

**ABRASIVE SLURRY-INJECTION JET (AS-IJ)
FOR CNC CUTTING SYSTEM**

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ABSTRACT

Since the introduction of abrasive water jet cutting over 30 years ago, two types of abrasive water jets have been commercially developed. An abrasive injection jet (known as an AIJ) and an abrasive suspension jet (known as an ASJ). The comparative studies done on the two jet generating systems have been in general agreement that the ASJ generates a more powerful, efficient and stable jet than the AIJ. However, despite its potential, there are no known ASJ CNC abrasive water cutting or machining units in commercial operation today (out of the estimated 20,000 AWJ units in operation). The main reasons for industry development with AIJ systems are their simplicity in operation, maintenance and controls. The major obstacles to using ASJ systems in CNC cutting operations were the requirement for instantaneous starting and stopping of cutting as well as improving operating reliability and limiting complexity. Jet-Net International Pty Ltd has developed a new CNC abrasive cutting system which is a hybrid of both the AIJ and ASJ systems. The AS-IJ combines the ultra-high pressure of the AIJ with the efficiency and power of the ASJ while being adaptable to a CNC cutting system. For the same hydraulic power, the AS-IJ at 40,000 psi will cut at least four times as fast as a 60,000 psi AIJ system and at least twice as fast a 90,000 psi AIJ system. It is envisaged that the introduction of the AS-IJ will enable abrasive water jet cutting to compete with plasma and laser cutters on the market today. This paper will present the technical innovations which enable conversion from existing AIJ CNC systems to an AS-IJ cutting system.

NOMENCLATURE

Symbol	Variable	Units
C_d	Coefficient of Discharge	-
K_a	Air acceleration	-
K_{pc}	Particle communiton	-
K_{pp}	Particle-particle interaction	-
K_{pw}	Particle-wall interaction	-
K_t	Turbulence energy	-
m_a	Mass of abrasive	kg
m_w	Mass of water	kg
\dot{m}_a	Mass flow rate of abrasive	kg/s
\dot{m}_w	Mass flow rate of water	kg/s
N_j	Jet power	W
η	Energy transfer coefficient	-
p	Pressure	Pa
ρ	Density	kg/m ³
ρ_s	Density of Slurry	kg/m ³
ρ_w	Density of Water	kg/m ³
R	Slurry concentration factor (by weight)	-
V_w	Volume of water	m ³
V_a	Volume of abrasive	m ³
v	Water jet velocity	m/s
v_a	Velocity of abrasive particles	m/s
v_s	Velocity of slurry stream	m/s
v_w	Velocity of water jet	m/s

1.0 INTRODUCTION

CNC abrasive water-jet cutting has been commercially available for over 30 years. Over this period improvements have been made in reliability and basic hardware (intensifiers, orifice's, focusing tubes, cutting heads etc.). Recently 90,000Psi units have been released into the market by some of the larger equipment manufacturers. The improvements which have been made in AIJ systems can be considered marginal in comparison with improvements made in the competing plasma and laser cutting technologies over the same period. The fact remains that today's AIJ systems are almost identical to the ones 3 decades ago. A large scale improvement in efficiency is required before abrasive water jet cutting may be able to compete with the alternative CNC cutting methods. To date two basic commercial methods of abrasive water cutting have been developed:

- 1) Abrasive Injection Jet (AIJ) Systems
- 2) Abrasive Suspension Jet (ASJ) Systems

1.1 Abrasive Injection Jet Systems Background

Ultra high pressure water 20,000Psi to 90,000Psi (usually generated by an intensifier-style pump), is pumped through a small orifice (typically between 0.0080" to 0.0160" diameter). A high velocity water jet passes through a mixing chamber creating a vacuum. Abrasive particles are introduced into the chamber and the water jet accelerates the abrasive through a Focusing Tube. An inefficient exchange of energies takes place in the Focusing Tube (the diameter of which is usually 3 times the orifice diameter). Only about one fifth of the potentially available cutting energy is transferred to the abrasive particles [9]. Most of the energy is dissipated in a dramatic reduction of abrasive particle size, destruction of the Focusing Tube, compressing air introduced with the abrasives, and as heat. Although AIJ systems have shown great promise in metal removal and machining applications, so far, they have not made any significant impact in those industries due to their extremely low cutting efficiency. Despite its inefficiency, almost 100% of all CNC Abrasive Water-Jet Cutting is done using AIJ systems. The reason is that the AIJ systems are simple, safe and reliable to operate.

1.2 Abrasive Suspension Jet Systems Background

ASJ systems are generally operated at pressures of between 10,000Psi to 30,000Psi, and are typically generated by multi-plunger positive displacement pumps (i.e. triplex pumps). Abrasive is introduced into a pressurized water stream and the mixture is pushed through an orifice typically between 0.030" to 0.080" in diameter. These systems typically operate at lower pressures and higher water and abrasive

flow rates than the AIJ systems, thus becoming expensive and problematic for an industrial cutting operation. Despite the fact that ASJ systems (in various forms) have been around for over 25 years and are a lot more efficient than AIJ systems, there are currently no ASJ CNC cutting systems commercially available today. The main reasons for the failure to adopt the ASJ system to industrial CNC profile cutting are:

- Lower pressure requires large water and abrasive flow rates to generate a sufficiently powerful jet for cutting of harder materials.
- Pressurized water-abrasive flows create both safety and reliability issues.
- Difficulty in maintaining a constant flow of abrasives.
- CNC profile cutting requires many starts and stops per minute. There is the issue of stopping the abrasive flow without depressurizing the whole system. Depressurizing and re-pressurizing makes it uneconomical and impractical for an industrial CNC cutting system.
- These systems can be unreliable, prone to blockages and generally require highly skilled operators.

Some ASJ systems are used in difficult, on-site cutting operations where the cutting is far removed from the pumps and abrasive supply. They are typically used where a high value contract justifies a highly skilled support team and where the cut is more or less continuous. Some such applications are decommissioning of live munitions, work on oil and gas installations, sub-sea cutting and cutting in other hazardous environments.

2.0 AIJ & ASJ SYSTEMS COMPARISON

2.1 Abrasive Loading

Various published test results have shown that an optimum abrasive concentration for maximum cutting velocity is in the range of 15 to 25% of abrasive by weight [2][6][8]. This is applicable to both AIJ and ASJ systems. Some studies indicate that the optimum abrasive concentration ratio is lower for increased operating pressures (velocities). *Figure 2.1 & Figure 2.2* show the effects of abrasive concentration on cutting depths in an AIJ system.

$$R = \frac{\dot{m}_a}{\dot{m}_w} \quad (1)$$

Or:

$$R = \frac{m_a}{m_a + m_w} \quad (2)$$

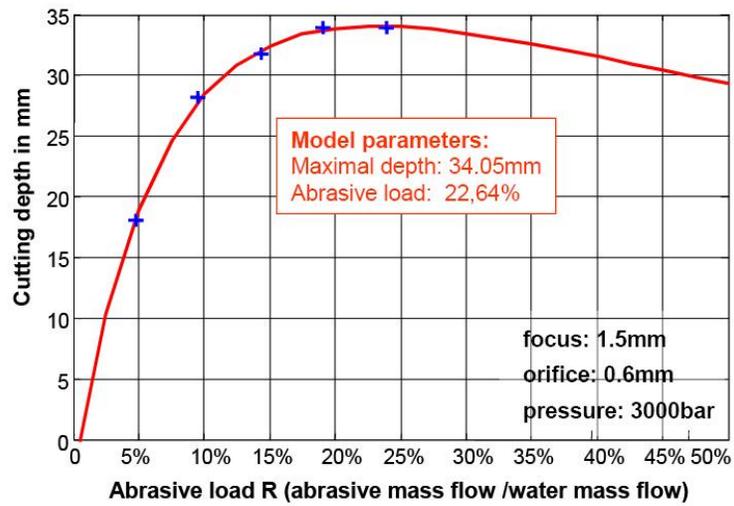


Figure 2.1 – Cutting Depth vs. Abrasive Loading Ratios [2]

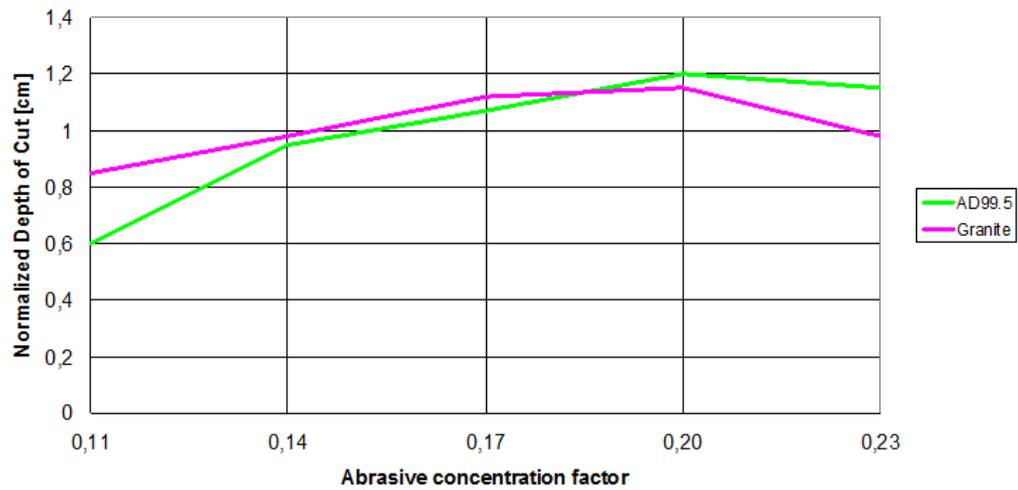


Figure 2.2 – Optimum Abrasive Concentration Factor [8]

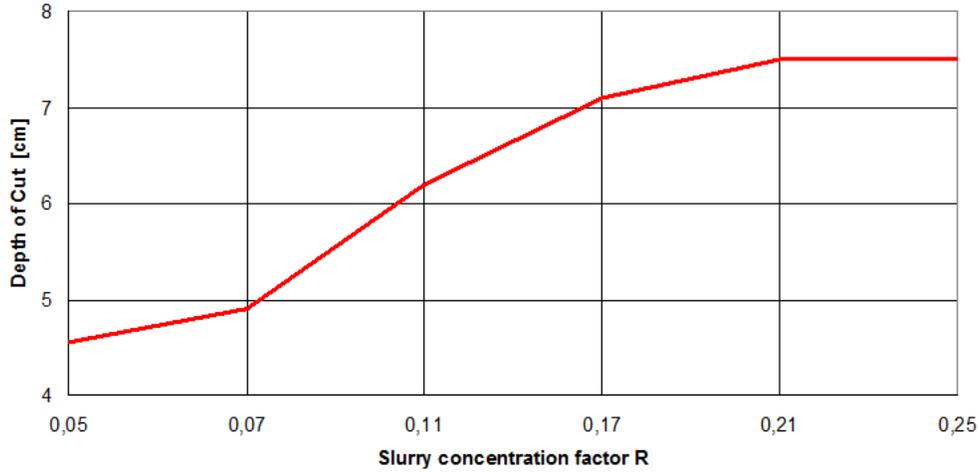


Figure 2.3 – Dependent Depth of Cut from Abrasive Concentration Factor [6]

As can be seen from the figures the jet cutting capacity is limited by the optimum abrasive concentration. A possible reason for an optimum limit to abrasive concentration may be due to energy loss through abrasive particle-particle interaction as well as a decrease in jet velocity.

2.2 Velocity Transfer Coefficient

The major difference between AIJ and ASJ systems is the velocity of the abrasive particles at any given pressure. Maximum jet velocity for a perfect liquid from Bernoulli:

$$v = \sqrt{\frac{2p}{\rho}} \quad (3)$$

For abrasive laden water jet streams (ASJ systems) the jet velocity at any given pressure can be estimated by the proportional difference in densities between pure water and the abrasive-water stream:

$$\eta = \frac{v_s}{v_w} = \sqrt{\frac{\rho_w}{\rho_s}} \quad (4)$$

For pure water: $\rho_w = 1,000 \text{ kg} / \text{m}^3$

$$\therefore \eta = \sqrt{\frac{1}{\rho_s}} \quad (5)$$

Where:

$$\rho_s = \frac{m_w + m_a}{v_w + v_a} \quad (6)$$

When abrasive loadings are low the approximation error will remain relatively low. Thus, for an abrasive loading of $R = 0.15$, $\eta = 0.95$. Hence, for a suspension jet (ASJ), at any given pressure with an abrasive concentration ratio of 15%, the ASJ jet velocity will be $0.95v_w$. Results published by Summers [5], show that the abrasive velocity is very close to the water velocity in the ASJ system.

In an AIJ system, energy is transferred from the water stream to the abrasive. This exchange of energies has been analysed theoretically and empirically. For traditional AIJ systems this energy exchange is described by the energy exchange coefficient. According to Momber [3] it is represented as follows:

$$\eta = K_{pp} + K_{pw} + K_{pc} + K_a + K_t \quad (7)$$

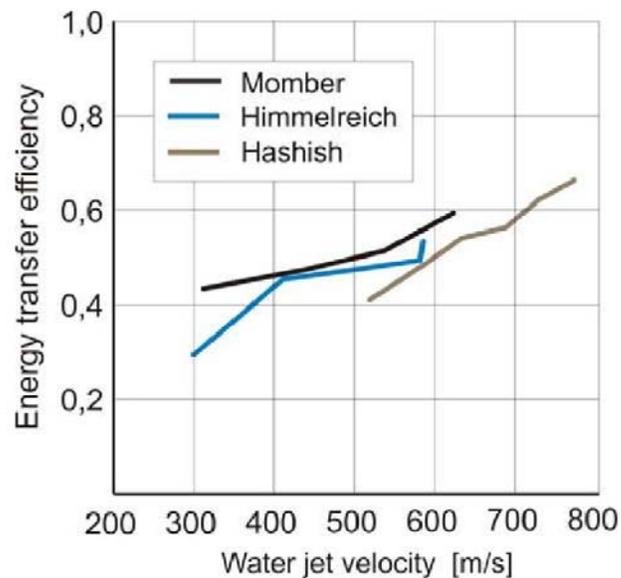


Figure 2.4 – Energy transfer coefficient [3]

It can be seen from **Figure 2.4** the average energy transfer coefficients for Hashish, Momber and Himmelreich are 0.55, 0.50 and 0.45 respectively. According to Heiniger [4] at an abrasive loading of 20% the energy transfer coefficient is 0.60 (**Figure 2.5**) and its value decreases with an increase in abrasive loading.

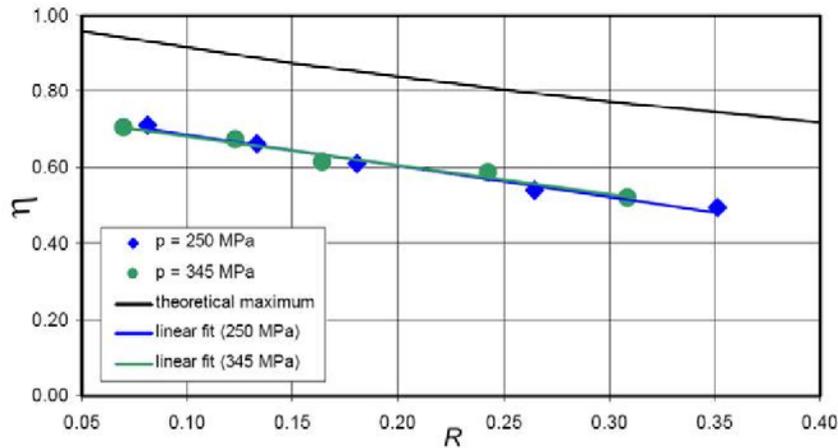


Figure 2.5 – Energy Transfer Coefficient for Varying Abrasive Concentration Factor [4]

So to determine the velocity of abrasives in both AIJ and ASJ systems the following formulas are applied:

$$v_a = \eta \times v_w \quad (8)$$

A graph showing the velocity of abrasives at various pressures after applying an average energy transfer coefficient (from the published data) is shown in **Figure 2.6**. For this graph, the abrasive loading ratio R, is given as 15% (R = 0.15).

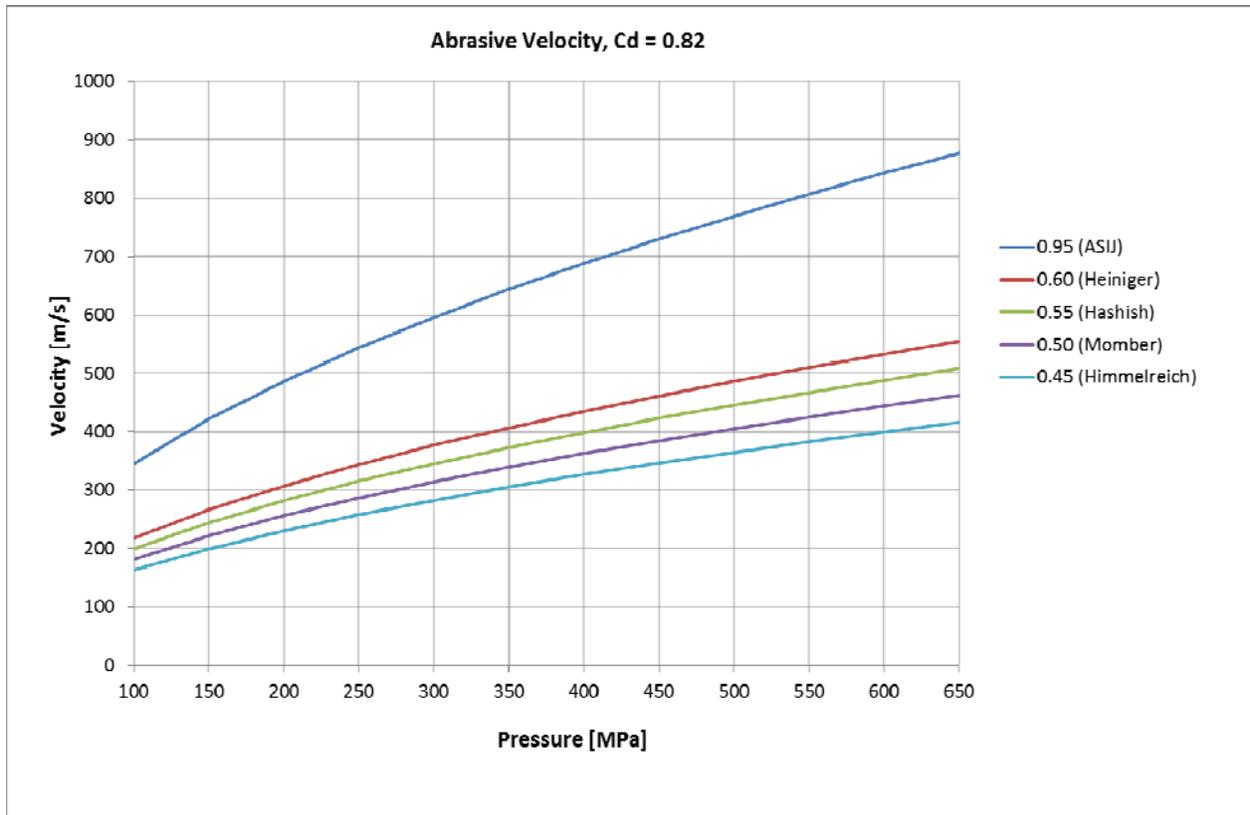


Figure 2.6 – Abrasive Velocity at various Pressures for an ASJ system (ASIJ) & various AIJ Energy Transfer Coefficients [4]

2.3 Abrasive Cutting Power

Cutting capacity of an abrasive jet is proportional to the jet power which is equal to the kinetic energy of the abrasive flow rate.

$$N_j = \frac{\dot{m}_a v_a^2}{2} \quad (9)$$

Assuming optimum abrasives loading for both an ASJ (ASIJ) system and an AIJ system are the same, a comparison of jet power at pressures from 100MPa (15,000Psi) to 650MPa (95,000Psi) is shown in **Figure 2.7**. The Energy Transfer Coefficients for the AIJ system were taken from previous research papers (**Figure 2.7** & **Figure 2.8**). The graphs show that at any given pressure and using the highest Energy Transfer Coefficient of 0.6 (Heiniger), the abrasive jet power of an ASJ (ASIJ) is about 4 times higher than of the AIJs.

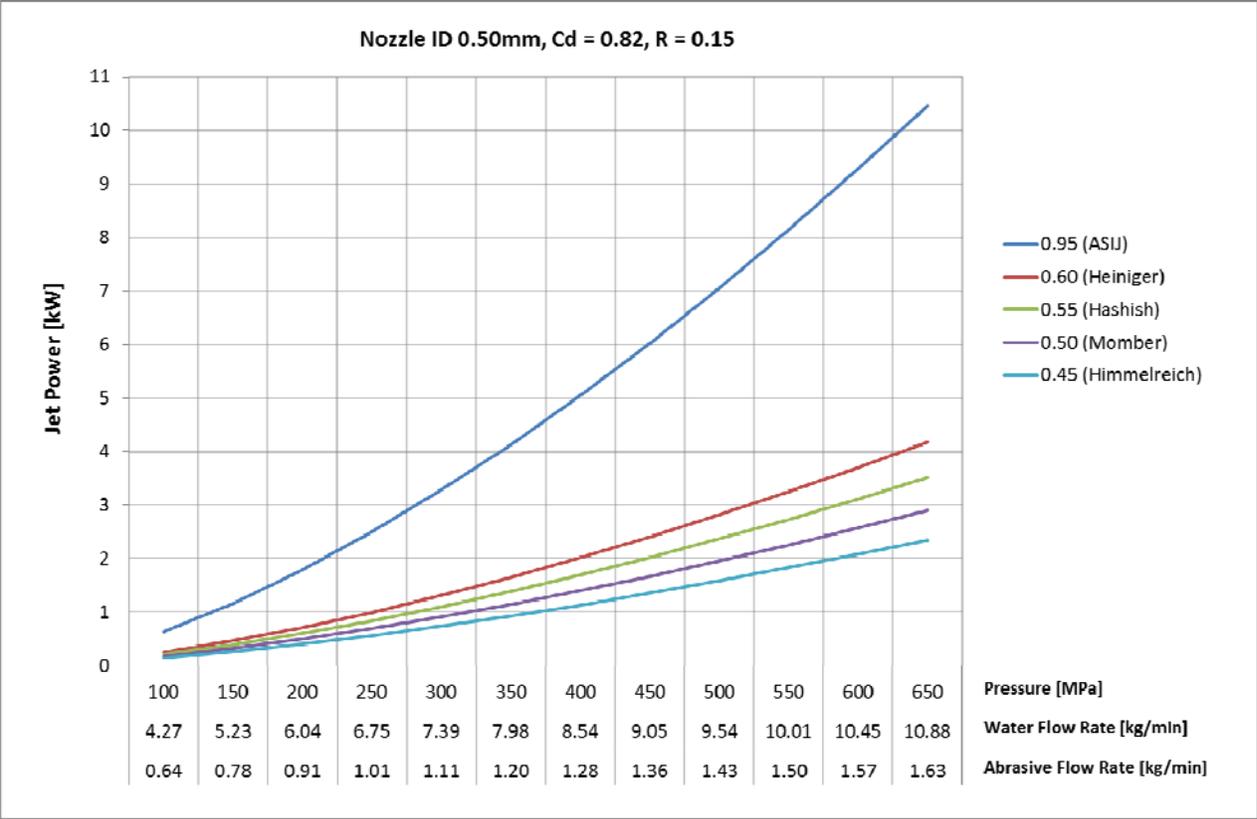


Figure 2.7 – Abrasive Velocity vs. Pressure for an ASJ (ASIJ) system (0.5mm Nozzle)

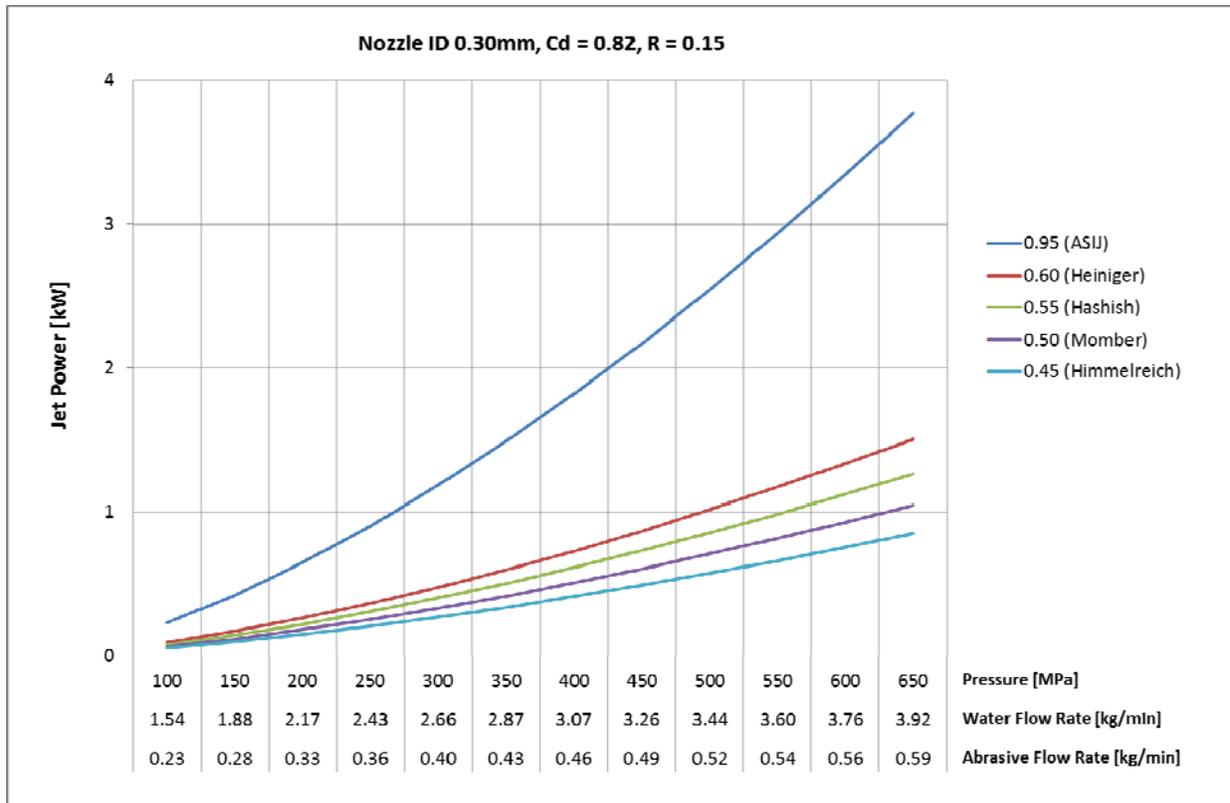


Figure 2.8 – Abrasive Velocity vs. Pressure for an ASJ (ASIJ) system (0.3mm Nozzle)

2.4 Cutting Power Relative to Kerf Width

For an AIJ system utilising a 0.3mm water orifice, the pure water jet stream overall kerf width will be approximately 1.20mm upon exiting the focusing tube. An ASJ system with a 0.3mm orifice will approximately result in a kerf width of 0.4mm. Due to the fact that the kerf width of AIJs is approximately 3 times larger than that of the ASJs (ASIJs), the jet power density (kW/mm^2) is correspondingly lower in AIJ systems. The significantly higher jet power density in conjunction with a higher energy transfer coefficient indicates that a suspension jet can theoretically cut significantly faster than conventional AIJ systems. Whether ASJ (ASIJ) cutting speeds of between 4 – 8 times faster than conventional AIJ systems can be achieved in practice remains to be seen. However, what is certain is that a large increase in cutting power can be achieved by changing from an injection to a suspension jet.

3.0 ABRASIVE SLURRY-INJECTION JET (AS-IJ)

The team at Jet-Net International set an objective to develop an abrasive suspension type cutting system capable of CNC operation. The new system has been termed an Abrasive Slurry-Injection Jet (AS-IJ)

3.1 Major Obstacles

The major obstacles facing development of the AS-IJ system were as follows:

- Starting and stopping an UHP abrasive flow without depressurizing the line
- Settlement of abrasive in pressurized slurry lines.

3.2 Objectives

The objectives in the development of the AS-IJ system were as follows:

- 1) Acceleration of abrasives by a pump:
 - The objective was to design and test a high pressure CNC Abrasive cutting system with abrasive accelerated by pump and not a venturi.
- 2) Abrasive to remain in suspension:
 - Suspending abrasive in a water stream requires constant flow conditions, lower velocities or stopping the flow results in settlement and line blockages. A CNC profile cutting requires constant changes to flow conditions (starting, stopping, pressure variations and orifice diameter changes) thus causing settlement. The objective was to create a slurry mixture capable of remaining in suspension during all facets of operation.
- 3) Instantaneous Start/Stop Operation:
 - Instantaneous starting and stopping of the cutting system is a prerequisite for any CNC profile cutting system. Inability to start and stop a pressurized abrasive flow (without first depressurizing the system) is probably the main reason why to date only AIJ systems are used in CNC abrasive cutting. The objective was to develop a system capable of starting and stopping at any time during its operation.
- 4) Jet Cohesion and Stability:
 - Accelerating abrasive particles through an orifice to a much higher velocity may affect jet stability and cohesion thus affecting cutting performance of the jet. The objective was to ensure that the AS-IJ cutting jet was both stable and cohesive.

5) Operational Reliability:

- The objective was to design the AS-IJ equipment and control system with a high degree of reliability required for an everyday CNC operation.

3.3 Conceptual Design

3.3.1 Hydraulic Lock

An essential requirement for Abrasive Jet cutting is instantaneous stopping and starting. This requires a shut-off valve to stop an abrasive stream at pressures above 7,500Psi and up to 90,000Psi. The solution was to divide the cutting liquid into two streams.

1. Stream 1 – A constant pressure stream, supplied by a constant pressure pump. This stream will automatically adjust its flow to maintain the set pressure irrespective of the other stream. Constant pressure is generated by an intensifier pump which is able to react rapidly to changes in system pressure requirements due to the hydraulic rotary swash plate pump driving the hydraulic side.
2. Stream 2 – A constant flow stream, supplied by a positive displacement pump. The flow in this stream can be varied without altering the set pressure for the system i.e. the multiplex positive displacement will continue to reciprocate at a constant rate through all ranges of pressure (the only outcome of which is loading & unloading of mechanical pump components).

Since the two streams are part of the same fluid system, the flow in Stream 2 can be reduced to zero without a pressure change in the stream. This occurs as a result of the intensifier pump in Stream 1 picking up the extra flow requirement to maintain set pressure. By maintaining a set pressure in a system while reducing the flow in one of the streams until a no-flow condition is reached (in Stream 2) has been termed the Hydraulic Lock. By creating a no-flow condition, the Hydraulic Lock enables valve operation in an abrasive environment. For the AS-IJ system, the constant flow in Stream 2 carries high density abrasive slurry and the constant pressure in Stream 1 carries water.

3.3.2 Abrasive Suspension

The abrasive slurry was required to stay in suspension for a considerable period of time irrespective of flow conditions and thus a suitable polymer and a mixing method were required. The abrasive stream can be regulated for abrasive loading and flow thus controlling the abrasive loading of the cutting jet.

3.3.3 Cutting Head

The two streams (Stream 1 & Stream 2) merge in the accelerating chamber of the Cutting Head thus facilitating a Hydraulic Lock as well as preventing abrasive settlement and blockages. The geometry of the accelerating chamber greatly influences jet cohesion and the effectiveness of the Hydraulic Lock.

3.4 System Design

The AS-IJ system works by pumping water at a constant pressure (Stream 1) and concentrated slurry in another stream (Stream 2). The two streams meet in the AS-IJ Cutting Head at the Interface Plane (Slurry Injection Cutting Head shown in **Figure 3.1**). In the AS-IJ system, the slurry is injected centrally and the water stream annularly into the accelerating chamber of the cutting head. This ensures minimal mixing of the two streams as well as providing maximum protection for the nozzle. Experimentation showed that heavier abrasive particles tended to gravitate towards the centre of the combined stream whereas the water formed a protective outer layer. The abrasive stream ensures a constant and stable abrasive supply and ease with which abrasive flow can be regulated. The independently controlled streams enable the frequent starting and stopping of cutting by stopping supply from the abrasive stream and allowing the constant pressure stream to automatically pick up the additional flow requirement to maintain the set pressure in the two streams. This in turn allows the valves on the slurry stream to be closed or opened at a no-flow condition (Hydraulic Lock). The fact that one stream is set to a constant pressure and the other to a constant flow results in a self-balancing fluid system i.e. when any fluid flow parameters change, the system will self-regulate.

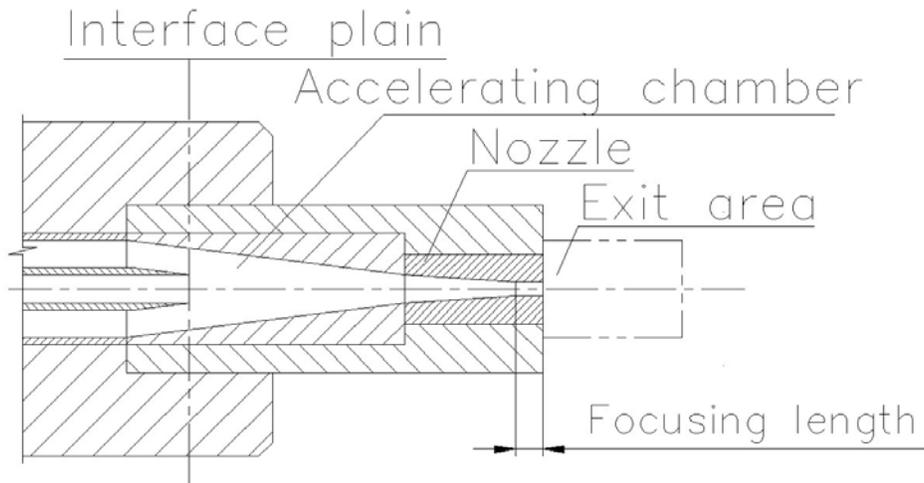


Figure 3.1 – Slurry Injection Cutting Head Cross-Section

ANSYS

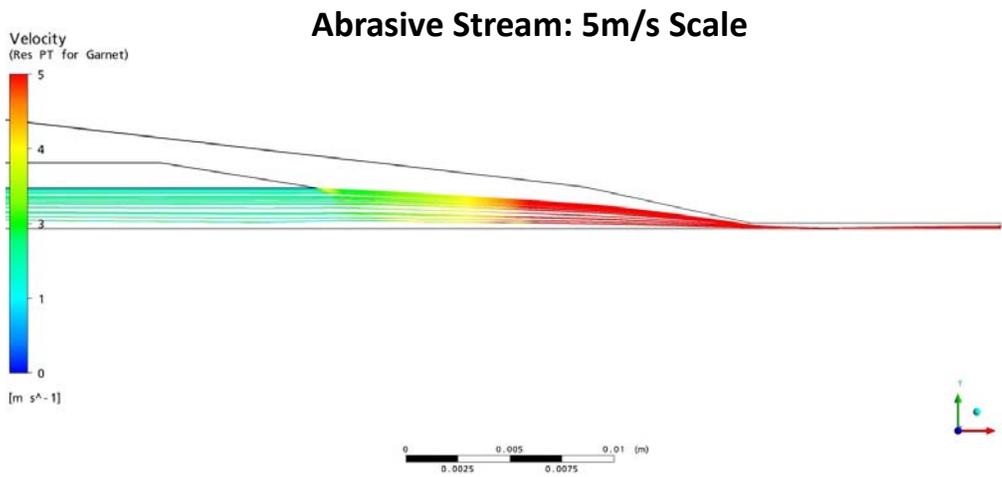


Figure 3.2 – CFD Analysis Results: Slurry Injection Cutting Head Abrasive Stream

Water Stream: 5m/s Scale

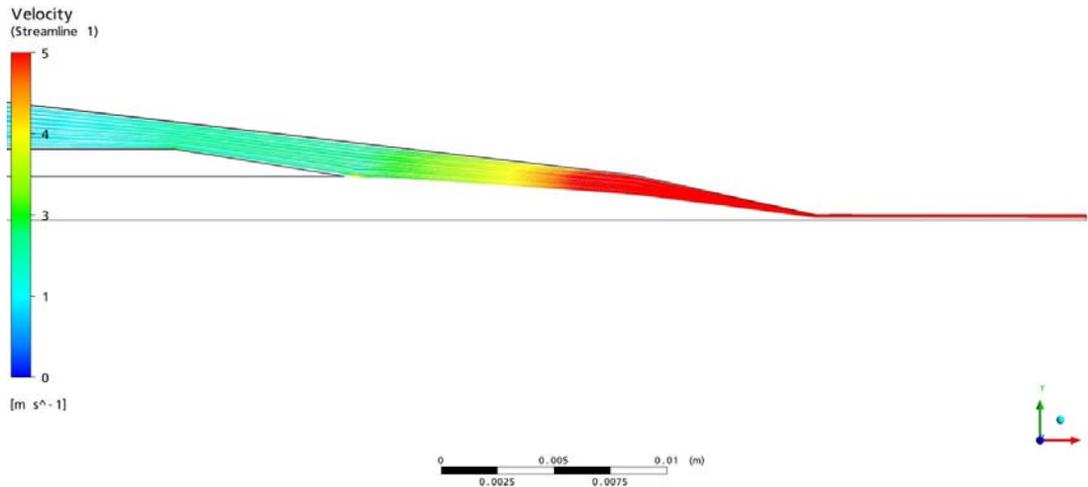


Figure 3.3 – CFD Analysis Results: Slurry Injection Cutting Head Water Stream

Close-up of Mixing: 5m/s Scale

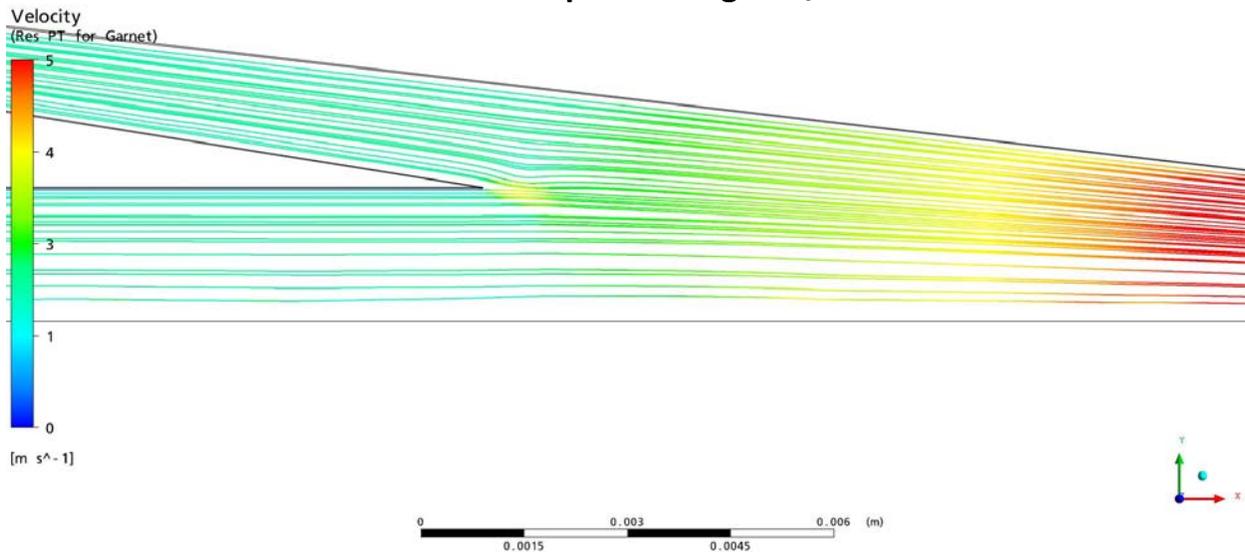


Figure 3.4 – CFD Analysis Results: Slurry Injection Cutting Head Mixing of Abrasive/Water Streams

The system is designed to create a Hydraulic Lock in the accelerating chamber of the cutting head in order to facilitate starting and stopping of the cutting operation without depressurizing the two stream supply. The most effective location for a Hydraulic Lock on a CNC abrasive cutting system is in the Cutting Head's Accelerating Chamber just prior to the orifice. This ensures instantaneous stop/start of

4.0 RESEARCH & DEVELOPMENT

4.1 Program

A R&D program was run by Jet-Net International to test the conceptual design of AS-IJ system. The program had following objectives:

- Test operation of Hydraulic Lock.
- Test overall system design for a continuous AS-IJ operation.
- Test the effect of cutting head design on jet cohesion.
- Test the effect of nozzle design on jet cohesion.
- Test rheology of slurry in various abrasive and polymer concentrations.
- Establish slurry behaviour in ultra-high pressure conditions.
- Set up a CFD analysis to compare the test results.

4.2 Testing

During the R&D test program, the Hydraulic Lock and continuous system operation were tested successfully.

A schematic of the AS-IJ test apparatus is shown in **Figure 3.5** and a photo of the original test equipment is shown in **Figure 4.1**. The various parts of the test equipment are numbered within the figure and are as follows:

- 1) Transfer vessel
- 2) Abrasive Slurry Supply Tank
- 3) Cutting Table
- 4) Main Hydraulic Pump
- 5) Hydraulic Pump
- 6) Monitoring, Controlling and Recording System



Figure 4.1 – Photo of AS-IJ Testing Apparatus

4.3 Cutting Head

A cutting head with a centrally oriented slurry supply orifice was designed and manufactured (**Figure 3.1**). Various nozzle focusing lengths were tested to establish the effect on jet cohesion. The tested lengths were 4, 8 and 12mm. **Figure 4.2** shows test results for cutting depth at 5 and 10mm standoff distances.

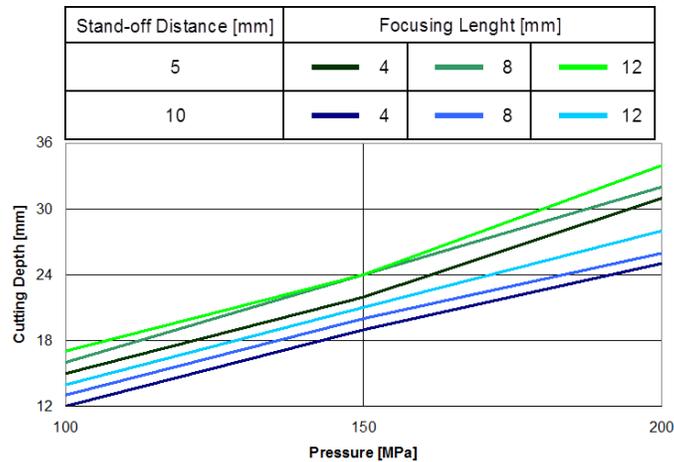


Figure 4.2 – Nozzle Focusing Lengths vs. Cutting Depth

The results indicate that jet cohesion increases with increased focusing length and becomes more significant with pressure increase. By shifting the slurry entry point within the accelerating chamber the

relative velocities at the “interface” of the two streams, were varied. The available range of velocities for the water stream were from $V_s = 2.14 V_w$ to $V_s = 0.25V_w$. The cutting ability of jets was then measured using various slurry entry points. **Figure 4.3** shows the test results for cutting depth at standoff distances of both 5mm and 10 mm.

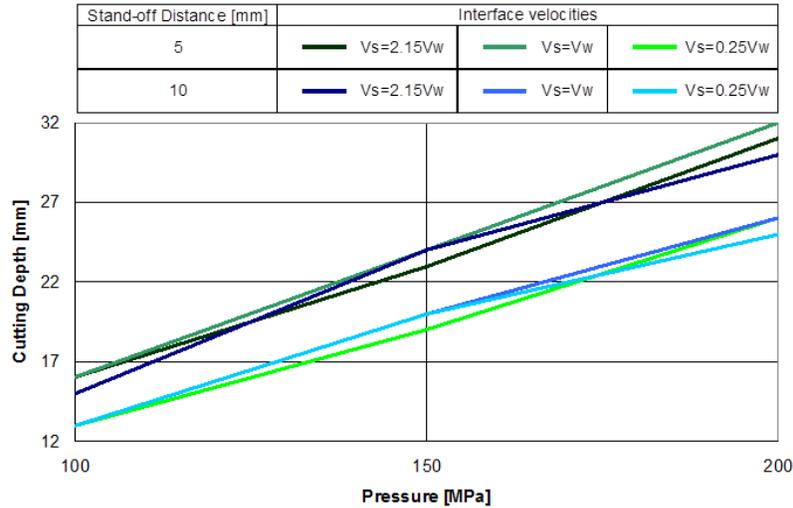


Figure 4.3 – Interface Velocities vs. Cutting Depth

The results indicate that there was no significant jet deterioration due to changing the ratio of the “Interface Velocities” for the two streams.

4.4 Abrasive Slurry

In conjunction with Curtin University of Technology, a study was undertaken to test for appropriate abrasive slurry which could be used in the AS-IJ system. The parameters for the slurry were set as follows:

- 1) Ability to hold abrasive particles in suspension for a minimum of 4 hours
- 2) Viscosity of the slurry to be kept to a minimum

After some preliminary testing using various polymers, Xanthum gum was chosen as the viscosity modifier to be used in the AS-IJ test system. Xanthum gum was chosen for its shear thinning characteristics, effectiveness, cost, ecological advantages and high gel strength. The test rig limitations drove experimental parameters, which determined that the solids loading by weight would need to be

between 50 – 60% with particle sizes characterized by 120 mesh & 150 mesh refined GMA garnet. The 120 mesh garnet refined for the purposes of the AS-IJ system would require particles no larger than 250µm (for use through a 0.8mm nozzle) whereas the 150 mesh refined garnet would require particles no larger than 150µm (for use through a 0.5mm nozzle). Core experimentation consisted of settling tests, stratification tests, viscosity tests and operational tests. The viscosity tests were conducted through the use of a patented settling viscometer as inconsistent results were obtained using a normal coaxial bob viscometer. This was put down to centrifugal effects not the ultimate gel strength of the slurry solution. Optimum slurry concentrations given the previously stated parameters were obtained with 0.5% Xanthum gum, 60% abrasive and 39.5% water (by weight). These concentrations resulted in a slurry which was useable inside the AS-IJ test system. Once an acceptable slurry solution was determined, it was tested inside the AS-IJ test rig to confirm its use in an operating environment. The gel strength of the slurry was sufficiently strong to ensure that no settling occurred within the system. From a rheological perspective the properties of the Xanthium Gum based slurry were that of a shear thinning, thixotropic (time dependant) fluid with a highly correlated power law determined experimentally. Due to these characteristics, the slurry mixing process was critical in the determination of its rheological properties. The research done to date was by no means all-embracing and further research would need to be conducted and extended to include other polymers.

5.0 CUTTING RESULTS

The AS-IJ test rig allowed preliminary cutting tests to be undertaken. A 25mm thick Aluminium sample was cut with a speed of between 17- 21 mm/s at 40,000psi with a 0.5mm diameter orifice. However this is only an indicative result as the AS-IJ system needs further optimizing to achieve optimal cutting results. For a similar powered AIJ system, manufacturers claim a 25mm thick Aluminium can be cut with a speed of 7 - 9 mm/s at 90,000Psi with a 0.28mm diameter orifice. It is also known that a 60,000psi AIJ system can cut 25mm thick Aluminium at between 2.5 - 3.5 mm/sec with a 0.28mm diameter orifice. These results more or less correspond to theoretical expectations which are based on previously published theoretical and empirical data.

6.0 CONCLUSIONS

The work done by the team at Jet-Net International and results obtained have demonstrated that the AS-IJ can be adapted to a CNC abrasive cutting system. Test results demonstrate that the two major obstacles, starting and stopping pressurized abrasive line and blockages due to abrasive settling can be

overcome with a hydraulic lock system and a dedicated slurry line. The AS-IJ has the potential to at least quadruple the cutting speed of the 60,000Psi AIJ systems and at least double that of the 90,000Psi AIJ systems. Introduction of AS-IJ CNC cutting systems has the potential to be a generational change in the water jet cutting industry. AS-IJ cutting systems have the potential to open up the large markets which have been dominated by Plasma and Laser cutting systems over the past 30 years.



Figure 6.1 – ASIJ CNC Cutting System



Figure 6.2 – Jet-Net International Pty Ltd Engineering Team

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