) which was available in the TMI shipyard, and hence selected for these feasibility trials. Although its capabilities were less than ideal, a testing technique (see below) eventually evolved which allowed us to achieve our objectives. Use of such

The original impetus for development of a self-resonating nozzle arose from the need to create improved submerged cavitating jets to augment the action of deep-hole drill bits (4). It was then realized that the same principles of self-resonance could be used to passively interrupt a water jet in air (5,6,7). This SERVOJET concept is now being developed for a variety of cleaning applications, ranging from removing soil from aircraft exteriors to stripping worn nonskid coatings from aircraft carrier decks. To date, enhanced erosivity has been obtained over a pressure range of from 4.1 to 68.9 MPa (600 to 10,000 psi), with systems of between 3.7 to 150 kW (5 to 200 hp).

A variety of self-resonating nozzle system designs have been developed (see Figure 1), for either enhancing the creation of cavitation in a submerged jet, or to interrupt a water jet in air. The "PULSER-FED" self-resonating jet (SERVOJET), shown in Figure 1c, was the design found to be most readily adaptable to creating an in-air pulsed jet, and it can be seen from the several configurations in Figure 1 that the PULSER-FED concept is a combination of the "PULSER" (Figure 1a) and "ORGAN PIPE" (Figure 1b) configurations. A tandem-orifice Helmholtz resonating chamber (diameter, dT, in Figure 1c) is tuned so as to excite a standing wave within the organpipe section (length, L, Figure 1c). Peak resonance in this system occurs when the frequencies of the Helmholtz chamber and the organpipe wave are matched to a preferred jet structuring frequency for the exit orifice (d_e in Figure 1c). By varying the several dimensions of this system and the operating pressure, first, second, or third mode resonances can be selected. See the references cited above for further details on the performance of these self-resonating systems.

It is emphasized that no moving parts are required to create the necessary pressure and velocity fluctuations in these nozzle systems. Therefore, the required high-frequency pulsations for optimum erosivity by the individual nozzles), and (c) achieving a sufficiently rapid (and constant) speed of translation to allow adequate evaluation of the effects of this parameter. Variations in the hull plates and the difficulty of steering the High Reach in a perfectly straight path parallel to the hull both contributed to the standoff control problem. However, as seen in Table 2, practice served to improve this control. During these preliminary tests a gap-free total path was achieved by multiple runs across a portion of the hull (see Figure 6).

The following method for analyzing the results was used in order to infer the rates of cleaning achieved in these tests:

(a) The individual-nozzle clean path widths, gaps between clean paths, and total path widths were all measured.
(b) A factor, p, was derived as the estimated fraction of the total path width, w, that was cleaned to each specified degree of surface finish (SA-1, SA-2, or SA-2.5).
(c) The rate of cleaning, A, for a given test run, was then calculated from:

$$A^{\cdot} = p\ w\ v \qquad [1]$$

where v is the speed of translation of the mozzles.

Two ship hulls were used for these trials. The first was the Exxtor I, a cargo ship with hull curvatures that made control of the test conditions particularly difficult. The second craft, the Revere Sun barge, was iseal for our purposes. Its straight flat hull surfaces provided large areas of fairly uniform fouling and paint conditions which facilitated the testing and interpretation of results. The Exxtor I hull had a vinyl coal tar primer, with a resin-based antifoulant coating. The Revere Sun barge had a mastic epoxy primer and a vinyl-based antifoulant paint.

Two types of exit orifice nozzle configurations (labeled d_e in Figure 1c) were used. For the majority of the a machine for serious commercial cleaning of ship hulls, however, is certainly not recommended.

TEST PROCEDURES AND CONDITIONS

A variety of approaches for moving the nozzle manifolds were tried with the High Reach machine before a method giving reasonably reproducible results was found. We tried swinging the boom in either horizontal or vertical planes; and various "booming-in" and out moves were discarded. The procedure which finally worked may be seen in Figure 5; But only the skill of the operator, Mr. Gary Cunningham, seen here braving the spray and keeping the High Reach moving at a reasonably straight and constant velocity, allowed the effort to succeed. As stated, we do not recommend this—a strictly experimental method—for a system designed to clean an entire ship the section of hull being cleaned, it was possible to complete runs of about 0.9 to 1.2 m (3 to 4 ft) in length at desired preselected speeds of translation—after a brief learning period by our operator.

Prior to a run, the desired operating pressure was set by adjusting the RPM on each diesel until the required pressure was indicated on the respective manifold gauge. A length to be cleaned was marked on the hull, and the time to traverse between the start and stop lines was timed by stopwatch. In addition to translation speed, the other variables were system pressure, standoff distance, and orifice nozzle type. When all 15 SERVOJET nozzles were used, the maximum flow capacities available allowed nozzle pressure drops of up to 48.3 MPa (7000 psi). By successive removal of nozzles (and plugging the openings in the manifolds), a range of pressures up to a maximum of 62.0 MPa (9000 psi) could be attained (with nine nozzles in operation).

The main difficulties with this experimental procedure were: (a) maintaining a desired standoff distance, and (b) adjusting the angle of tilt and relative positioning of the two manifolds so as to avoid "gaps" (uncleaned strips between the paths clean tests (Runs 1 through 21), a circular orifice of diameter 1.1 mm (0.042 in.) was used. This orifice configuration provided a relatively narrower but more intense path of cleaning intensity. The remainder of the tests (Runs 22 to 30) utilized a 15° fan type nozzle, with an equivalent circular orifice of 0.9 mm (0.036 in.). This configuration delivered a wider but less intense clianing path in comparison to the circular jet.

DISCUSSION OF RESULTS

The conditions and results for these preliminary hull cleaning trials are summarized in Tables 2 and 3. The cleaning rate effectiveness, e_a, is defined as:

$$e_a = A^{\cdot}/P \ .$$

The cleaning rates, $A^{\cdot}$, were calculated using equation [1[, and P, is the hydraulic power delivered by the full set of nozzles used for a given run (values are listed in Table 2). The cleaning rates, for a given surface finish and nozzle pressure drop, are seen to vary widely. These variations were due to changes in standoff distance and in the speed of translation. Over the limited range of speeds available (up to only about 6.5 cm/s (2.5 in./s) which was the limit of the operator's ability to control the High Reach machine), there was essentially no measurable effect from the translation speed parameter. Therefore, this parameter was not listed in Table 3.

Based on laboratory testing, the SA-1 surface cleaning rates seen in Table 3 are as much as an order of magnitude lower than what might have been achieved if we could have translated the nozzles in a more rapid and controlled manner. A desirable standoff distance for SA-1 cleaning was in the range of about 7 to 12 nozzle diameters or about 8 to 13 cm (3 to 5 in.) for the round 1.1 mm nozzles, and about 5 to 10 cm (2 to 4 in.) for the fan nozzles. In summary, these results indicated that pulsed fan jets at a pressure of 48.2 MPa (7,000 psi) are able to achieve an SA-1, " brush-off cleaning," at rates of well over 32 [illegible]/hr. (350 ft ^{2}/hr.), with a 150 kW (200 hp) pump power. The fan nozzles delivered an erosive intensity which was only marginally capable of producing an SA-2 finish on the Revere Sun barge hull.

A pressure of 62.9 MPa (9,000 psi) was required, with the more intensive round nozzles, to achieve an SA-2.5, "near-white blast." The difficulty of maintaining nozzle alighnment made it impossible to achieve a full (ungapped) SA-2.5 path, hence, as noted in Table 2, multiple passes were made in order to assess the feasibility of achieving this type of surface. For this reason, we could only infer the SA-2.5 cleaning rates to be at least 7 m^2/hr (75 ft ^{2}/hr), i.e., about one-half the SA-2 rates for the same pump power. Standoff distances for the SA-2.5 finish were comparable to those for the SA-2 surface.

RUST INHIBITING

A water-blasted bare steel surface will rapidly be covered by so-called "flash rust." Hull areas cleaned to an SA-2 or SA-2.5 finish during the SERVOJET trials at Tracor Marine showed this red layer of oxidation within a few hours of exposure to the humid Florida environment. Although it is common practice in Europe to paint over this tightly adhering oxide film (8), there is a resistance in the U.S., from shipyards, ship owners, and paint manufacturers, to placing the AC (anti-corrodant) coating over a flash-rusted hull. To examine this facet of possible reluctance to using water blasting for ship hull cleaning, a paintability study was conducted.

A total of twelve test panels were used in this study. Four were cleaned to an SA-2.5 finish by conventional grit blasting; the other eight by water jetting. Of the latter eight, four panels were allowed to thoroughly flash rust before being painted, while the last four were protected with a rust inhibitor having the following components:

Percentage by Weight	Component
0.33	Sodium nitrite ($NaNO_2$)
1.28	Diammonium phosphate $(NH_4)_2HPO_4$ (also known as: secondary ammonium phosphate (dibasic))
98.4	Water

This inhibitor has been recommended by the U.S. Navy (9) and the Steel Structures Painting Council (10), as being a safe and very inexpensive way to prevent flash rusting of bare steel surfaces. The cost for inhibitor chemicals to protect the complete hull of a typical ship serviced at Tracor Marine would only be about \$2.61. Depending on the thoroughness of the application and the environmental conditions, this inhibitor can prevent flash rusting for as long as seven days (10).

All of the test panels were then protected with AC, top coat, and AF (antifouling) coatings at Tracor Marine, using the save procedures and materials as employed on ship hulls. The panels were then subjected to three months of dynamic seawater immersion testing on the Dynamic Drum Apparatus at the Miami Marine Research and Test Station, Miami Beach, Florida. Virtually no difference was seen in the adhesion of the AC layer to the steel surfaces prepared by the three methods. Our consultants (Mr. Carlos Perez, President, MMR&TS; and Mr. Leon S. Birnbaum, formerly head of the Coatings Branch, Naval Sea Systems Command, U.S. Navy) advised that only one to two months of such testing is sufficient to cause adherence failures (blistering, debonding) if an improperly prepared surface is present. This result of no adherence failures merely served to reconfirm the British and European experiences with what has become routine practice in the water jet preparation of ship hulls in drydock.

COMPARISON WITH GRIT BLASTING

The results from the preliminary SERVOJET hull cleaning trials were compared, on a cost per unit area basis, with typical shipyard costs (1983-84 \$) for each specified type of surface cleaning by their existing grit blasting method. The assumptions and conclusions from this preliminary cost analysis are summarized in Table 4. It is seen, for each category of surface, that the SERVOJET costs per unit area are competitive with typical grit-blasting costs. And, it should be emphasized that these prices do not include the periodic cleanup efforts necessitated by accumulations of the grit both in and adjacent to the drydocks and synchrolift at this shipyard. These encouraging cost comparisons, based as they were on the admittedly less than ideal test configuration of the preliminary field trials, and the potential for greatly reducing the pollution problems, have motivated our company to decide to continue with the development of SERVOJET-based equipment for cleaning ship hulls in drydock.

CONCLUDING REMARKS

Preliminary drydock hull cleaning trials, using a multi-nozzle SERVOJET self-resonating water jet device, have demonstrated the feasibility of this method as a replacement for existing grit blasting procedures. Although the equipment used for these field trials was rather makeshift, the results showed that costs per unit area of cleaned hull, with an operational system, should be competitive with present grit-blasting costs, and the pollution problems associated with existing blasting methods. Acceptable hull surface finishes, up to SA-2.5, "near-white blast," were achieved by the erosive action of impulsive water jets without any additives in the water.

This in-house project is continuing, based on the results reported here, with an on-going effort to design and build equipment which can rapidly and accurately deploy a multi-nozzle SERVOJET cleaning head. This cleaning head will be mounted in a framework which contains hydraulically actuated devices to provide variable and efficient translation speeds for the pulsed nozzle array for each required degree of surface cleaning. The framework will be affixed to a self-propelled, wheeled vehicle, such as one of TMI's scissor lifts, for the next round of field trials. Anticipating successful completion of these evaluations, design and construction of production equipment will follow.

ACKNOWLEDGEMENTS

The authors wish to thank Tracor, Inc., and particularly Dr. William C. Moyer and Mr. Marcel E. Gres for their support and encouragement for this project. The help and creativity provided by Tracor Marine, Inc. was outstanding and unstinting; we particularly acknowledge the efforts of Mr. Douglas A. Briggs, Mr. Gary E. Cunningham, Mr. Eric Benare, Ms. Jennifer Ripple, and particularly Mr. Joseph D. Deal, Jr., President of TMI, for so graciously allowing us to disrupt the normal work routines in the shipyard. At Tracor Hydronautics, we thank Mr. William T. Lindenmuth (now with the U.S. Navy's DTNSRDC), Mr. Gary S. Frederick, Mr. George E. Matusky, Mr. Ronald E. Watson, and most essentially, Mr. Virgil E. Johnson, Jr., our continued source of new inventions and inspirations.

REFERENCES

1. Conn, A.F., and Rudy, S.L., "A Cavitating Water Jet for Fouling Removal," Proceedings, Fourth International Congress on Marine Corrosion and Fouling, Juan-les-Pins, France,pp 97-103, June 1976 (also see Hydronautics Incorporated Technical Report 7510-1, July 1975).

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Table 1
Surface Cleaning Definitions

Type	Definition
Brush-Off Blast Cleaning SA-1 (also: SSPC-7, or NACE-4)	Brush-off blast cleaning is a method of preparing metal surfaces for painting or coating by rapidly removing loose mil scale, loose rust, and loose paint. A brush-off blast cleaned surface is defined as one from which all oil, grease, dirt, rust-scale, loose mil scale, loose rust, and loose paint or coatings are removed completely, but tight mil scale and tightly adhered rust, paint, and coatings are permitted to remain provided that all mil scale and rust have been exposed to the abrasive blast pattern sufficiently to expose numerous flecks of the underlying metal fairly uniformly distributed over the entire surface.
Commercial Blast Cleaning SA-2 (also: SSPC-6, or NACE-3)	Commercial blast cleaned surface finish is defined as one from which all oil, grease, dirt, rust-scale, and foreign matter have been completely removed from the surface, and streaks or discolorations, caused by rust stain, mil scale oxides or slight, tight residues or paint may be found in the bottom of pits; at least two-thirds of each square inch of surface area shall be free of all visible residues, and the remainder shall be limited to the light discoloration, slight staining, or light residues mentioned above.
Near-White Blast Cleaning SA-2.5 (also: SSPC-10, or NACE-2)	A near-white blast cleaned surface finish is defined as one from which all oil, grease, dirt, mil scale, rust, corrosion are completely removed from the surface except for very light shadows, very slight streaks, or slight discolorations caused by rust stain, mil scale oxides, or slight, tight residues of paint or coating that may remain. At least 94 percent of each square inch of surface area shall be free of all visible residues, and the remainder shall be limited to the light discoloration mentioned above.
White Metal Blast SA-3 (also: SSPC-5 or NACE-1)	A white metal blast cleaned surface finish is defined as a surface with a gray-white, uniform metallic color, slightly roughened to form a suitable anchor pattern for coatings. The surface, when viewed without magnifications, shall be free of all oil, grease, dirt, visible mil scale, rust, corrosion products, oxides, paint, or any other foreign matter. The color of the clean surface may be affected by the particular abrasive medium used.

Table 2
Summary of Test Conditions -- SERVOJET Hull Cleaning Trials

Run No.	Ship	Exit Nozzle Type	Nozzle Pressure Drop, MPa (ksi)	Translation Speed, v		Standoff Distance, X		No. of Nozzles	Total Flow Rate, Q ℓ/m (gpm)	Total Hydraulic Power, P kW (hhp)
				cm/s	in./s	cm	in.			
1	EXXTOR I	Circular Orifice, diameter = 1.1 mm (0.042 in.)	48.2 (7.0)	1.7	0.67	>10	> 4.0	15	193 (51.0)	155 (208)
2				3.5	1.39	9-11	3.6-4.4			
3				4.0	1.57	8-15	3.0-6.0			
4				6.5	2.54	8-15	3.0-6.0			
5				3.6	1.40	8-20	3.0-8.0			
6				1.3	0.52	12-21	4.7-8.2			
7			45.5 (6.6)	2.8	1.11	10-20	4.0-8.0		187 (49.5)	142 (191)
8	REVERE SUN BARGE		48.2 (7.0)	3.4	1.33	10-13	4.0-5.0	13	167 (44.2)	134 (180)
9				2.4	0.96	10-13	4.0-5.0			
10				3.9	1.52	8-13	3.2-5.2			
11				4.6	1.83	5-16	2.1-6.4			
12			55.1 (8.0)	4.0	1.57	8-9	3.1-3.6	11	152 (40.2)	139 (187)
13				3.9	1.52	8-11	3.1-4.2			
14				4.9	1.91	>25	> 10.0			
15				3.2	1.26	8-11	3.1-4.2			
16				3.3	1.28	9-10	3.5-4.0			
17				2.3	0.92	9-10	3.5-4.0			
18				3.5	1.39	9-10	3.5-4.0			
19			62.0 (9.0)	3.1	1.24	8-9	3.0-3.4	9	133 (35.1)	137 (184)
20				3.0	1.18	8-9	3.0-3.4			
21				4.3	1.70	8-9	3.0-3.4			
22		15° Fan equivalent dia. 0.9mm(0.036in.)	48.2 (7.0)	4.3	1.71	6-9	2.5-3.6	15	153 (40.5)	123 (165)
23				0.9	0.34	5-6	2.0-2.5			
24				3.4	1.33	6-7	2.2-2.7			
25				2.5	0.97	4-5	1.5-1.9			
26				0.8	0.32	3.5-4	1.4-1.5			
27				1.5	0.61	4-6	1.5-2.4			
28			62.0 (9.0)	4.3	1.71	6-7	2.2-2.6	9	102 (27.0)	106 (142)
29				3.8	1.50	6-7	2.2-2.6			
30				2.0	0.78	6-7	2.2-2.6			

Note: The following sets of runs were repeated over areas of the hull (two or three runs per a given area): (10, 11), (12, 14, 15), (16, 17, 18), (19, 20, 21), (28, 29, 30).

Table 3
Summary of Test Results -- SERVOJET Hull Cleaning Trials

Exit Nozzle Type	Surface Finish	Nozzle Pressure Drop MPa(ksi)	Cleaning Rates, Ā				Cleaning Rate Effectiveness, e_a			
			Range of Results		Typical Values[a]		Range of Results		Typical Values[a]	
			m^2/hr	ft^2/hr	m^2/hr	ft^2/hr	$m^2/kW\text{-}hr$	$ft^2/hp\text{-}hr$	$m^2/kW\text{-}hr$	$ft^2/hp\text{-}hr$
Circular orifice, diameter 1.1 mm (0.042in)	SA-1	48.2(7.0)	9.7-54	104-584	16.7-29.7	180-320	0.06-0.35	0.5-2.8	0.12-0.19	1.0-1.5
		55.1(8.0)	20.4-22.6	220-243	20.8-21.9	224-236	0.15-0.16	1.2-1.3	0.15-0.16	1.2-1.3
		62.0(9.0)	14.8[b]	159[b]	14.8	159	0.11	0.86	0.11	0.86
	SA-2	48.2(7.0)	4.0-33.9	43-365	8.5-18.6	92-200	0.02-0.22	0.2-1.8	0.06-0.12	0.5-1.0
		55.1(8.0)	5.5-17.7	59-191	6.6-13.3	71-143	0.03-0.12	0.3-1.0	0.05-0.10	0.4-0.8
		62.0(9.0)	5.3[b,c]	57[b,c]	5.3	57	0.04	0.3	0.04	0.3
15° Fan, equivalent dia 0.9mm (0.036in.)	SA-1	48.2(7.0)	5.3-32.8	57-353	10.3-21.5	111-231	0.04-0.26	0.3-2.1	0.09-0.17	0.7-1.4
		62.0(9.0)	21.5[b]	231[b]	21.5	231	0.20	1.6	0.20	1.6
	SA-2	48.2(7.0)	2.1-10.0	23-108	4.2-7.5	45-81	0.01-0.09	0.1-0.7	0.04-0.06	0.3-0.5
		62.0(9.0)	1.0[b,c]	11[b,c]	1.0	11	0.01	0.1	0.01	0.1

[a] Typical values are defined as within one standard deviation around mean value of full range of results (± 0.5σ).

[b] These single values are because, although multiple runs were made at each pressure, in several cases (as noted in Table 2), repeated runs were made over the same hull area.

[c] Cleaning rates based on time required to make three passes over same hull area.

Table 4
Cost Analysis of SERVOJET Hull Cleaning System

Assumptions (All costs are 1983-84 dollars)

1. Yearly Hull Cleaning: 88,250 m^2 (950,000 ft^2)
2. Equipment Cost Range: $150,000 to $300,000 (including maintenance)
3. Depreciation: Five years, linear
4. Labor: Two men at $23.75 per hour; total: $47.50 per hour
5. Power: $0.07 per kW-hr; 150 kW (200 hp) system: therefore: $10.50 per hour
6. Water: $0.50 per 3785 ℓ (1000g); 114 ℓ/m (30 gpm) flow rate: therefore: $0.90 per hour
7. Cleaning Rates: SA-1: 32 m^2/hr (350 ft^2/hr)
   SA-2: 14 m^2/hr (150 ft^2/hr)
   SA-2.5: 7 m^2/hr (75 ft^2/hr)

COST FACTORS: $/$m^2$ ($/$ft^2$)

Surface Finish	SA-1	SA-2	SA-2.5
Equipment	0.34-0.68 (0.032-0.064)	0.34-0.68 (0.032-0.064)	0.34-0.68 (0.032-0.064)
Labor	1.46 (0.136)	3.41 (0.317)	6.81 (0.633)
Power	0.32 (0.030)	0.75 (0.070)	1.51 (0.140)
Water	0.03 (0.003)	0.06 (0.006)	0.13 (0.012)
Total Cost Range for SERVOJET System	2.15-2.58 (0.20-0.24)	4.63-4.95 (0.43-0.46)	8.82-9.15 (0.82-0.85)
Typical Grit Blasing Costs	3.12 (0.29)	5.06 (0.47)	7.31 (0.68)