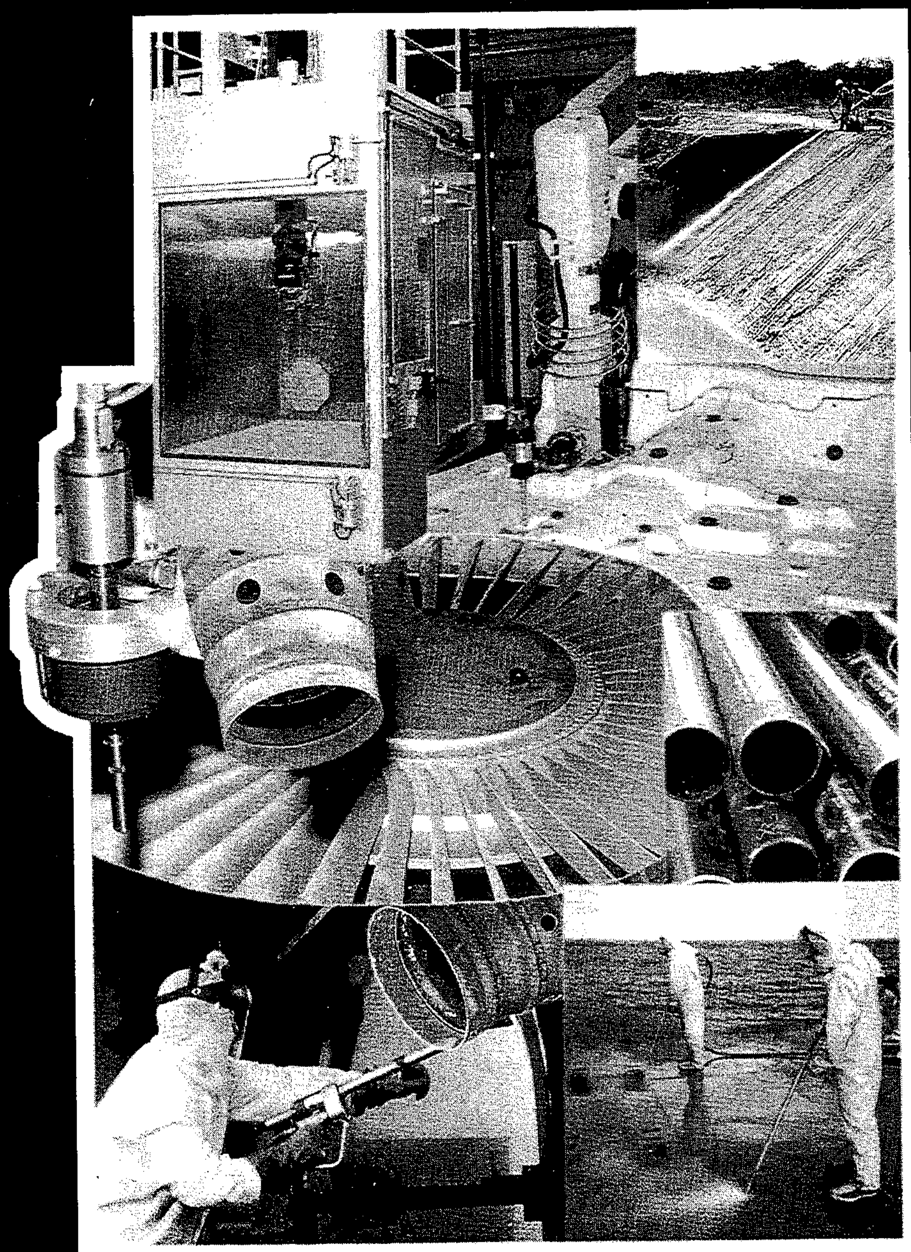
Proceedings of the 9th American Waterjet Conference

Volume II



August 23-26, 1997

Dearborn, Michigan

Edited by Mohamed Hashish, Ph.D.

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Published by the

Waterjet Technology Association

Cover: The photographs on the cover are obtained from several sources in the industry. The photographs reflect the contents of these *Proceedings* such as mining (upper right corner), factory and field cleaning (lower pictures), stripping of cans, 3-D cutting of blisk and automotive carpet cutting. (For a detailed description, see illustration on page iv).

Proceedings Of The 9th American Waterjet Conference

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Forward

These *Proceedings* give you an indication of the present state of the art of waterjet technology and an elucidation of the direction that waterjetting will advance in the near future. Before the advent of waterjet conferences, it was much more difficult to predict the direction in which waterjet technology would develop.

Modern waterjet technology had its genesis in the solution of the technical challenges of the 1850s, i.e., a practical way to mine the gold-bearing gravel of California. Hydraulic mining was the method of choice until the 1880s when it was abandoned because it caused silting of the rivers.

Industrial waterjet technology then entered into a period of decline until the 1960s and 1970s when the United States government funded research on waterjetting as a method of rapid excavation for the military and privately-funded research was conducted on waterjet cutting of wood products.

This research began the process which has led to the development of the thriving waterjet technology of today. This technology has developed in a way unforeseen by the early waterjet researchers. Waterjets have become the routine tool of choice in many industries (for example, industrial cleaning), and is undergoing rapid adoption in other sectors of the economy (e.g., manufacturing) and is an active area of research. The success of waterjet technology illustrates the value of research. A small investment 30 years ago has led to the existence of the multi-billion dollar waterjet industry of today. The contrast between where the technology is now and where it was 30 years ago is amazing.

Research is an acorn which can grow into a mighty technological oak.

George A. Savanick, Ph.D.
President

Fluid jet technology is accepted as a viable process for use in a wide variety of industrial, construction, and cleaning applications. In some industries it is the standard to which other technologies are compared. There are many of us in the world-wide fluid jet community that can remember the technology in its infancy, and the struggle for acceptance by industry. Growth rates have been substantial and sustained over the past twenty years, and the future looks bright with new technological developments on the horizon. Opportunities abound, but care must be taken to use the technology wisely and safely.

The Waterjet Technology Association has grown in similar fashion, due to the support and commitment of its members and industry. The individuals and organizations that I have worked with are consummate professionals, dedicated to making it a quality association.

It is especially gratifying to see the growth of this conference through the years. The individuals and companies that support the conference should be proud of their work. This forum provides a basis for the exchange of ideas and stimulating discussion. I look forward to meeting many of you, and trust that the conference will meet your expectations.

Thomas J. Labus, P.E.
Chairman of the Board, Waterjet Technology Association

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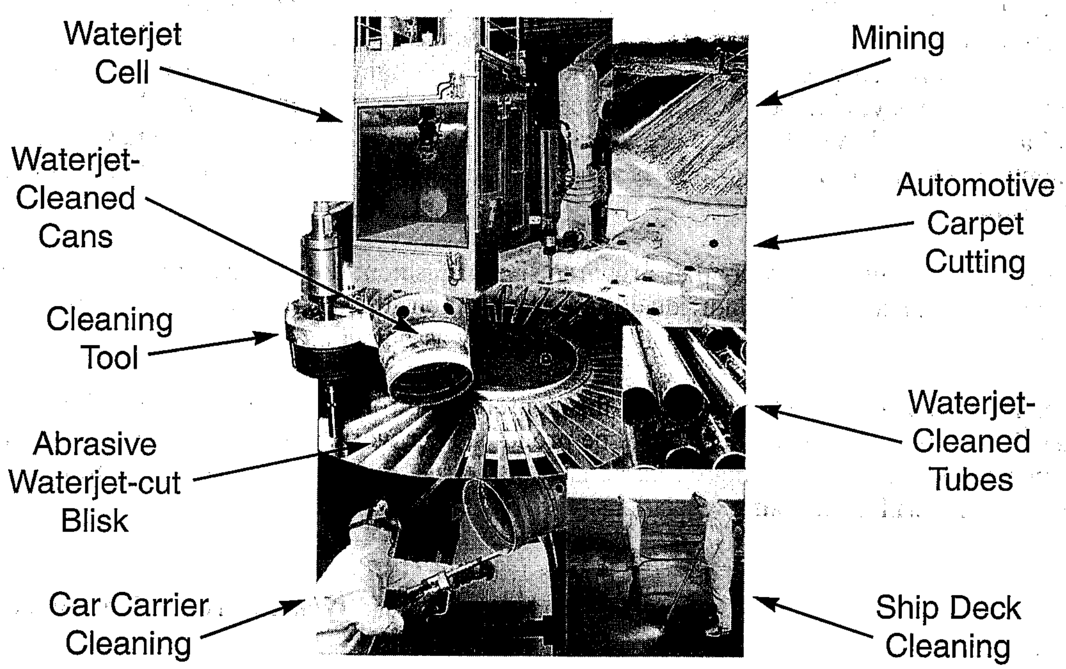

Preface

The 1997 American Waterjet Conference, which is the ninth in this biennial series, continues in the original spirit and purpose of these conferences. The Waterjet Technology Association (WJTA) is again organizing the conference, as it has since the association's inception at the second conference in 1983. WJTA continues to provide a means of cooperation among government, industry, and academia, to promote the general interest in waterjet technology, and to foster domestic and international trade in waterjet products and services. The founders of this association should be proud of their accomplishments.

At the first conference in 1981, 23 papers were presented. These papers did not contain terms such as abrasive jets, suspension jet, ice jets, milling, turning, surgery, demilitarization, waste recovery, and surface preparation, which are common topics at this conference. This conference proceedings contains 62 papers covering a wide range of research topics as well as field and factory applications. The papers are contained in two volumes. The first volume is related more to research, while the second is related more to applications. The picture on the cover reflects robotic machining operations and surface preparation.

The success of this conference can be attributed to a large number of people who deserve recognition for their efforts. Foremost among these are the researchers who submit their work for publication and agree to present and discuss their work. The conference committee members, Thomas Labus, Thomas Kim, and Bruce Wood, provided timely and scholarly reviews for the selection of papers and for the best paper award. They deserve special recognition and thanks for their contributions. Birenbaum and Associates continues to provide excellent and much-needed administrative support to WJTA, especially in managing the publication of this proceedings. Many thanks to Mark Birenbaum, Ken Carroll, LeAnn Hampton, and Rhonda Stevens. Special thanks to Jan Tubbs for efficiently logging abstracts and papers, sending review requests, notifying authors, and communicating with numerous national and international authors in a most pleasant and professional way. Finally, I would like to thank my wife Nadia and my two sons Ameer and Rami for their continued support and patience.

I hope that this proceedings will be a valuable contribution to the state of the art and will significantly enhance our knowledge of waterjet technology.

Mohamed Hashish, Ph.D.
Editor, *Proceedings of the 9th American Waterjet Conference*

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Paper 33

ENHANCING THE DRILLING POTENTIAL OF POLYCRYSTALLINE DIAMOND IMPACT TOOLS

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ABSTRACT

Work on the development of mechanical tools to remove rock has, for a number of years, been restricted by the increasing wear rates of conventional carbide bits. Performance can be increased by using diamond coated tools, but in their initial application these give penetration rates of equivalent level to those of existing tools. For drilling to be made more economic, penetration rates in harder rock must be significantly improved - a problem with conventional tools, and an area in which PDC equipment has yet to be validated.

By examining the damage pattern under PDC tools it can be shown that the damage can be divided into two zones, one of intense rock crushing and one where the rock is severely cracked but not liberated. Where the loading of the tool can be increased (a benefit of the use of the diamond coating) then a crushed zone of greater than twice the penetration depth is created. When this material is removed by the short pulse of a high pressure jet stream, then the penetration rate of the combination can, thus, be more than doubled.

The results from laboratory tests with a suite of rocks, ranging from sandstone to quartzite and basalt are discussed both using static and dynamic impact loading. A preliminary novel design for a rock drilling bit is proposed and discussed.

Organized and Sponsored by the Waterjet Technology Association.

1. INTRODUCTION

Some 25 years ago the first International Symposium on the use of High Pressure Waterjets as a new cutting tool took place in Coventry in the United Kingdom. Some 200 delegates attended that Conference, and a significant number of the papers (18 out of 37) dealt with cutting rock and coal. At the 12th International Conference held in Rouen in 1994, of the 56 papers presented only six dealt with rock cutting. In the intervening years one of the most promising technologies had been one in which high pressure waterjet streams had been directed into the cutting zone of a mechanical tool as it traversed the rock. This subject was the focus of 10 papers at the 8th International Conference but had fallen to only three at the last Conference in Sardinia in 1996.

One reason for the change in emphasis, is that the need to find new techniques to cut rock has moved from softer rock formations and coal, where current technology seems adequate to meet current demand, to harder rock. In softer rocks the ability to increase penetration speed does not have a significant impact on overall economics, relative to gains which can be achieved by improving other parts of the operation. Thus, it is only in cutting harder rock, where current speeds are very slow, and wear rates high, that an interest in improving bit performance is still high.

The problems of cutting harder rock are compounded by the need to operate with stronger and more resistance cutting tools, and the operational lifetimes of the more conventional carbide materials has restricted their use in many locations, so that drilling and blasting has remained the most popular method of excavation. In the intermediate years most of the emphasis has been on adapting waterjetting technology to systems which can cut softer rock, such as coal and limestone, so that it is often forgotten that the original work which evolved the concept of an integrated waterjet and mechanical cutting system was designed to work in very hard rock.

2. WATERJET ASSISTED CUTTING

Back in 1976 a relatively young Ph.D. student in South Africa was tasked with improving the cutting performance of drag bits for cutting the hard abrasive rocks surrounding the gold bearing layers (or reefs) of that country. Realizing that a primary need was to keep the cutters cool, he (Hood, 1977), added water at increasing pressure and discovered that at a pressure of 400 bar, waterjets combined with mechanical cutters were able to cut the rock significantly deeper and faster than without the jets (Figures 1 and 2).

That young student has gone on to greater and better things as has the technology which he began. Its most immediate application was in the addition of high pressure waterjet systems to the mechanical picks used to cut rock mechanically. The machines used for this are called roadheaders and comprise an array of picks which sequentially cut into and break out the rock from a solid face in a controlled pattern. The benefits achieved by the addition of waterjets can be simplified by stating that without waterjet-assisted cutting (WAC) cutting rock with a strength of 1,200 bar would require a roadheader weighing over 100 tons and costing around $1 million. The addition of the WAC system to a 35 ton roadheader made it possible to cut the same rock, but with a relative cost on the order of $250k for the machine and $100k for the WAC addition (Figure 3).

There has been some considerable debate about the relative success of jet-assisted cutting which Dr. Hood developed. Summers (1995), and many investigators have failed to grasp two of the fundamental requirements which must be provided for the system to be effective. This was particularly evident in the papers presented at the 8th International Waterjet Symposium where investigators reported on results using a wide range of test parameters, a number of which were beyond effective use. It is in exploiting the excavation built on these two fundamental requirements which is currently under study at UMR, and it is, therefore, appropriate to review these requirements.

In WAC cutting the waterjets impact the rock in the zone of interaction between a cutting tool and the rock surface across which it is dragged. The first requirement for the system to work is that the water must reach the rock with a large proportion of the energy with which it left the nozzle. This may seem to be an obvious criteria, but it has been disappointing to note that few investigators appreciate this point.

When a high pressure waterjet issues from a nozzle it is moving into a fluid that is essentially at rest, while the jet moves at a velocity of around 400 m/sec. Thus, there is an immediate and continuous deceleration of the jet, which works from the outer contact inward to rapidly degrade the jet quality and velocity. The effective range of the jet is measured in terms of the initial jet diameter, since a larger jet will carry further before it is totally disintegrated. For a normal jet nozzle, a throw distance of around 100 diameters can be considered typical (Figure 4).

A typical jet nozzle which might be used in a roadheader application has a diameter of 0.5 mm, which means that the effective range of that jet is 5 cm. Thus, if the bit block and nozzle assembly require that the nozzle be placed 10 cm. from the rock surface, then the jet power will not reach the rock. Engineers (who do not have eyeballs calibrated to picture events in microsecond intervals) look at the stream issuing from a nozzle and do not appreciate the rapid decay of the jet from a solid stream into moving droplets which occurs within the visible jet. However, the decay is sufficiently rapid to negate the effect of the jets and to significantly reduce machine performance. For example Canadian investigators, Haslett et al. (1986), examined a system where the jet diameters were 0.43 mm., giving an effective jet throw of around 4 cm., but located the jets at a distance of 10 cm. from the cutting zone.

The problem, however, with integrating the waterjet system into large pick rock cutting of this type is that the picks are designed to cut into the rock to a considerable depth on each pass, and that the mechanical requirements of the holding block to retain the picks can often constrain the designer to requiring the larger standoff distance such as that used by the Canadians, among others. Fowell et al. (1996), has shown that in cutting harder rocks shallower depths of cut are preferred, and that in these circumstances cooling the bit with a waterjet spray at pressure can be very effective in extending the life of the tool. This is a critical step in the development of machines to mechanically cut the rock, given that, as Hood first found, that the high temperatures generated with dragging the pick over the surface will otherwise wear it out in only a short distance. Fowell found that while a tungsten carbide tool will erode in only a meter of cutting path, changing to a polycrystalline diamond cutter extended the life so that over twice that distance no wear could be seen on the cutting surface.

Polycrystalline diamond coatings are becoming increasingly popular as a surface to protect the cutting tools when penetrating harder rock. They are also being used in oil well drilling and other operations as an economically viable alternative to carbide, since their longer operational life more than justifies the greater initial cost. However, in cutting harder rock, the susceptibility of the diamond to higher temperature must be recognized. Without effective cooling the bits will still suffer considerable damage over short traverse lengths, particularly where the depth of cut is increased.

3. WATERJETS AND POLYCRYSTALLINE DIAMONDS

A high pressure waterjet is most efficient when it is traversed rapidly over the rock surface. At this speed the jet will make only a small cut into the rock, much less than that of a conventional rock pick. However a polycrystalline diamond coated (PDC) cutting tool also only takes shallow cuts into the rock, and is most effective when moved at high speed over the rock surface. A combination of the two would synergistically assist in the performance of each, and since the cutting tool and the depth of cut achieved is shallow, it is easier to bring the nozzle body closer to the cutting surface where it can provide more useable power. In passing it might be commented that, while WAC will also work with carbide tools, there is an inexorable move toward the use of PDC tools in drilling - up to 30% of the bits used in oil wells now use this facing, Livesay (1997), - and it is thus appropriate to adapt to this changing technology.

Tests at UMR combining a high pressure waterjet with a PDC cutting edge have shown that penetration rates for a rock drill can significantly increase over that achieved with PDC tools alone. However the combined tool creates rock in a very fine particle size, and thus is only a partial solution to the problem. An alternative requires the larger pick sizes such as those used by Fowell, but through understanding of the fragmentation process, it might be possible to enhance the penetration performance of the tool. This requires a greater examination of what goes on in the crushed zone, as the bit advances both into and along the rock.

4. WATERJETS IN THE CRUSHED ZONE

A second fundamental requirement for a WAC system to work is that the jets must strike the rock in the zone where the tool is crushing the material. Because the jets work at relatively low pressure when compared to the rock strength, it is futile to have the jets strike intact rock outside this zone, which is generally within two millimeters of the tool impact zone. Thus, equipment which has been manufactured to use a WAC system, but in which the jets strike the rock 4 mm. from the impact point are inherently doomed not to work well. Unfortunately this has not always been understood, as evidence by one or two of the papers back in 1986. The importance of this can be seen by reference to the size of the crushed zone generated, when a PDC bit is forced into a rock surface (Figure 6). The rock sample is basalt. In order for the jet to do useful work, given that the pressure is too low to cut the rock by itself, the jet must impact and penetrate along the zone of rock which is being crushed by the tool. this gives a relatively narrow range of position and angle within which the jet can be effective (Figure 7).

Most of the work which has been carried out with the addition of waterjets to cutting bits has considered that their most effective use would be in the rock ahead of the bit. However, as Hood showed (Figure 8) there is also a reduction in the thrust force when the bit is assisted by jetting action. It is in this area that the current interest is concentrating. When one examines the rock damage induced under an impacting cutting tool the penetration and damage can be correlated with the impact energy (Figure 9), resulting in an equivalent damage pattern. The underlying damage is, however, frequently not exploited, but merely accepted as a "conditioning" of the rock which occurs as part of the continuous excavation of the surface with repeated passes.

Yet if this damage zone can be exploited, then the performance of the tool can be considerably increased. It is not productive to crush the rock on one pass, and then have to work through that cushion of material to cut into the underlying rock in subsequent passes. One approach to combining the waterjets with the tool and to remove than material might be to use the jet as a subsequent "cleaning" jet to scour the surface before the next pass of the tool.

However, when the jet, at a pressure of 6,000 psi, was applied to the crushed zone, after the indenter had been removed (Figure 10) the jet did not remove all the crushed material, even though it penetrated to the full 3 mm. depth of the zone. The hole which it punched was not at the diameter of the indenter (0.75 in.) so that, when the tool revisited the site, it would still have to do some work on the remaining damaged zone from the previous pass, before it could cut fresh rock. Note that in both the first case, and this test, the indenter was penetrating roughly 1 mm. into the basalt surface during the test.

In contrast, when the jet was fired at the rock concurrent with the blow of the indenter, then all the crushed zone, and some of the material in the cracks was all removed (Figure 11). The opening of the cracks and their extent, together with the penetration of the indenter to the full depth of the crushed zone, on the initial pass, not only means that the penetration rate can be quadrupled. Concurrently it means that the cracked material on either side should be removable without the need for additional waterjet assistance, and that the surface will not be cushioned by damaged material when the indenter returns to continue the penetration on the next pass. This latter point is significant since it also means that there will be no loss in penetrating force to the cushioning material, and thus the initial gain in penetration rate can be continued. It is interesting to note, furthermore, the scale of this depth of penetration - some 2.5 times or more the original penetration achieved by the indenter. This is consistent with the gain in depth achieved by Hood and shown in Figure 8.

While this illustrates the benefits of having the two events occur simultaneously, it also suggests that it is only necessary to have the jets acting on the bit when it is actively crushing the rock. For the remaining time it is unnecessary. Since this requires the jet to operate for less than half the time involved with a continuous jet stream it provides an opportunity to develop a tool which gives the same effect but at half the energy and with half the water usage. In some locations the second advantage is the greater of the two.

5. CONCLUSIONS

During the past few years several advances in equipment and knowledge of the cutting process indicate that significant improvements in drilling and rock excavation technology are possible. Concurrently, as a significant industry has developed, equipment improvements have included reliable pumps, nozzles, swivels, and fittings. Without such reliability, improvements in performance would be problematic. Rock cutting is an extremely tough environment and the waterjet equipment is now available to meet its challenge.

How to better use the improved equipment has been guided by significant advances in the understanding of the rock failure and waterjetting processes. Different approaches to effective cutting of rock can now be identified, both of which can be applied to hard rock conditions. An increased understanding of jet behavior will allow waterjets to effectively and economically assist mechanical excavation techniques.

The advances in knowledge and equipment can be summarized in the statement: our ability to combine waterjets with mechanical rock tools has reached the point where these advances should be implemented.

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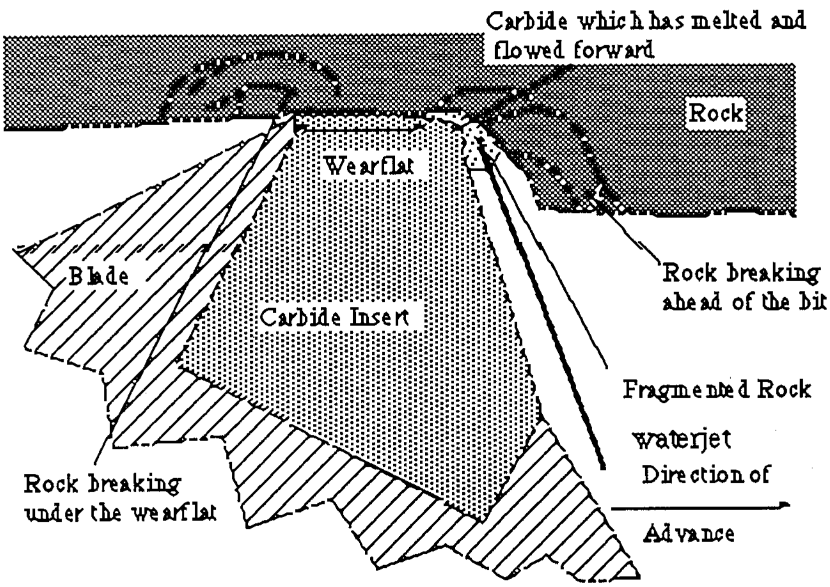

Figure 1. Configuration for Waterjet Assistance (after Hood, 1977).

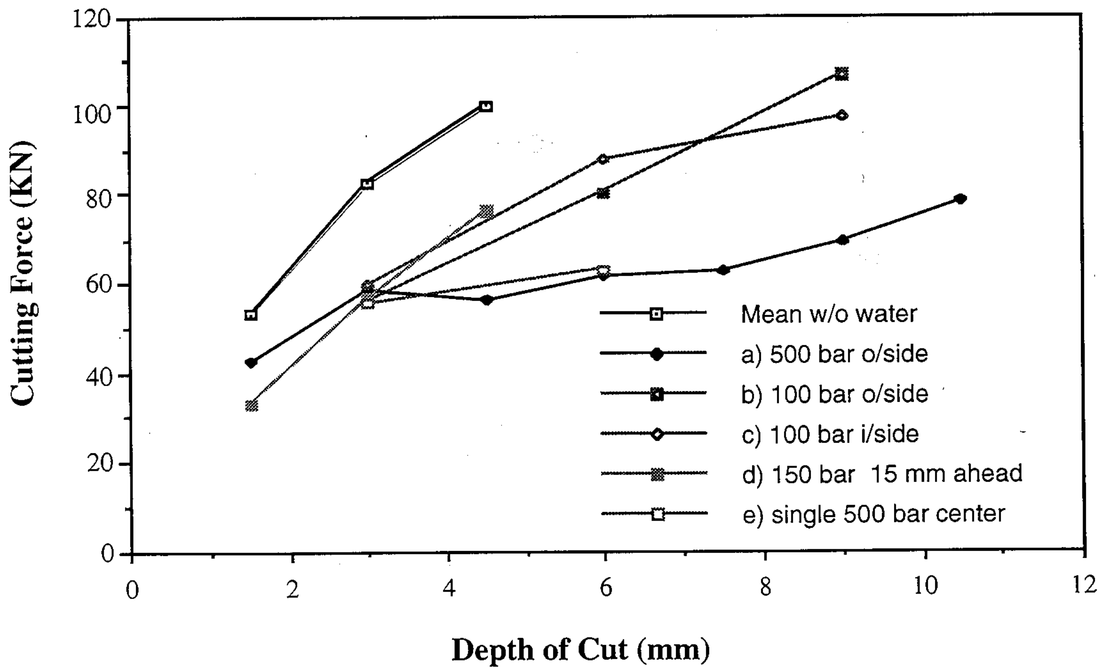

Figure 2. Reduction in Cutting Force with Jet Assistance (after Hood, 1977).

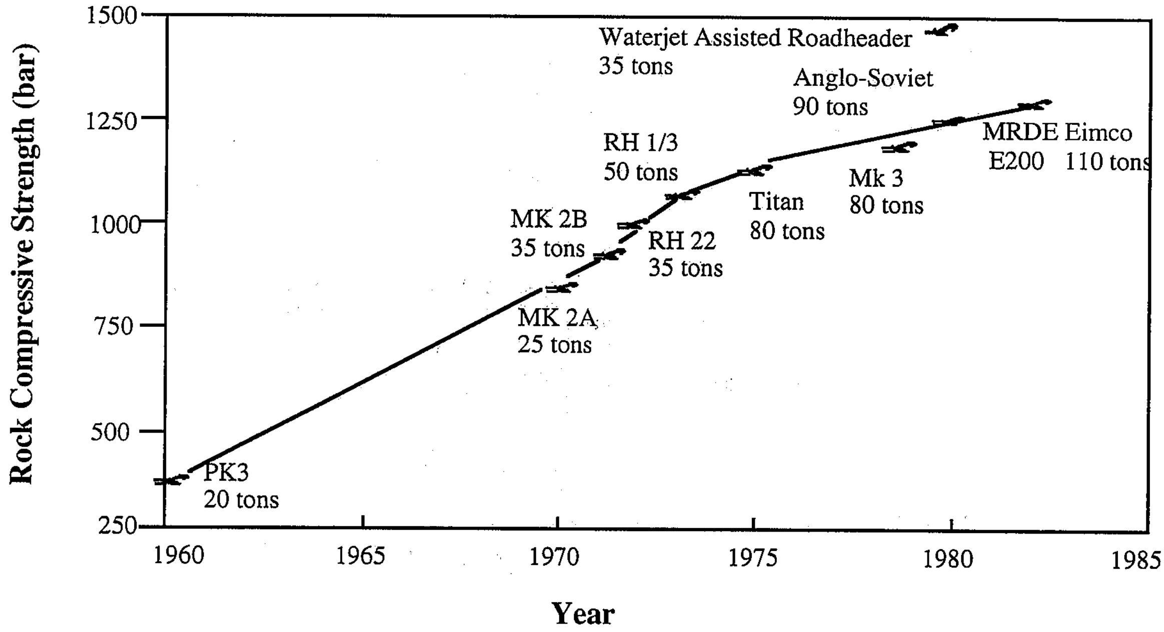

Figure 3. Strengths of Rock Cut by Roadheaders of Varying Weight.

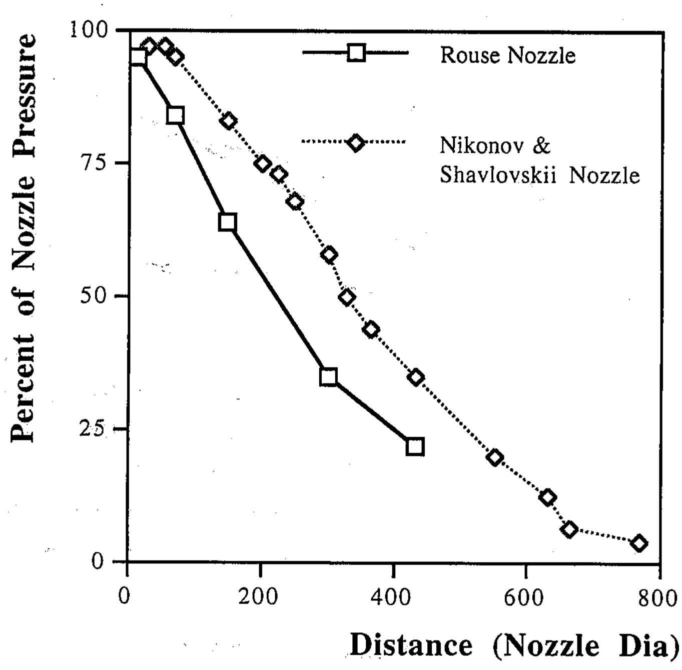

Figure 4. Range of a Waterjet Stream (after Leach and Walker, 1966).

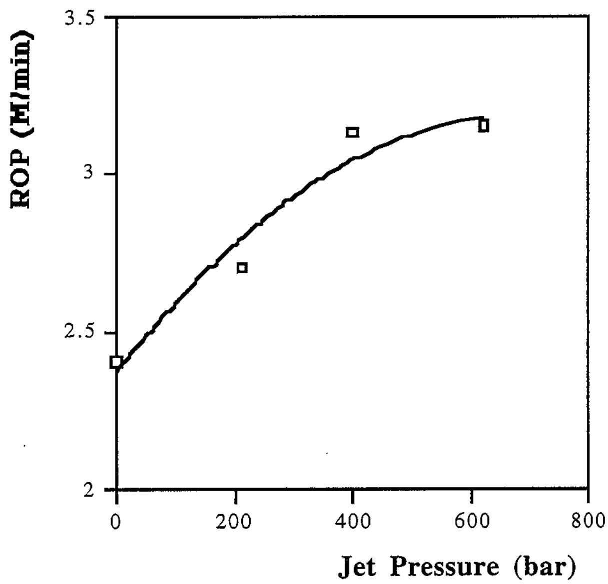

Figure 5. Change in PDC Drill Penetration Rate with Jet Pressure. (Note that this is from a factorial experiment and does not reflect the full potential of the gain available.)

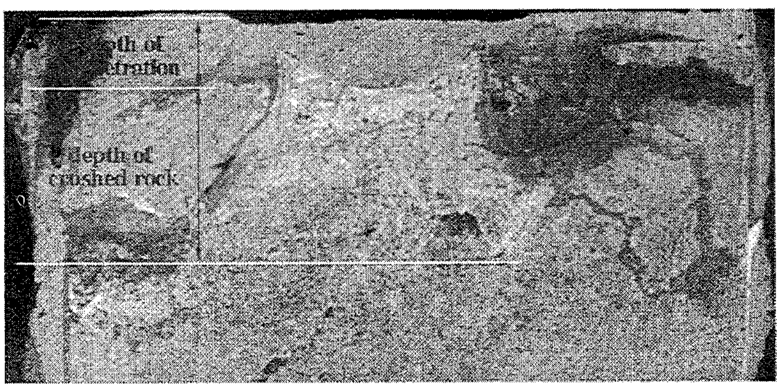

Figure 6. Indentation Without Waterjet Impact - Depth of Penetration is Roughly 0.1 Inches (2.5 mm.) It can be seen that the access passage to reach the crushed zone is considerably less than this.

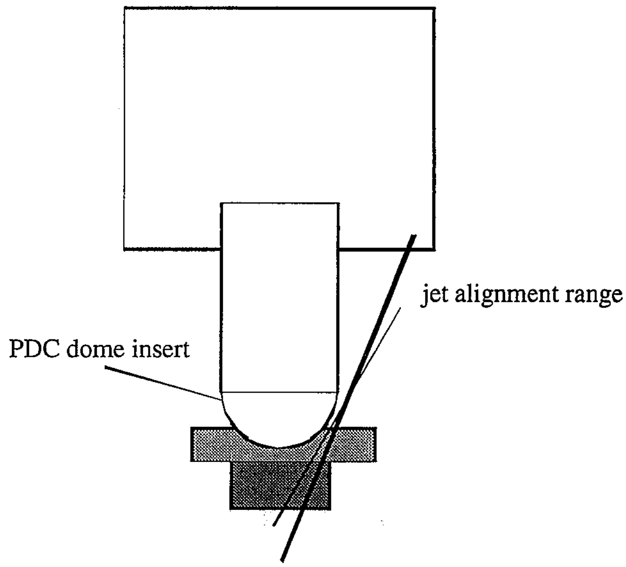

Figure 7. Waterjets Directed Under an Impacting PDC Cutter.

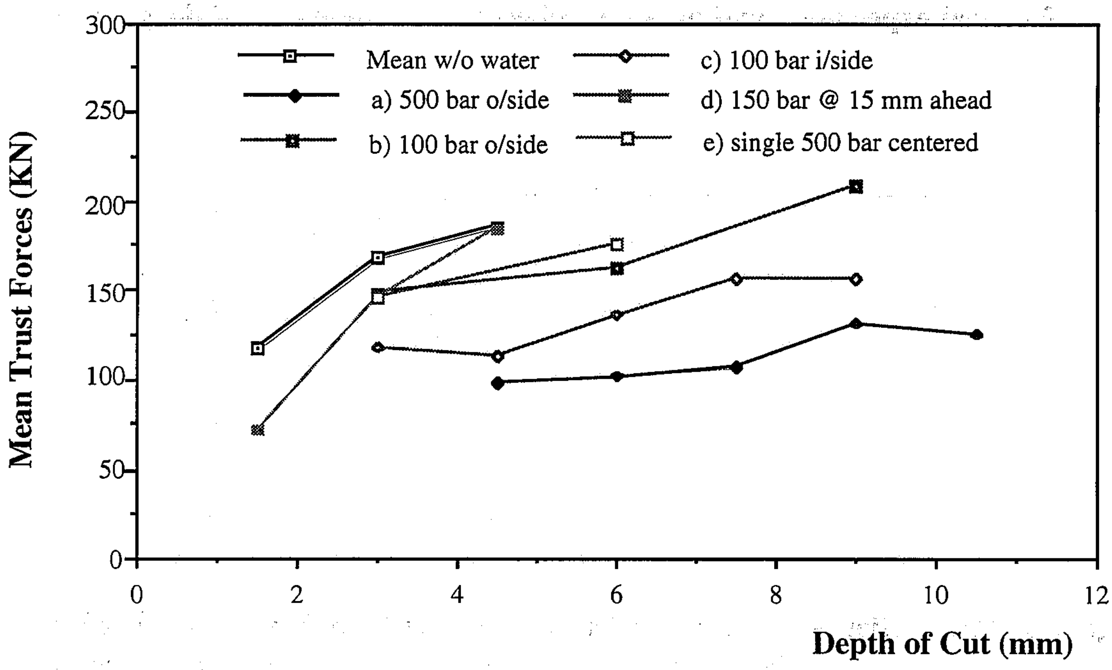

Figure 8. Effect of Waterjet Assistance on Cutter Thrust Forces (after Hood, 1977).

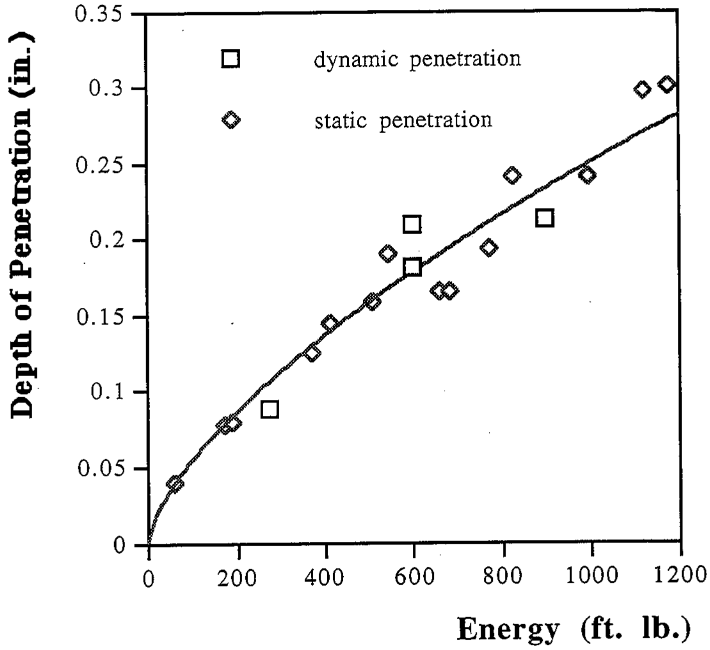

Figure 9. Penetration as a Function of Impact Energy Under Static and Dynamic Loading.

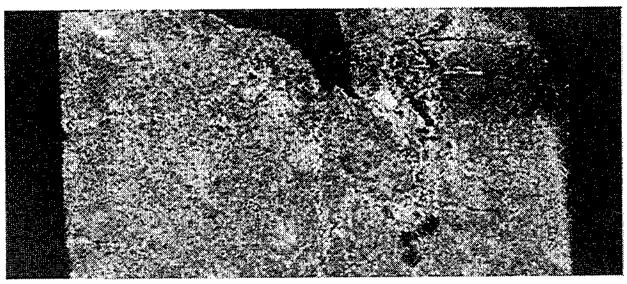

Figure 10 Indentation with Subsequent Waterjet Impact - Only the Central Third of the Crushed Material has been Removed.

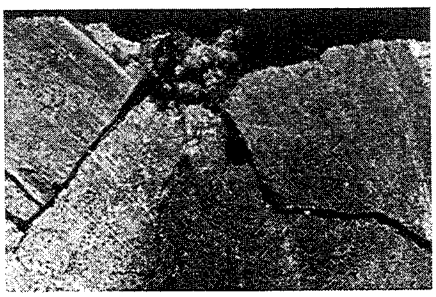

Figure 11. Indentation with Concurrent Waterjet Impact, all the Crushed Material has been Removed and the Insert Penetrated to the Full Depth of the Cavity Created.

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Paper 34

TOOL/ROCK INTERFACE ASSISTED BY HIGH PRESSURE WATERJETS

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ABSTRACT

The main reason for the quick wearing of mechanical tools is the excessive heat generated in the tool/material contact area. Significant tool life extension is possible by applying active, low friction layers of pressurized liquid between friction pairs.

Observations of metal machining and hard rock excavation by picks, based on high pressure liquid jets assistance is presented in this paper, and suggestions for new practical solutions are made.

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1. INTRODUCTION

All of the mechanical tools for materials processing are designed with careful consideration based on the principle of minimum specific energy and maximized tool life. The material processes efficiency depends on the tool's and mechanical properties, its geometry, processed material properties and working parameters. These rules are applied for machining regular homogeneous ductile materials as well as for brittle rocks. The tool wear process takes place in the tool/material interface, and its intensity depends on the conditions in the contact area. The common understanding is that the wearing process is strongly related to the thermal conditions in the tool/material interface. Significant amounts of money and time were spent on the search for hard and heat resistant tool materials. Progress made in this area is astonishing. The most up to date materials are composed for the highest possible heat and wear resistance conditions. The mechanism of the tool distraction is the heat generated in the tool and material processed contact area. The harder contact condition, and high relative tool/material movement, more effective heat generation and more effective tool material mechanical properties declination. The first thing which can extend tool life is the heat generation reduction in the tool/material contact area. In practice, this reduction is made by applying lubricoolants into tool/material contact area for friction reduction and heat absorption. At first, it may be difficult to understand how the lubricoolant can act on the tool/material interface to reduce the friction given the high local forces which exist in this area.

A close examination of the area of contact, shows, that these surfaces are not smooth and that the contact between tool and material in the front of the tool, mainly contact the hilltops but never touch the valleys. The system of capillary channels as discussed by Williams (1977), Spragg et al. (1977), thus created, act as a sponge which draws in the lubricoolant. On the other hand, the conditions at the tool/material interface are extremely severe. Localized pressures in the points of contact can reach several hundreds of MPA. The temperature at this these points also run very high.

With the very severe conditions found at the tool/material contact point, there is little chance for improvement of the material separation action by pouring lubricoolant over this area. It has been reported by Pigott et al. (1952), Nappal et al (1973), Sharma et al. (1971), Spencer (1964), Mazurkiewicz et al. (1989), and Doyle et al. (1979), that a high-velocity lubricoolant jet directed at the tool/material interface is a very effective coolant, and acts so as to reduce the friction force on the tool. For such concept, the primary function of the lubricoolant was changed, on pressurization, from that of lubrication of the interface to that of prevention of the growth of contact between tool and processed material.

Previous investigations by Doyle et al. (1979), Wright et al. (1979), Horne et al. (1978), into the nature of the frictional interaction between the tool and chip in the metal machining have shown that this contact is most intimate in the immediate vicinity of the cutting edge. These studies also prove that interfacial shear strength in the contact zone is lower than that of the shear strength associated with the chip material. The normal pressure diminishes with increasing distance from the tool tip. The shear stress distribution along the tool/chip interface depends on the extent of lubricant penetration. When the lubricant penetrates through to the tool tip, the mean stress at this point is reduced to that associated with the fully lubricated contact region (Figure 1).

The mechanism of the chip formation for ductile homogeneous materials are completely different than for brittle homogeneous materials and especially for brittle non-homogeneous materials like rocks. Whatever cutting metals by tool, or cut the rock by picks, from mechanical point of view is based on intimate contact between tool and material and stresses generation required for material separation. Relative movement between cutting tool or pick is the source for high friction and heat generation. In both cases friction limitation is the key for limiting heat generation and tool life extension.

The authors of this paper are experienced with the metal cutting and rock excavation with high pressure water jet assistance. The conclusion of their extended discussion over the lubrication mechanism and friction issue are presented in this paper.

2. HIGH PRESSURE LUBRICATION EXPERIENCE

Through the last decade, high pressure water jet technology has grown significantly and now is widely applied in many different operations, because of certain unique water jet properties. One of them, important from the point of view of tool/material friction, is that the water jet has an excellent ability to penetrate all kinds of discontinuities and by creating hydrodynamic force, change significantly friction conditions in this area. Evaluation of the work done in the area of high pressure lubrication by Pigott et al. (1952), Nappal et al (1973), Sharma et al. (1971), Spencer (1964), Mazurkiewicz et al. (1989), and Doyle et al. (1979), indicate that it is a promising approach with a high potential for significantly increasing the performance of the tool. Also, the application of high pressure fluid jets to enhance cutting has been found to be of considerable advantage in cutting rock, see Hood (1977), Sitek et al. (1995), Vasek (1995).

The influence of the high pressure water jet injection into tool/chip interface during orthogonal cutting of the 1020 steel was demonstrated during extended research program in the Rock Mechanics & Explosives Research Center at the University of Missouri-Rolla by Mazurkiewicz et al. (1989). The most notable results achieved are shown in Figures 2 and 3. Figure 2 presents the cutting force X and Z measured for selected cutting parameters performed for four different lubricooling techniques and the friction coefficient calculated for these tests. It should be noticed that the feed force and cutting force are practically the same for each of the first three cooling techniques evaluated (without cooling, conventional overhead cooling, axiparallel cooling, and high pressure water jet cooling), but feed force was observed to fall by more than 50% and the cutting force by approximately 23%. The triangular symbols used on this figure represent the calculated value of the mean coefficient of friction associated with each of the cases investigated. The average value for the first three cases is approximately 0.75. For similar cutting parameters (180, 0.4 mm/rev) with high pressure cooling, the coefficient of friction was reduced as low as 0.50. At a cutting speed of 36 m/min the mean coefficient of friction was reduced as low as 0.40 when high pressure cooling was applied.

Friction reduction in the tool chip/interface observed, means that the heat generation must be reduced also. The proof of this expectation is documented in Figure 3. Temperature measured very close to the cutting edge and rake face surface during cutting, for studied parameters, was reduced 50%

with respect to conventional overhead cooling, when high pressure cooling was applied. Further study indicated that temperature reduction improved tool life in the range of 12 times and created many important technological effects. These results were proven by work done by Oskarsson et al. (1994), Cherukuthota et al., (1995), on turning and milling.

A special challenge in picks life extension in hard rock cutting was also undertaken. Hood (1977), carried out experiments under 69 MPA jets of both fan and solid round shape, directing them both centrally or to the corners of conventional cutting tools. He observed considerable improvement in performance with the addition of the high pressure jets. It proved possible to double the depth of cut, with a reduced force being exerted on the tool, when the jets were directed at the corners of the tool.

Laboratory experiments performed by Sitek et al (1995), Vasek (1995), on hard and abrasive rock supports earlier observations. To verify the best possible high pressure jet introduction to the conical point attack revolving bit, four different possibilities shown in Figure 4 were tested. The cutting forces were measured by three component dynamometer for different depth of cut and different water jet pressure. The results for the jet located 2 mm above the bit nose are presented in Figure 5. The comparison with traditional dry cut indicate remarkable decrease of the cutting forces when a water jet is applied. You can see that in some places along the cutting lines, the cutting forces for the short period of time dropped even closer to the zero level. From time to time cutting forces were rapidly increased and again came back to the zero level. The only explanation for the effect observed is that the bit/rock contact is pressurized by high pressure hydro wedge which effectively breaks rock into chunks along the cutting line. For the moment, the bit is free from contact with the rock and the recorded forces are close to the zero level.

Forces recorded for dry cuts or cuts with the pressure of 50 MPA are significantly higher. The surface of these plots represent work done during rock cutting and contrasting so much for dry cuts and high pressure cooling. Figure 6 also allows us to see how severe contact between pick and rock took place when dry cut was performed or when the jet pressure was not sufficient high. Comparison of these passes plainly shows what is the reason for rapid pick wear and how to prevent such effect.

The comparison of the waterjet location 2 mm ahead of the jet with the jet supply through the pick's center is shown in Figure 7. This means that the water cushion created in the pick/rock contact area is more effective when a water jet is supplied through the pick's center. Also, such waterjet delivery makes the cutting forces diminish when the depth of cut changes from 3 mm to 4.5 mm. It could be explained that a hydro wedge formation and splitting force generation for this particular test condition is better for deeper cuts.

3. TOOL/MATERIAL INTERFACE CONDITIONS

The presented experiment results makes us ask the question, "What is the mechanism of the tool/material friction reduction and tool life extension?" Based on the results achieved during extensive tests it must be admitted that the intimacy of the tool/material contact is diminished when a pressurized water cushion is introduced into this area. It means that the tool and material in the contact area must be partially separated. To separate these surfaces, force generated by the liquid cushion must be high enough to do so. To get an idea what the range of this force could be, a calculation for the idealized tool/material contact model was conducted and the results presented in Figure 8. It can be read from this plot that for circular contact between flat hemisphere and plate with a radius of 9.0 mm, the force acting on the plate when water is supplied through the channel 102 microns in diameter under pressure 70.0 MPA, is in the range of 200 kG. The water discharged for the gap between them equal 12.5 microns is in the range of 870 ccm/min. It seems that these results justify the authors' concept about lifting force creation in the tool/material contact area. More accurate interpretation of the results achieved require thin film and squeezed film mechanical properties study.

4. CONCLUSION

Based on the results generated in two different research centers and different mechanisms of cutting assisted by high pressure water jets, the following remarks and conclusions could be formulated:

High pressure water jet injection into tool/chip or tool/rock interface during metal cutting or rock cutting processes, decreases friction on the contact area and change conditions from seizure to those of sliding.

- Friction reduction results in cutting force reduction, heat generation reduction and tool life extension.
- Creation of the pressurized water film between tool and material creates condition for partial separation of the chips from the tool.
- To make pressurized film more effective in friction reduction in the tool/material interface, a new concept of tool design needs to be applied. As discussed by Mazurkiewicz, et al. (1989), a new cutting tool needs to be developed where the liquid supply into the friction area will be through the tool by a bleeding effect.

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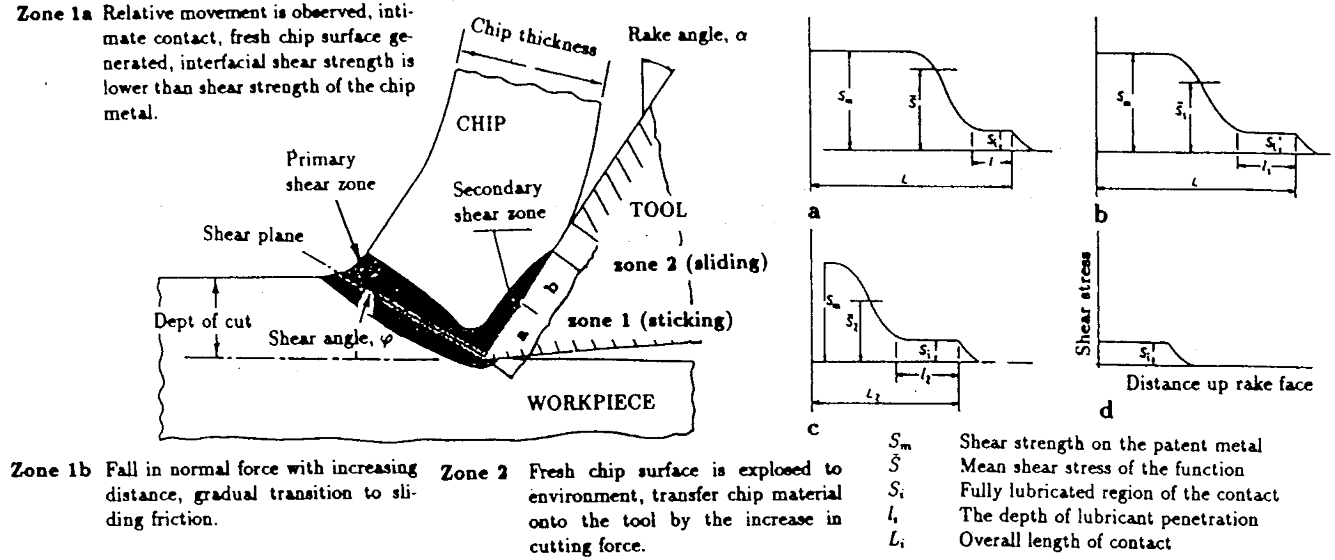

Figure 1. Contact zones at the tool/chip interface and shear stress distribution for different lubricated conditions.

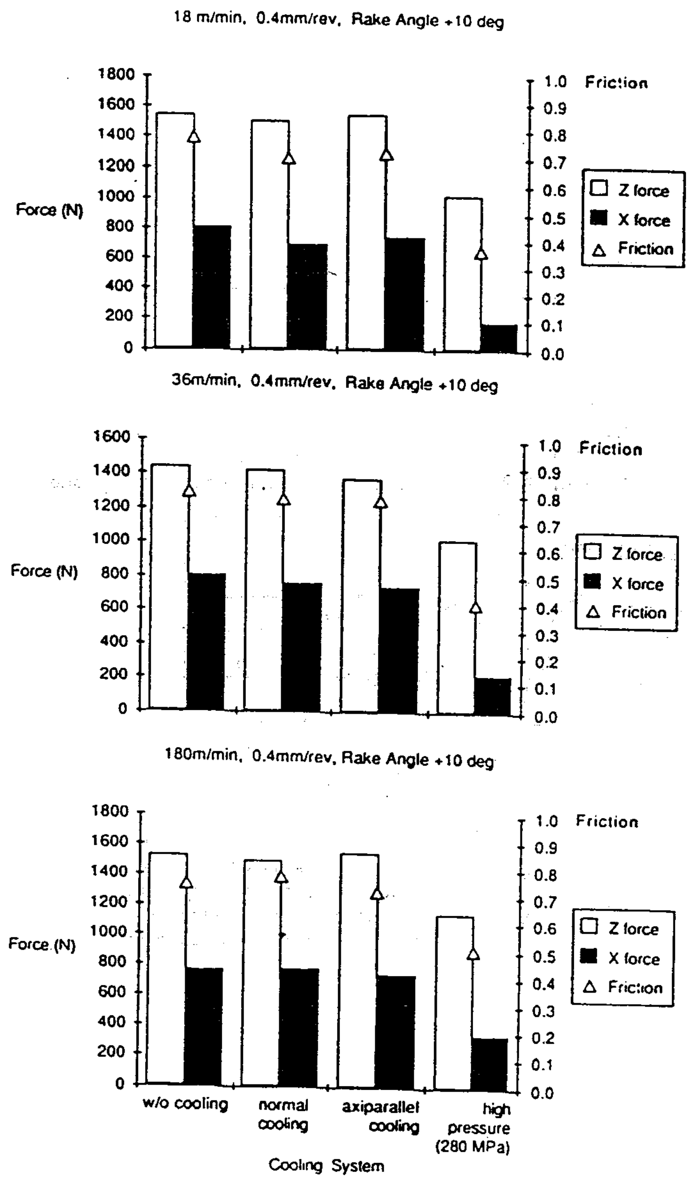

Figure 2. Cutting force, feed force and coefficient of friction for orthogonal cutting of UNS 1020 steel by TPG322F insert: without cooling; with conventional overhead cooling; axiparallel cooling; high pressure waterjet cooling (280 MPa, 0.25 mm nozzle dia) at a cutting speed of 18, 36 and 180 m/min and feed rate of 0.4 mm/rev. Each point represents the average from 7 tests.

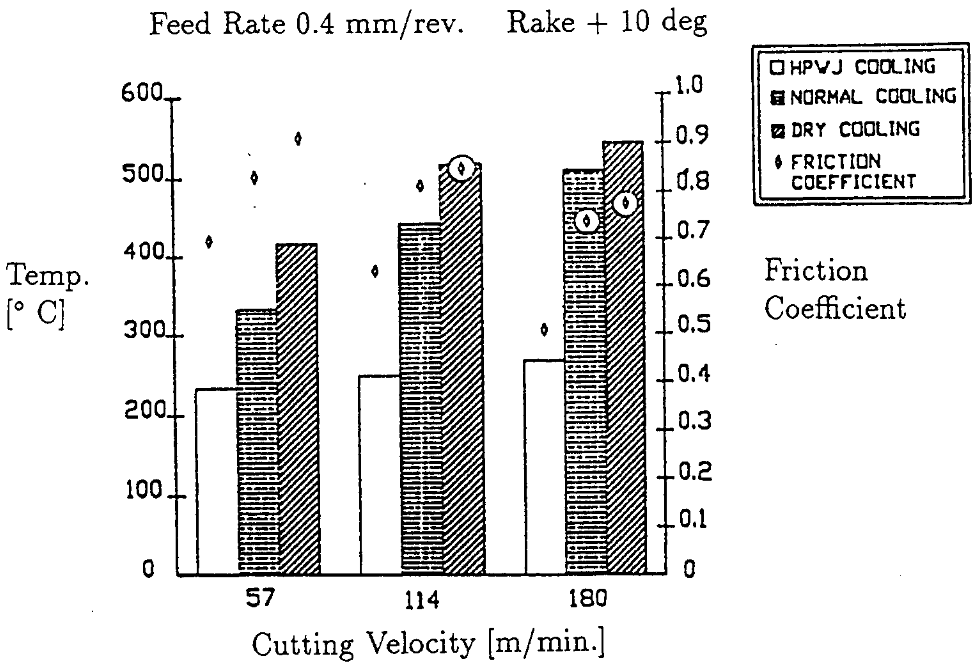

Figure 3. Temperature measured in the tool/chip interface vs. cutting speed for dry cutting, normal cooling and high pressure cooling for UNS1020 and pressure 280 MPa.

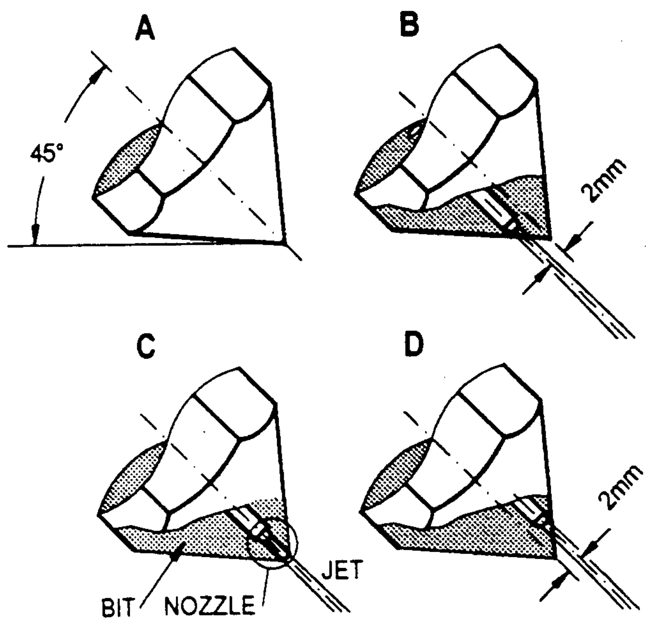

Figure 4. Bit types used for experiments. A - without jet, B - with the jet below tip, C - with the jet at the tip, and D - with the jet above the tip.

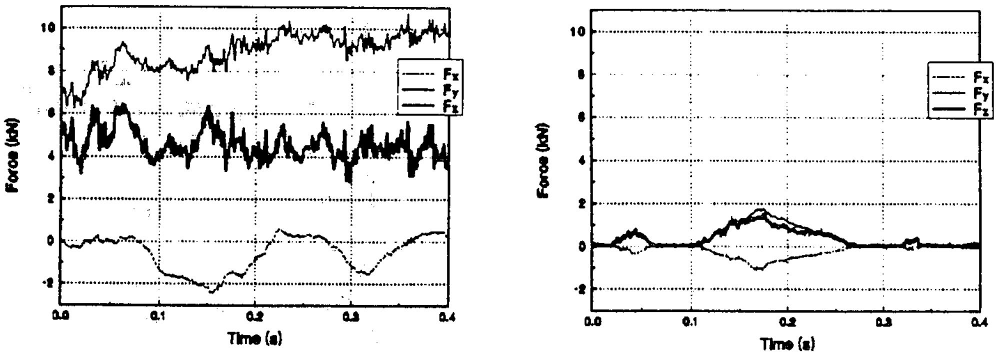

Figure 5. Forces recorded for 121 MPa Sandstone for bit type A (depth of cut 3mm) and for bit type D (right) when jet under pressure 100 MPa was applied (depth of cut 3mm).

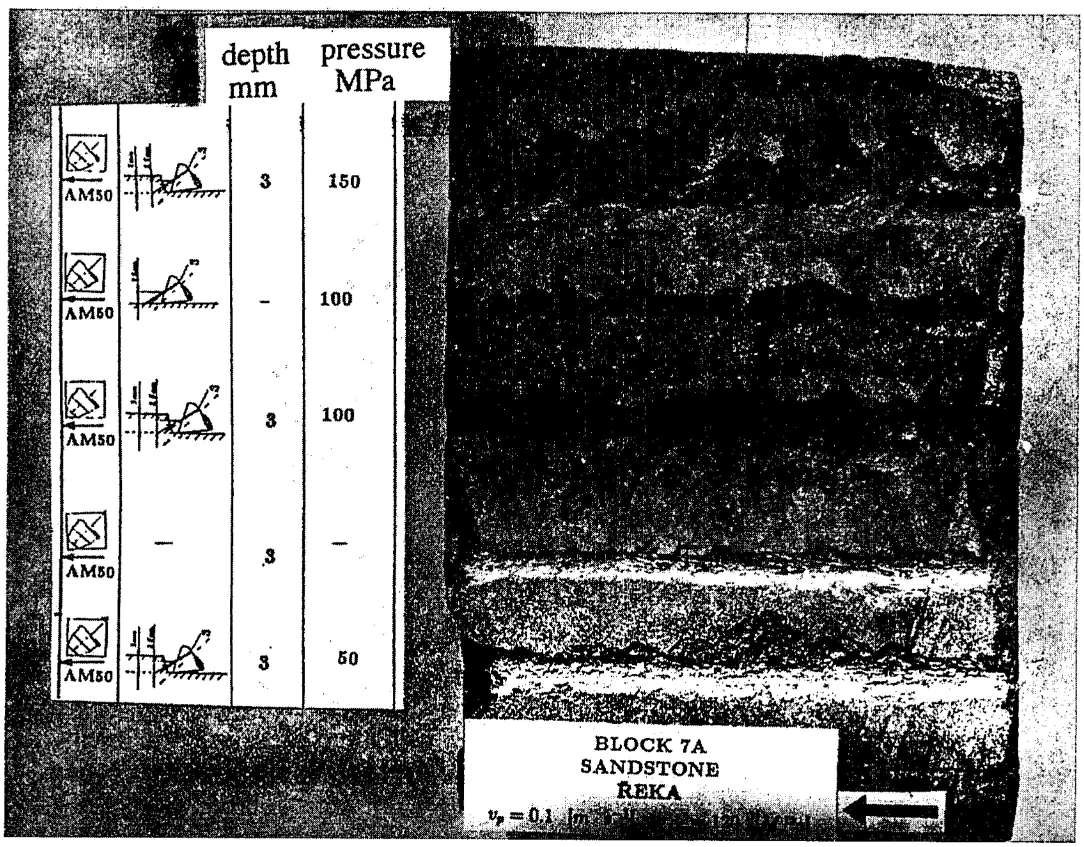

Figure 6. Cuts developed on sandstone (121 MPa) when bit D was applied for depth of cut 3mm and pressure indicated.

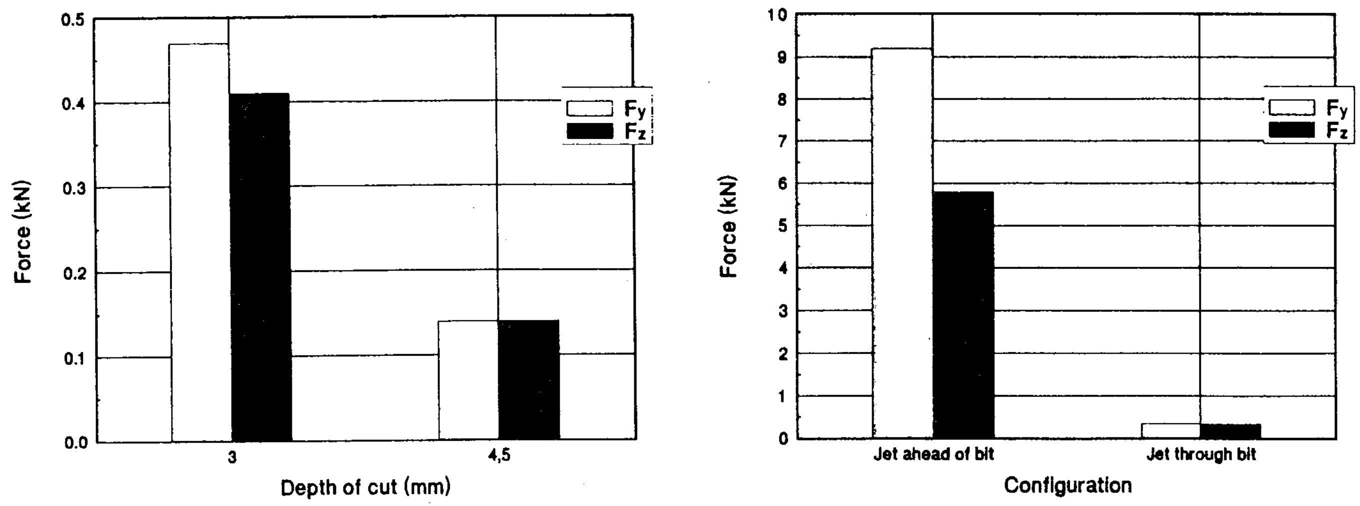

Figure 7. Force versus jet application point for sandstone. 121 MPa pressure 150 MPa and depth of cut 3mm (left), and for bit type D under 100 MPa and depth of cut 3mm (right).

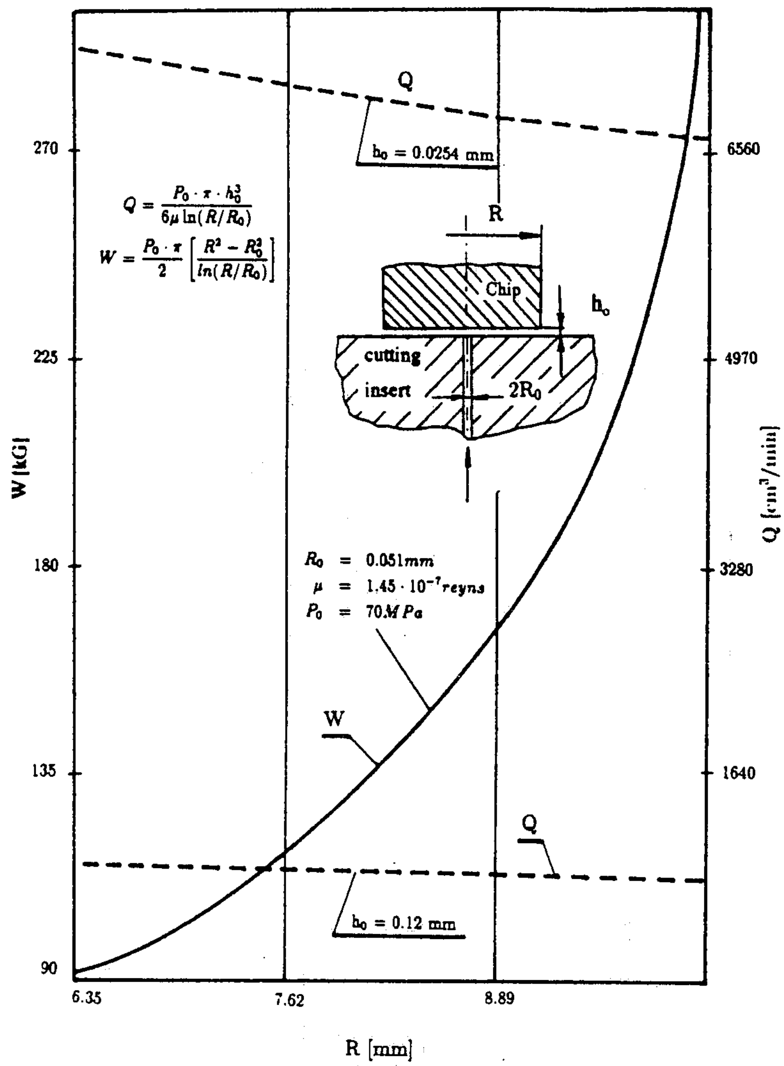

Figure 8. Lifting force vs contact radius R, pressure p_o, supply channel dia $2R_o$ and gap h_o.

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DEVELOPMENT OF WATER JET CUTTING IN EXTREMELY HARD GRANITE QUARRIES 10 TO 20 FEET DEEP

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ABSTRACT

The use of robotic, high-pressure water jet slotting equipment has become the preferred method of quarrying hard granites. Production of cut depths to 6.1m (20 ft) deep and over 30.5m (100 ft) long prove to be an economically viable alternative to existing "less safe" quarrying methods. Four primary benefits that have encouraged the use of waterjet are: improved production rates, reduction of operating cost, substantial increase in recovery, and automation improving safety and health concerns.

Organized and Sponsored by the Waterjet Technology Association.

1. INTRODUCTION

In addition to drilling tools, loaders, and cranes, every dimension stone quarry requires some type of slotting equipment 4.5 to 13cm (1.75 to 5") wide. The most common types of slotting equipment available to granite quarries prior to the water jet were fuel burners, oxygen burners, and slot drills. Traditionally, slotting was the least preferred method because it was the slowest cutting approach available to the quarrier and in many cases the most damaging to the quarry. Today, reducing waste and MSHA pressure to minimize noise and dust have opened the eyes of quarriers to alternative methods. The high pressure Ned-Jet 2000 slot cutting system offers a superior solution that requires no changes to the present quarrying methods.

Water jet slotting has improved recovery dramatically. Quarriers are slowly changing their method, choosing to water jet slot more to recover more. Automation, increased production rate, low operating cost, and the elimination of dust and reduction of noise have drawn the interest of quarriers with high labor cost and a high level of safety standards.

2. EQUIPMENT

2.1 Objective

The Ned-Jet 2000 was designed to replace current slotting methods. This equipment should cut as fast as current methods at comparable cost/ m^2 of cutting. The system should also exploit the advantage of technology and automation, provide a safer work place, better efficiencies, and require less labor.

2.2 Method

The Ned-Jet 2000 uses 276 MPa (40,000psi) water at 27 liters/minute (7 gpm), a cohesive nozzle, and an oscillating mechanism to cut slots in granite 5-7.5 cm (2-3") wide and 6.1 m (20') deep. A long lance or wand assembly delivers the high pressure water to the oscillating nozzle. The wand acts as a support and stabilizing structure for the nozzle when the nozzle is lowered into the cut while oscillating. The unit is powered by a 150kw (200-hp) diesel engine.

2.3 Automation

Currently the standard equipment is hydraulically operated and controlled by a 24vdc PLC (programmable logic controller). All sensors and coils are also 24vdc. Prior to initiating auto cycle the operator enters the alarm settings and cut parameters i.e. length of cut, depth of cut, oscillation speed, rise and fall speed, etc. Once operating in automatic, the wand and nozzle assembly travels up and down the cut (y-axis) to a maximum of 6.1m(20 feet). When the wand and nozzle assembly reaches the top or bottom of the cut the PLC normally outputs a signal to move one index value horizontally (x-axis). This action is repeated until an alarm shuts the system down, an obstruction in the cut is encountered, or the desired cut length is reached.

In the case of an obstruction, the PLC will initiate the "hard spot" cycle (Figure # 1). The hard spot cycle marks and remembers the current x (x1) and y (y1)-axis position. The wand and nozzle assembly rises or falls (opposite of the direction traveled prior to the obstruction) and, backs up a distance x2 (usually 5 cm(2")) previously entered by the operator. Once x3 (x3=x1-x2) is reached, the PLC initiates a short auto cycle, 30cm up and 30cm down (12"up 12"down) on either side of y1 where the obstruction was encountered. Indexing at top and bottom will occur as in normal auto cycle (the index value within "hard spot" x4 can be different than normal auto cycle). When the index value reaches x5 (x5=x1-x4) the PLC continues the normal auto cycle prior to encountering the hard spot.

The use of a 345Mpa (50,000psi) pressure transducer enables an operator to let the machine operate unmanned regularly. The Ned-Jet 2000 operates unmanned for extended periods of time. It will shut down safely if pressure moves above or below limits set by the operator. This will increase production and reduce operating cost by reducing both depreciation and labor cost per square meter.

2.4 Set-up

Careful consideration was given to equipment set-up. Ease of use is critical to productivity, safety, and operator fatigue. (Photo #1 and Figure 2)

- The Ned-Jet mast is pivoted to the horizontal position ready for transport between quarries (#1 noted on photo #1). This feature is very important for operations with more than one quarry. If the quarry managers have the flexibility to relocate the equipment with ease they will. The result is better utilization, lower depreciation cost, and a greater dependence on our equipment.
- Note that each corner of the machine has a mechanical screw driven by independent hydraulic motors (#2).
- The rail (#3) extends past the legs on the platform so the machine and operator are further from the edge of the quarry.
- The high-pressure hose is contained in a heavy cable carrier (#4) that controls the hose bending-radius. In the event of a hose failure the hose is safely contained inside the hose carrier.
- The lift cylinder (#5) allows the operator to adjust for irregular quarry terrain (Photo #1).
- The zoom beam (#6) simplifies set-up by allowing up to 25cm (10") of adjustment if the loader improperly aligns the machine with the cut.

3. QUARRYING

Photo #2 illustrates a traditional bench quarry where 4 Ned-Jet 2000s are in use. Several levels or benches are required to efficiently utilize the equipment and maximize productivity. There are 3 types of cuts on each bench, primary cuts, secondary cuts, and block trimming. Traditionally the most expensive and most difficult cuts are the primary cuts.

A primary cut or slot is the first cut a quarrier makes to help free a piece of granite from the earth. Quarriers prefer a wide slot (5 to 7.5 cm (2 to 3") at the primary step. This 5 cm (2") space gives them room to use other methods i.e. blasting and splitting without damaging the material that will be quarried next. The typical primary block size is 6.1 m (20') high, 6.1m (20') deep, and 25 m (80') long (Figure #3).

Secondary cuts are made in the primary block along the 25 m (80') length. Three or four secondary cuts are made along the length dependent on the desired final block width. The primary block is now cut into 4 long pieces. These pieces are tipped over so that the (5') wide dimension is now the height of the block. At this point, trimming is the most common method of breaking these pieces into final block size (Figure #3).

Dimension stone granite quarries for the most part are open pit operations. Very few are under ground.

3.1 Many methods are used (Table #1)

Drilling -	A series of holes spaced apart in a line used to split with wedges in one plane or to be used in conjunction with controlled blasting in one, two or three planes.
Slot drilling-	A series of 63 to 116 mm (2.5" to 4") holes are overlapped to create a slot about 5 cm (2") wide.
Blasting-	Minimum strength, slow acting, explosive used for propagating cracks between a series of holes on a given plane used in conjunction with drilling.
Burning-	Applying heat to the stone expands and contracts the stone causing the natural grain boundaries to break and flake off, resulting in a slot 7.5-13 cm (3-5") wide.
Wire sawing-	Diamond wire, silicon carbide wire saw and diamond belt saw.
Splitting-	Inducing a directional force using wedges or plugs and feathers. The wedges are placed in a line of pre-drilled holes resulting in predictable crack propagation if applied slowly.

Historically, in the pictured quarry photo (#2), burners created most of the primary cuts prior to the Ned-Jet 2000. Burning is a slow process, and the heat from the burners causes damage to the stone. The dust created by burners can result in respiratory problems eventually leading to silicosis.

The method of drilling and blasting is used to create the secondary cuts. Drilling and blasting a line is relatively fast but some waste is naturally encountered. Poor drilling, and improper explosive loading can result in extensive damage by sending cracks into both the material that is being freed as well as the next bench to be taken. Some materials lend themselves well to blasting and others do not.

Block trimming is accomplished by drilling and blasting or drilling and splitting with wedges.

4. FIELD RESULTS

When Ned-Jet began in 1991, Ned-Jet cut 760 square meters (8,300 square feet) of slot in a handful of quarries. In 1996, with 6 units in operation Ned-Jet cut over 10,300 square meters (112,000 square feet). The results vary greatly from quarry to quarry as well as within each quarry. Refer to (Table #2) for some listed results.

The data in Table 2 is the result of a contracted rental program with labor cost applied 100% to the task of water jet cutting. If the equipment is owned by a quarrier, the quarrier can be more efficient because the labor can perform other tasks while the machine is cutting slots automatically.

The operating cost of the Ned-Jet 2000 will go up if the production rate goes down because the cost remains fairly constant on an hourly basis. The reason for varying production rates within one quarry can be a result of pressure within the formation or a random occurrence of a different material within the deposit.

In comparison, the Ned-Jet 2000 consistently cuts 30% faster than the burner in hard materials even when pressure exists.

4.1 Various types of slots.

4.1.1 Starting a slot from the face of a quarry bench

The most common slots are cut vertically and start from an open face in a quarry. The Ned-Jet 2000 is positioned near the edge of a quarry bench. The rail extends over the edge of the bench giving the wand enough clearance to begin cutting on the face of the bench. Temporary railings are installed and the machine is anchored. A dry pass of the wand and nozzle assembly is made and the index start position (x-axis) is brought within 1.3 cm (½") of the bench face. Bottom and top software limits are set defining the bottom and top of the slot. Until the wand cuts enough to actually enter the cut, the wand will fluctuate more than normal. Once the wand is inside the slot, the sides of the slot help to control the fluctuation.

4.1.2 Starting from a drilled hole

In one case a hole, 4.6 m (15') deep and 20 m (8") in diameter was drilled in the middle of a granite formation. From this hole the Ned-Jet 2000 cut over 280 m^2 (3000 square feet) averaging 1.4 m^2 (15 square feet) per hour. A grid of slots were cut to a depth of 4.3 m (14'). The grid was sized for standard gang saw block size 1.5 m x 2.9 m (5' x 10'). All 280 m^2 (3000 square feet) was cut with the nozzle submerged in water. Underwater cutting offers two advantages worth noting. First, the noise level is nearly eliminated. Second, the erosion of parts in close proximity of the nozzle is dramatically reduced, thus reducing consumable cost.

To turn corners the cut is first widened by turning off the index travel (x-axis). The machine will continue cutting at the proposed corner for 10 to 20 minutes. If needed, the hydraulic zoom cylinder is actuated to move the wand toward the 90 degree turn and/or the nozzle is gradually turned toward the proposed slot. Once this section of the cut is large enough for the wand to fit, the machine is repositioned (turned 90 degrees).

In long slots and slots that start from a hole the cutting fines can settle at the bottom of the slot directly under the nozzle. The water jet force itself is not sufficient to push these fines out of the way. We found the most practical way to minimize this problem, particularly when cutting from a hole, was to keep the cutting fines suspended in the water. This was accomplished by supplying air pressure to the water at the deepest part (y-axis) of the cut within .9 m (3 ') of the current x position. For this to work well there must be sufficient water in the slot otherwise the concentration of cutting fines is too high and particle suspension is difficult and impractical.

5. COST/EVALUATION

The water-jet-cutting cost/square meter is in line with alternate methods (Table 2). To consider the overall effect of waterjet slotting on the cost per cubic meter of saleable stone, we must take a closer look at the cost /cubic meter produced not cost/square meter of slot cut. A typical US granite quarry of building or monument grade material will waste 90 to 70 % of the material that is quarried. Some of the waste is a result of natural cracks and inconsistencies in the material itself. The rest of the waste is related to the quarring method and the block shape and size customers can use.

5.1 Evaluation of waste

In one case study, after 3 years with water jet in use recovery has more than doubled. In the beginning one Ned-Jet 2000 was put to use. The following year one more machine was added. Currently this customer is using 2 machines in one quarry. The equipment is utilized for ½ year at one location before relocating to another quarry operation for another ½ year. The cost to operate these machines including labor, fuel, depreciation, and consumables is:

$70.82*2602 m^2/half year = $184273.5**

** This is not an added cost because it replaces current methods at a similar cost. Quarry spending over a given period remained relatively constant.

@ 9% recovery the quarry's income was:
$635.58/^{M3}*1416 ^{M3}/year produced = $900,000

@ 22% recovery the quarry's income:
$635.58/ ^{M3}*2265.6 ^{M3}/year produced = $1,440,000

The difference in income between 9% and 22% recovery is:
$1,440,000-$900,000 = $540,000

It is debatable whether or not to credit all of the increase in recovery to the use of water jet but as additional water jet equipment was added the net recovery improved from 9% to 22% and increased production followed.

5.2 Capital Justification

Crediting all or even a portion of this increase in income to the Ned Jet 2000 justifies the capital investment required. It is evident in this case that in ½ year the quarry can nearly pay off the capital cost of the equipment. It is important to note that these results did not happen over night. It can take years to quarry the damaged material from a formation depending on the extent of the damage.

Not only is the operating cost competitive with current methods and the increase in recovery a worthwhile discovery, there are other benefits worth mentioning. The waste generated in a quarry requires removal and thus additional hauling equipment. Generation of waste is a sign of difficult quarrying. For example, if a burner is cutting very slow because a natural crack is difficult to cut through, the excessive heat generated along that crack will generate heat cracks .3 to 6 meters long. In this example, the quarrier will suffer both recovery and burner productivity.

6. SAFETY

The water jet does not create any air-born dust that could contribute to silicosis. Silicosis is a disease that is caused by inhalation of silica. Silica is a liability to employers and a serious hazard to employees. If exposure is sufficient, dust created by drilling equipment and burners will encourage this disease and could lead to death. The waterjet also helps to reduce the noise level. The field measured "Noise Dose" is 90 to 107 dba depending on the depth of cut. When cutting from a hole the nozzle noise is completely muffled once the hole fills with water. Noise and dust levels are two MSHA health concerns that are regularly monitored. Comparable equipment (slot drills & burners) operates between 114 and 126 dba.

Other concerns are the hazards of everyday quarrying; steep rock faces, blasting safety, large mobile equipment mixed with on foot traffic, and operator fatigue can all lead to accidents. Ned-Jet 2000 reduces the exposure to these everyday quarry hazards with the help of automation by removing the man from the quarry. Obviously some time for maintenance is required i.e. replacing nozzles, repairing pump packing, and equipment set up. The Ned-Jet 2000's unmanned mode can be set to operate unmanned until an alarm condition occurs or for a period of time entered by the operator.

7. SUMMARY

The introduction of the Ned-Jet 2000 slot cutting system into hard granite quarries is impacting the industry through increased cutting rates, successful application of automation, and improved operating cost under safer working conditions. Operationally the Ned-Jet 2000 cuts slots 30% faster than comparable equipment. Automation efficiently adjusts to many of the material uncertainties or hard spots that are encountered within the formation. Sensing these hard areas and automatically cutting through them enables unmanned operation of this equipment for extended periods of time. Operating cost of the Ned-Jet 2000 is very competitive with current methods-especially in very hard granites. Economically, one of the most important benefits is the reduction of waste. In one case quarry spending remained constant over a given period. Net recovery dramatically increased over the same period resulting in 60% more saleable stone. The Ned-Jet 2000 is one of very few automated tools used in quarries. Unmanned operation of this equipment has been successfully implemented for extended periods of time. Less employee exposure to quarry hazards is an important safety benefit to the unmanned operation. Dust created from conventional slotting method is eliminated with the Ned-Jet 2000. Noise also is much lower than comparable equipment and can be nearly eliminated if cutting underwater.

8. REFERENCES

1. MSHA- Tech Support, Lloyd, Tom, "Summary of Noise Levels for Quarry Equipment" (8/13/1992).

2. Mayo Clinic Health Disc 2.0 Copyright © 1995 IVI Publishing Inc.

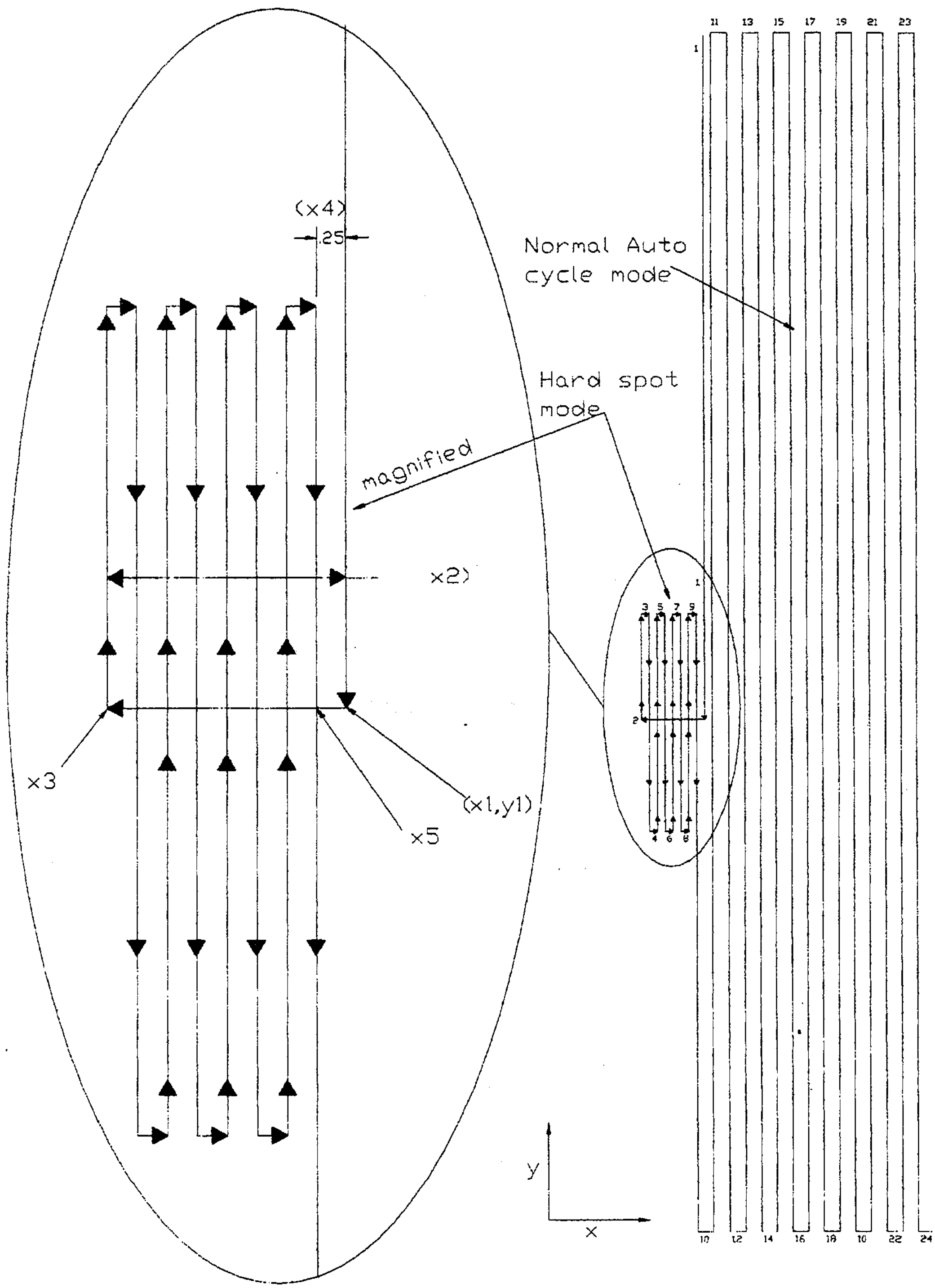

Figure #1 — Hard Spot Cycle

This figure illustrates the nozzle path when an obstruction in the cut is encountered.

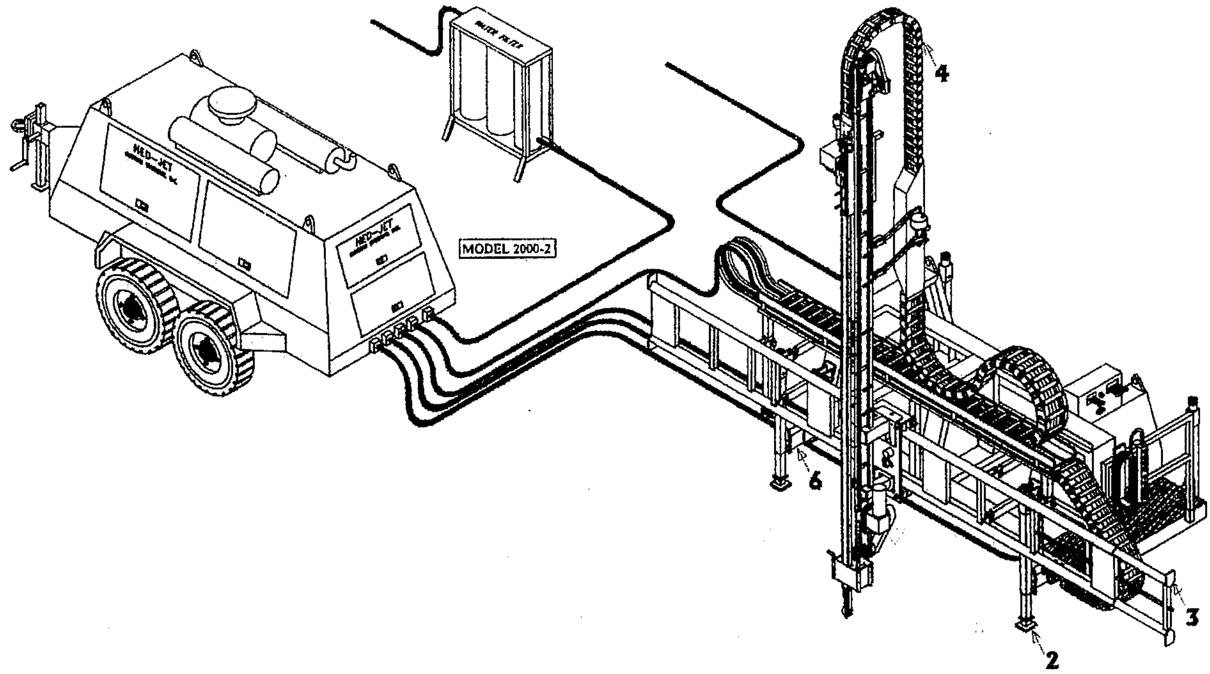

Figure #2 — Equipment Setup

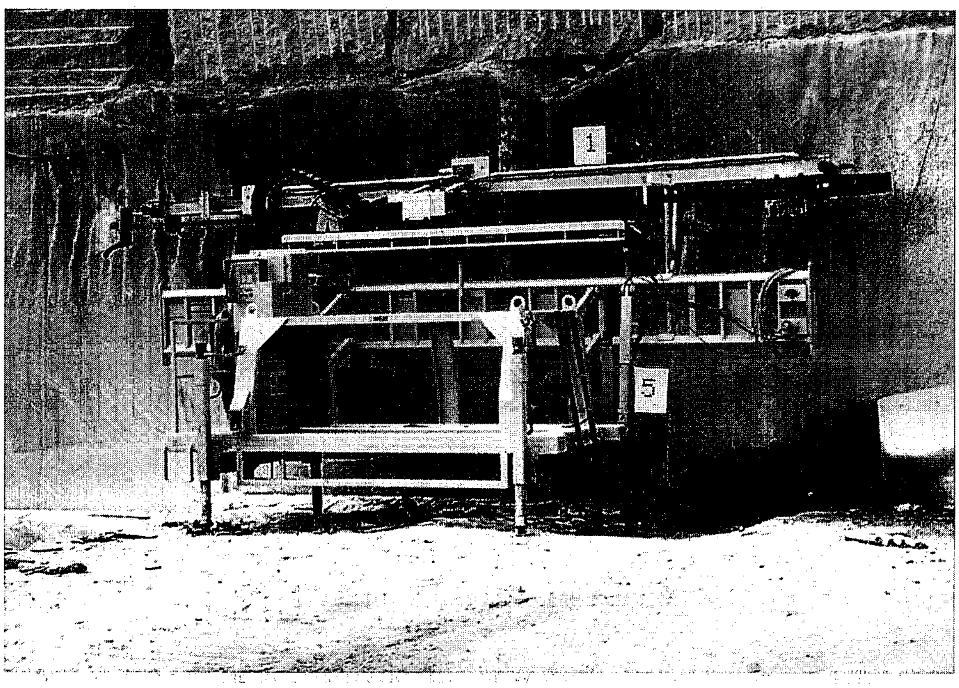

Photo #1 — Equipment Setup

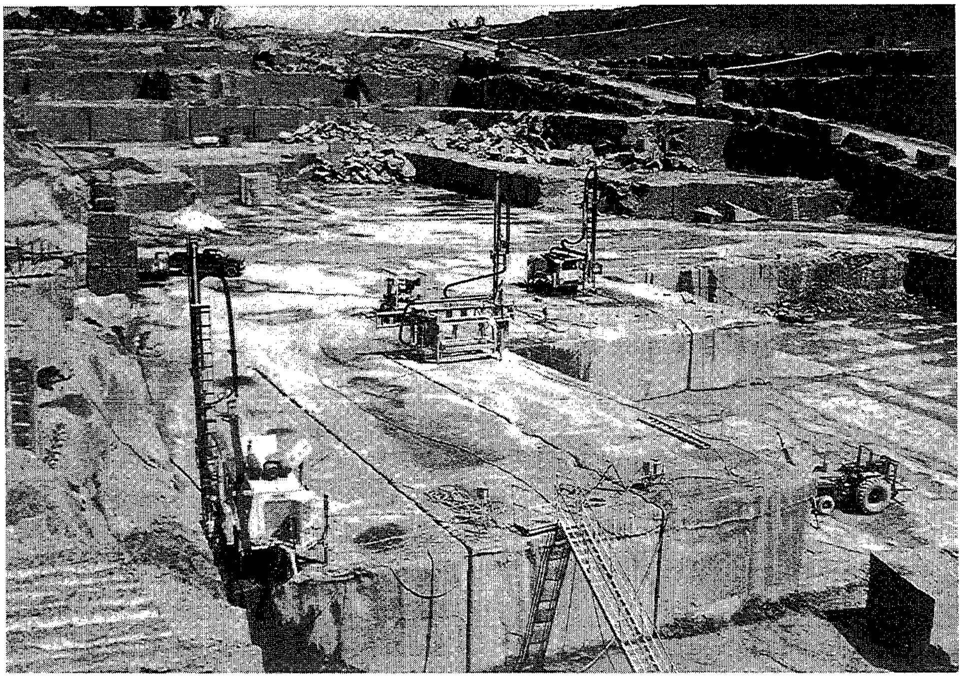

Photo #2 — Bench Gantry

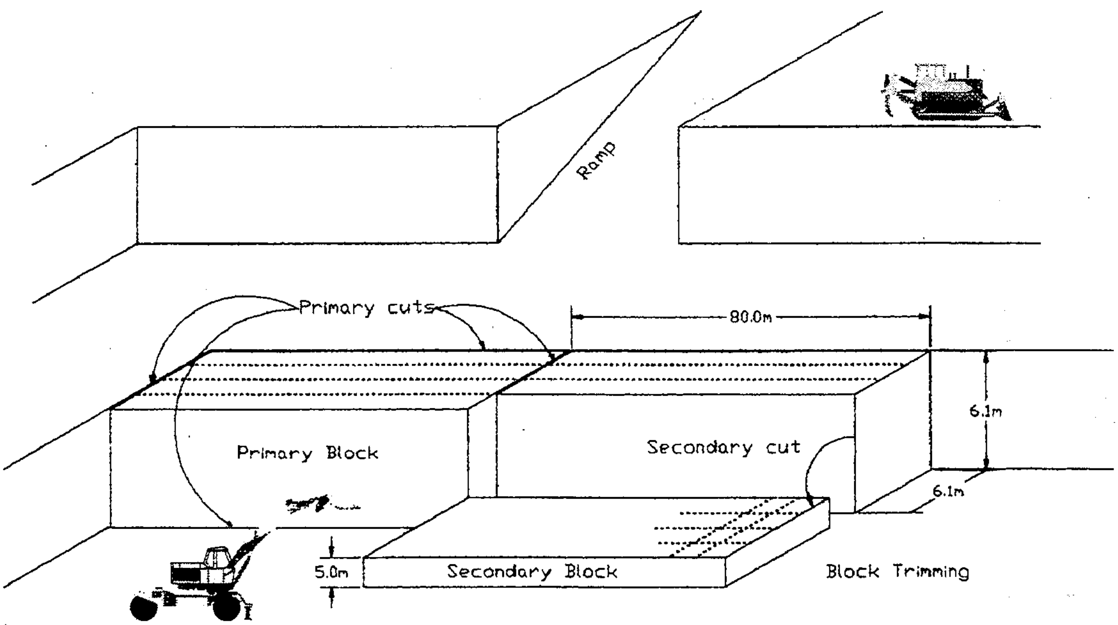

Figure # 3 — Typical Primary Block Size

Table 1 — Comparison

	Pros	Cons
Water jet	Automatic, reduced noise level, no damage to stone. Increase in recovery, substantial increase in production.	Requires a substantial capital investment.
Slot drilling	Does not damage stone, unless webs remain from poor drilling.	Dusty, noisy, physical, difficult to operate.
Drilling	Quick, versatile, norm.	Dusty, noisy, physical.
Blasting	Fast.	Dangerous, damaging, noisy.
Burning	Small capital outlay.	Regulated against. Dusty, damaging to stone. Low production rate
Splitting	No damage.	Slow process, limited depths.
Wire sawing	Fairly fast, quiet.	Expensive in hard granites, small 1.3cm (1/2") wide cut. Takes a long time to set-up.

Table 2 — Field Results

Customer	Average BURNER production rate/hour	Burner $ / m^2	Average Water Jet production rate/hour	Labor $/ m^2	Depreciation $ / m^2	**Consumable $ / sqft	Total $ / m^2	Material description
Quarry #1	.93 m^2/hr	$73.62	1.30 m^2/hr	$10.00*	$26.37	$35.52	$70.82	Dark red–coarse grain
Quarry #2	.84 m^2/hr	$79.54	1.05 m^2/hr	$27.02	$32.72	$33.90	$94.28	Gray – fine grain
Quarry #3	1.02 m^2/hr	$83.63	1.53 m^2/hr	$13.13*	$22.39	$33.15	$68.67	Beige– very coarse grain
Quarry #4	1.16 m^2/hr	$73.83	1.75 m^2/hr	$10.11*	$19.59	$30.67	$49.62	Pink – very coarse grain

(Depreciation 7 years, labor 20$/hr, labor *two machines one operator 20$/hour, and fuel @$.73/gallon. **excludes water)

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APPLICATION OF HIGH PRESSURE JET GROUTING IN THE FIRST STAGE OF THREE GORGES PROJECT

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ABSTRACT

This paper presents the construction experience of adopting 3-pipes & 4-pipes method of high pressure jet grouting to build the anti-seepage walls in the first stage of Three Gorges Project. Some new approaches have been made. Such as to perform the high pressure jet grouting within the strong or weak weathered rock stratum; to build the anti-seepage structure by overlapping the high pressure jet grouted wall & plastic concrete; to connect the high pressure jet grouted wall with the curtain grouting etc.

Organized and Sponsored by the Waterjet Technology Association.

INTRODUCTION

The world-famous Three Gorges Project, located in theXiling Gorge & within 37Km downstream to the completed Gezhouba Project, is the largest water conservancy project in the world. It comprises water-retain dam,spillway,power house & navigation structures etc. and aims at flood control as well as giving consideration to the power generation & navigation. There'll be instaslled 26 sets of units with total capacity of 18200 Mw & annual output of 8.47 billion Kwh. It's comprehensive benefits as flood control & power generating etc will be gigantic.

Three Gorges Project construction is divided into 3 stages & will last for 17 years including the preparation period. The main items to be constructed in the first stage at left bank include the excavation of temporary & permanent shiplocks,ship-lift & power house for No.1~6 units, concrete placing for temporary shiplocks & ship-lift. While the main items to be constructed in the first stage at right bank consist of the construction of the first stage cofferdam & diversion open channels, concrete placing for longitudinal cofferdam, construction of Maopingxi discharge structures as well as the backfilling of Maopingxi protective dam etc.

The first stage earth & rock cofferdam at right bank is being constructed for the excavation of diversion open channels, construction of longitudinal concrete cofferdam & the foundation excavation of third-stage upstream roller compacted concrete cofferdam. With 3 years service life of the first stage cofferdam, it consists of upstream horizontal & longitudinal sections, downstream horizontal & it's extension sections. The axis length of cofferdam is m with upstream cofferdam crest EL 80.5m & downstream cofferdam crest EL 79.0m. The embankment of cofferdam must be anti-seepage structure as designed.

The partition dyke of permanent shiplock downstream pilot channel at left bank, located at the left side of main channel of Yangtze River & 150~250m away to the bank,is the permanent structure to separate the main channel from downstream pilot channel. Among which the axis length is 360m,crest EL is 70m,top average width is 36m & bottom width is 60~130m. According to the design requirements, the partition of dyke & cofferdam must carry out the anti-seepage treatment to ensure the safety of excavation works at downstream pilot channel & the seepage control of partition dyke.

In the first stage cofferdam of right bank, except the part from upper horizontal section to down horizontal section will be plastic material anti-seepage wall. The lower part of anti-seepaged wall of sections from upper horizontal point 3 to longitudinal section point 5 and down horizontal extension section (station 2+574.96~2+646.96m) will build the high pressure jet grouted wall for anti-seepage.

At the partition dyke of left bank, except the section of station 0+ 560~0+780, 0+880~1+030, 1+995~2+285 & 2+905~3+300m will be plastic anti-seepage walls, the rest section & cofferdam will build the high pressure jet grouted wall for anti-seepage.

1. Engineering Geological Condition

It's known from the drilling, there're 3 layers of strata from top to bottom. It's artifical recharge,fine-grained sand or accumulation of slope & flood, bedrock.

1.1 The Artifical Recharge

The geological components in partition dyke of left bank are yellow-orange coloured & medium-grained weathered sand mingling with blocks of granite stone concentrated at some place. The average thickness is 12~20m. In the first stage cofferdam of right bank is mixed recharge with mainly composition of weathered sand mingling with rubbles & broken bricks 2.5~5.0m thick.

1.2 Fine-Grained Sand or Accumulation of Slope & Flood

The geological compositions of partition dyke are grey & grey-orange coloured and fine-grained sand with large density,saturated & easy liquidized prior to the construction of GJ cofferdam & partition dyke.Cleaning works had been done to the solt where the sand thickness were 1~4m & average thickness of other places were 4m. On the bottom of some sections, there're 0~1.0m thick aggregates. S49~S55 section of cofferdam, in the first stage, was accumulated layer of mountain slope & flood. It's mixed with fine-grained sand & 0.5~ 27m thick.

1.3 Bedrock

The bedrock was glimmer plagio granite with light grey or grey-white colours & medium-grained structure. Thickness of the weathered layer in the lower horizontal extension section was large & generally 1~6m thick in partition dyke section mingling with spherical rocks. In strong weathered zone, large angle of inclination fissure grows & have heavy perviousness causing the grouts heavy loss during the drilling process . While the weak weathered zone, the rock relativily integrated & strong.

2. The Anti-seepage Structure

Different wall structures of high pressure jet grouting had been adopted according to the requirements of engineering geological condition & feature of each section. Detail see sketch 1.

2.1 The part between upper horizontal section 3 & longitudinal section 5

The construction of this part proceeded very slowly & difficultly due to the large blocks of eluvial weathered spherical rocks on the cofferdam foundation. Also it caused difficult to keep the quality of finishing drilling holes & left some hidden trouble to the anti-seepage structures. So, the lower part of plastic anti-seepage wall must be overlapped with the high pressure jet grouted wall with lapping length 3~4m .

2.2 Lower Horizontal Extension Section

The structure of swing jet grouted wall had been adopted.

2.3 Partition Dyke & construction Cofferdam

The GJ cofferdam located on the outerside of partition dyke & faced to the shoking of water. It's excavation EL is low (EL 38~46m) & the cofferdam retained large water. The foundation rock were fracture, fissure growing & heavy pervious. In order to ensure the construction safety & have steady seepage after been put into operation, the anti-seepage wall was designed to perform the high pressure jet grouting by single raw (GH & GJ Section) & double raws (HI Section).The lower part of high pressure jet grouted wall was overlapped with grouted curtain as the compensated treatment to the water seepage of bedrock. The anti-seepage of rest section of partition dyke, CD & EF cofferdam had applied the swing jet grouted walls.

3. Major Technical Requirements

3.1 High Pressure Jet Grouting

The single raw holes to be rotary & swing jet grouted shall be arranged the axis of anti-seepage walls. The arragement for double raws holes of GJ cofferdam & overlap of wall & jet grouting of first stage cofferdam at right bank see sketch 1. The main technical requirements were:

1). Ditch of holes: The space between holes 0.8m for rotary jet grouting of single raw, 1.2m for double raws, 1.4m for swing jet grouting of partition dyke & cofferdam, 1.5m for swing jet grouting of first stage cofferdam as well as 0.8m(upperstream) & 1.0m (down-stream) for the outerlap section.

2). Depth of holes: The depth of holes in partition dyke was the length from the crest to the top surface of weak weathered zone plus one meter more downward. In the first stage cofferdam was the length from crest to 3~5m inside the strong weathered rockbed.

3). Control of Hole's Strike & Aperture

All holes must be vertical & less than 1% deflection. The aperture deviation must be within 10cm.

3.2 Curtain Grouting Under the High Pressure Jet Grouted Wall

Grouting holes were arranged on the overlap area for single raw rotary jet grouted wall & along the river side for double raws(see sketch 2). The major technical requirements were:

1). Control of hole strike & aperture was the same as that for high pressure jet grouting.

2). Depth of hole: 10~12m downword from the bottom of high pressure jet grouted wall.

3). Grouting pressure: Pressure for the first section to overlap the high pressure jet grouted wall by 2m was 0.5Mpa; for 2nd & 3rd section were 0.9Mpa & 1.3~1.5Mpa separately.

4). Condition for stopping: Under the designed pressure, the rate of absorption is less than 0.4 L/min & to continue grouting for 60 min. It could be ended.

4. Major Specifiction for Quality

4.1 High Pressure Jet Grouting

1). Wall thickness: The thickness of swing jet grouted wall shall be more than 20cm. While the rotary jetting of single raw & double raws shall be more than 60cm & 100cm separately.

2). Pressure resistance: R28 $\geqslant$ 5Mpa.

3). Seepage coefficient: K $\leqslant$ i*10 cm/s.

4). Allowable percolation-gradient: J>50

4.2 Curtain Grouting Under the High Pressure Jet Grouted Wall.

The standards for inspection qualification is that the water percolation rate q $\leqslant$ 5Lu.

5. Construction

5.1 Bore holes & Jet grouting devices

All holes were drilled by geological boring machines (type XY-Z,JU-100,XU-300,XY-2PC & ZT-100 etc.) and adopting the extension section of lower horizontal had applied the jet grouting machine type BZK-3A 4-pipes, two-way, axisymmetric & double nozzles to perform the high pressure jet grouting. Two sets of high pressure pumps had been set to control the nozzles. Water

& cement grout fluid consumption was one time larger than that for general grouting machine. It enlarged the punching shear & mixing ability of high pressure water jetting to the stratum & made great advantages to the wall thickness, strength & impervious function as well as raised the reliability of wall-connection. The rest section had applied the jet grouting machines (type GP-II ,SGP30-5) by adopting 3-pipes, 2 nozzles & in 2 stages processes.

5.2 Material Used for Jetting

The material to be jet grouted was Portland cement 425# & it's grains were that the surplus through the square screen opening (0.08mm) was less than 5%. The specific ratio of cement grout fluid was 1.6~1.7 for injection & 1.3~1.4 for return.

5.3 Technical Specifiction for Construction

The following parameters have been decided through many tests & inspections after being excavated:

1). 4-pipes jet grouting method: water pressure 35~40Mpa, discharge: 130~150L/min, grouting pressure: 0.4~0.6Mpa, cement grout quantity 150L/min, air pressure: 0.5~0.7Mpa, ventilation: 3m /min & speed-up: 15~20cm/min, rotary speed: 5~8r/min.

2). 3-pipes jet grouting method: water pressure 25~38Mpa, discharge: 80L/min, cement grout fluid consume 80L/min,speed-up: 5~10cm/min & the other were same as 4-pipes method.

3). Swing jet grouting: speed: 7~8r/min, swing angle: 25~30 °

5.4 Vegetable Slurry drilling Method

In order to avoid the accident of cave-in of bore walls, burying & clutching of drills, the low solid phase of vegetable sulrrying had been applied when drilling in the fine-grained layers to strengthen the cling property, reduce the water discharge, improve cement grout property and raise the capacity of wall protection, cave-in-proof & boring.

5.5 Treatment of High Jet Grouting without Cement Grout Return

In the places of block stone or spherical mass & in the section of fissure grouws, if no cement grout return as perform the high pressure jet grouting, the steps of static jet grouting & backfilling with sand had been applied, till the cement grout returned & to raise the grouting machine.

5.6 Curtain Grouting Under the High Pressure Jet Grouted Wall

The general grouting procedure had been used for construction starting from 2m above the bottom of high pressure jet grouted wall to strengthen the impervious effect of the overlap part.

6. Quality Inspection & Results Analysis

6.1 Excavation to Inspection

It shows, after the inspection to the column cap & excavated specimen of walls, the contour of forworked wall was very clear & swing angle was obvious. Walls were more than 20cm with maxi. reaching 50cm. The formwork's diameter of swing jet grouting was about 1m, but it was a little bit large for bores of process I. Some single formwork formed oval-shape. All overlaps between high pressure jet grouted walls & plastic walls, adhesived with around rock were perfect. The formed structures were consolidated rocks in shalow artifical layer and have homogeneous texture in the weathered sand. Walls gummed compactly & especially the formworked walls had high strength comparing with the swing jet grouted walls. Wall were integrately without occuring of omit-jetting, bed-separation & fault-forms. But the cement grout filling was not enough in partial places where the block stones concentrated.

6.2 Borehole Cores Inspection & Specimen Test

22 inspection bores were arranged in GJ cofferdam while the oillets were located at the joints of rotary jet grouting holes for single raw & the centre for double raws. Most of the cores were column-shape with gumming perfectly, cement grout jetting compactly & connecting firmly between the formworks. But in the overlap section of double-raw walls & fractured zone, cores were block shape or single-grained structure with cement grout jetting badly. In the upper of strong weathered bedrock,some filled cement grout could be seen in the fissure while no cement grout in the lower & the weak weathered bedrock. All fissures were the original form.

Specimen had been taken from partition dyke coffers of CD & EF cofferdam and 1st stage lower horizontal extension section & coffers of cofferdam. Physical mechanical test had been made & all indicatrix compiled with the design requirements. Details see Table A.

6.3 Water/Pressure Injection Test

Water/pressure injection test had been performed to the specimen of coffer & high pressure jet grouted walls to inspect the perviousness function of anti-seepage walls.

Coffers had been arranged as follows: 4 for parttion dyke, 3 for CD cofferdam & 1 for lower horizontal extension section. Water/pressure injection test had been carried out in the coffers. The results conformed with the design requirements with perviousness factor $K \leqslant i*10$ cm/s.

Water/pressure injection test also had been carried out to the inspection bores of wall for 88 parts of which 77 parts' perviousness factor K were less than i*10 cm/s(87.5%). The rests were larger than i*10 cm/s & majorly concentrated on the bedrocks. It indicated that it's feasible to build the high pressure jet grouted walls on the full & strong ability of rockbodies. But due to the limits of cutling ability of high pressure jet grouting it's little improvement of the anti-seepage ability to rocks located under the strong weathered layer & within the weak weathered layer. In the double-raw rotary jetting walls of GJ cofferdam, the gumming on the joint part were discompactly & the perviousness factor were generally K= i*10 cm/s due to the hole pitches were larger & the oval-shape formwork diameter.

6.4 Auto-electric Testing Meters

Prior to starting of curtain grouting under the high pressure jet grouted wall, the meters (type SX-II & TZT-I) had been applied to inspect the hidden faults of dams through grouting holes of GJ cofferdam. The results, proved by the drilling was that the test curve of all section had no abnormal condition except the water leakage at the joint of wall bottom hole HW25 & bedrock. It shows the high pressure jet grouting has no fracture or joints.

6.5 Results Analysis On the Curtain Grouting

The grouted distance for GJ cofferdam under the high pressure jet grouted walls were 2609.01m with total weight of slurry was 210.93t of which the unit injection of 79.27Kg/m, maxi.injection of 1.8t/m & mini.injection of 0.13Kg/m. prior to the grouting, at the bottom of high pressure jet grouted wall the arverage rate of permeable of contact section was 50Lu & section of finishing drilling bore was 5.5Lu . It indicated that the rate of permeable & cement grout absorption was uneven due to the affectin of structure of rockmass structure & high angle inclination fissure growing. After grouting completed & inspection, the average permeable rate of rockmass was less than 5Lu & conformal with design requirements. Table B was the statistic of grouting for the high pressure jet grouted wall & bedrock section.

It show the wall structure were compactable, a little permeability & small unit absorption. No fixed regulars between the sequence .The consumption of cement njection is larger for the bedrocks under the walls decreasing between the sequence was Obviously.

In the construction of curtain grouting & inspection bores of wall, precautions of deepen & enlarge to the density of drilling & grouting had been applied to the section which had big water consumption. Steps of adding separated bores of swing high pressure jet grouting also been applied as compensation of curtain grouting under the wall. Regrouting works to each bore had been performed to increase the impemeability of high pressure jet grouted walls & fundation.

7. Conclusion

7.1 During the 1st stage construction of Three Gorges Project, to build the anti-seepage structures of temparay & permanent was very successful, proved by tests, by adopting swing grouting,rotary grouting of single,double-raw of high pressure jet grouting, overlapping the high pressure jet grouted wall & plastic anti-seepage wall, connecting the high pressure jet grouted wall & curtain grouting etc. The thickness & strength of walls as well as the impermeability conformed with the requirements of desin & construction.

7.2 To build the anti-seepage wall at the top of full & strong weathered rocks could obtain the satisfied imperviousness effect by high pressure jet grouting technology. But it difficult to build the anti-seepage structures at the bottom & within the weak weathered zone due to the hardness of rocks & the limits of high pressure jet grouting.

7.3 To perform the curtain grouting under the high pressure jet grouted walls was a new approach for forming the anti-seepage system to improve the leakage condition of foundation.

7.4 In the section & places where the churn drills couldn't be used, to overlap the concrete anti-seepage walls by high pressure jet grouting to form the new anti-seepage wall. This method could be used for reference.

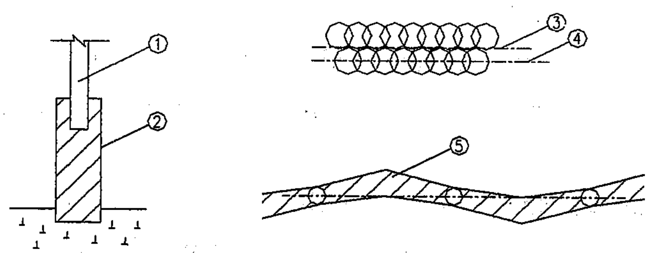
7.5 Applying the 4-pipes method of high pressure jet grouting would consume more larger quantities of water & cement grout, comparing with the 3-pipes method. But it could make great advantage to enlarge the wall thickness, increase the wall's strength improve the impermeability, raise the lifting speed & accelerate the construction speed.

Table 1: Mechanical Test on the Specimen of High pressure Jet Grouted Wall.

location	specimen N0	compressive strength(Mpa)	breaking strength(Mpa)	impermeability test	unit weight (g/cm3)
partition dyke	W5~8	19			2.08
CD cofferdam	W9~11	20			2.04
EF cofferdam	W1	17			2.24
1st stage cofferdam		12.7	5.1	below 0.9Mpa	1.60

Table 2: Result Statistic of Grouting for the Walls & Bedrock.

Location	classfication	unit injection (Kg/m)	
		procedure I	procedure II
GH section	wall	1.91	2.50
	bedrock	64.85	22.48
HI section	wall	6.98	15.26
	bedrock	138.18	52.07
IJ section	wall	3.57	1.39
	bedrock	135.68	46.31



Sketch 1

Sketch 1:

The Anti-seepage wall structure of High Pressure Jet Grouting.

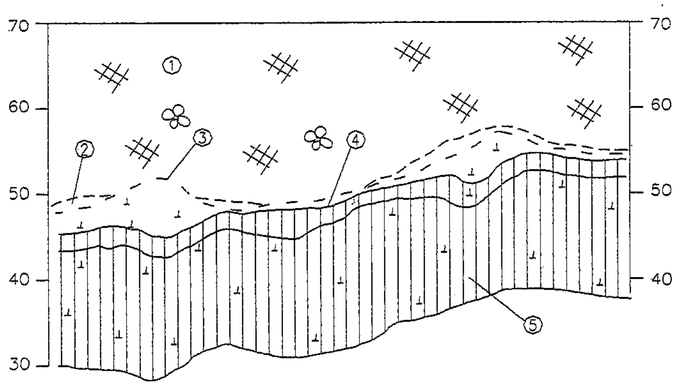
① concrete anti-seepage wall;

② high pressure jet grouted wall;

③ axis of anti-seepage wall;

④ axis of grouted curtain under the walls;

⑤ swing jet grouted wall;



Sketch 2: Sketch of Curtain Grouting
IJ Section(0+330.6~0+381.8m)

Sketch 2:
The curtain grouting sketch of IJ section(0+330.6~0+381.8m)
① artifical recharge
② fine-grained sand
③ top line of strong weathered zone
④ top line of weak weathered zone
⑤ grouted curtain

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Paper 37

MATHEMATICAL MODELING OF WATERJET CLEANING

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ABSTRACT

The use of stationary waterjet for the removal of coating material from the substrate is investigated analytically and experimentally. In the analysis, the cleaning width as a function of standoff distance, water pressure, and nozzle radius is derived by considering the structure of waterjet and the cleaning mechanism. Also derived are the relations of the optimal cleaning standoff distance and maximum cleaning width to the critical cleaning standoff distance, and how the water pressure and nozzle radius affect this critical standoff distance. These derived analytical relations are verified with experimental results.

Organized and Sponsored by the Waterjet Technology Association.

1. Introduction

Pure waterjets have been used for removal of various coatings or deposits from the substrates as well as cutting of many materials. Waterjet cutting normally involves the penetration of a solid by a continuous jet. Waterjet cleaning, on the other hand, is often achieved by an erosion process involving discrete droplets. Present knowledge on waterjet cleaning has come mainly from experiments (Labus, 1982; Louis and Schikorr, 1982; 1984; Leu, et al., 1994, Geskin, et al., 1995; Meng, et al., 1996). Because of the lack of mathematical models, the present understanding of parameter effects in waterjet cleaning and hence the ability to optimize the cleaning process is quite limited.

The continuous water flow gradually becomes a stream of water droplets after it comes out of an nozzle due to a continuing interaction between the water and its surrounding air. The water droplets impinging on the target coating create impact forces. The mechanism of material removal is highly complex. Adler (1979) reported that material erosion by the droplets consists of four damage modes. These are direct deformation, stress wave propagation, lateral outflow jetting, and hydraulic penetration. One or more damage modes may exist in a particular erosion process. The first two modes are responsible for initiation of cracks. The effect of direct deformation is not obvious if there exist few low velocity impacts. The propagation of stress waves caused by the impact forces is generally responsible for crack initiation in the erosion process, as reported by many researchers (Springer, 1976; Louis and Schikorr, 1982; Ramulu, et al., 1991; Li, et al., 1992; Kang, et al., 1993; Watson, 1993). Lateral outflow jetting and hydraulic penetration cause the extension, enlargement and propagation of existing cracks. In the erosion of coating material, the adhesion between the coating and the substrate may also need to be considered.

Experimental observations have shown that there exists an optimal standoff distance at which the volume of material removal is the greatest (Louis and Schikorr, 1982; Kang, et al., 1993). It has also been shown that the rate of cleaning increases with the standoff distance until the maximum cleaning rate is reached at a certain standoff distance, after that the cleaning rate reduces with increase in the standoff distance (Galecki and Vickers, 1982; Xu and Summers, 1994; Geskin, et al., 1995; Wu and Kim, 1995). The optimal standoff distance is related to the coating and substrate materials and the operating parameters such as nozzle (orifice) size, water pressure, jet travel speed, etc. Although useful knowledge has been generated from the various experimental studies in the past, there exists no theoretical model that is capable of explaining the observed experimental results.

This paper describes an analytical and experimental investigation of waterjet cleaning. At this stage the study is limited to the stationary waterjets. A mathematical equation is developed to express the cleaning width as a function of standoff distance, water pressure, nozzle radius and other system parameters based on the waterjet structure and a material erosion model. In the erosion model, removal of material occurs when the equivalent dynamic stress generated by the water droplet flow exceeds the endurance limit of the coating material under fluctuating stress. The maximum cleaning width is shown to exist at a certain standoff distance which has a certain ratio with the critical cleaning standoff distance. The mathematical relations derived are verified experimentally.

2. Structure of Waterjet

It is generally recognized that there exist three waterjet regions: the initial, main, and final regions, as illustrated in Fig. 1. In the initial region, which is close to the nozzle exit, the instability of the tangential surface separation in the continuous flow stream causes eddies. The eddies bring about an exchange of matter between the water and air. The surrounding air medium is entrained into the water stream and breaks up the continuous water stream into water particles due to an intensive transverse transfer of mass, momentum, heat, and constituents. Inside the jet there is a wedge-like region known as the potential core, which is surrounded by a mixing layer. The velocity inside the core is equal to the jet velocity at the nozzle exit. The waterjet in the initial region is considered to be a continuing flow having very little air inside the jet. At the end of this region, the effect of air dynamics and continuous interaction of the water with the surrounding air medium results in the breakup of the waterjet stream into droplets. This begins the main region. In this region, the mixing of the waterjet stream with air medium continues to the full extent, and the jet stream is disintegrated into droplets continuously due to the entrained air. The smaller the distance to the center line of the waterjet stream, the bigger the water droplet size, and the more concentrated the droplet flow. This results in a gradual expansion of the cross section and reduction in the velocity and pressure of the waterjet. Between the droplet zone and the surrounding air, there is a mist zone consisting of very fine droplets. The droplets at the boundary of the droplet zone and the mist zone can be considered to have zero velocity. The final region is a diffusion region in which the waterjet is totally broken up into small droplets. Detailed discussions on the structure of waterjet in air can be found in (Yanaida and Ohashi, 1978; Yanaida and Ohashi, 1980; Yanaida,1974; Zou, et al., 1985).

From the investigation of Yanaida and Ohashi (1978) and Zou, et al. (1985), the radius of the jet in the droplet zone, R, relates to the distance from the nozzle exit, x, as follows

$$R = Cx \tag{1}$$

where C is the spreading coefficient. Its value was experimentally observed by Yanaida and Ohashi (1978) to be about 0.03 in the main region and increased to about 0.06 in the diffusion region. Although C may be a function of water pressure and nozzle radius, this dependence relationship is recognized to be complex and it is not available from the literature. We will assume C to be independent of water pressure and nozzle radius in the latter part of our mathematical derivation, and will show that despite this simplification, the numerical results from our analytical model agree well with experimental results.

According to Erastov's experiment (Abramovich, 1963), the mass flow rate in a waterjet has the following relationship

$$\frac{\dot{m}}{\dot{m}_m} = (1 - \xi^{1.5})^3 \qquad (2)$$

where $\dot{m}$ is the mass flow rate of water droplets per unit area at some point of consideration in the flow field, $\dot{m}_m$ is the mass flow rate of water droplets per unit area at the center of the same cross section, and ξ is a dimensionless parameter defined by

$$\xi = \frac{r}{R} \qquad (3)$$

where r is the distance of the point of consideration from the jet center line (see Fig. 1). $\dot{m}$ is equal to ρU multiplied by the volumetric ratio of water in the water-air mixture, where ρ is the water density and U is the flow speed.

During the waterjet spreading, the total mass flow rate in each cross section is equal to the total mass flow rate at the exit of the nozzle. Therefore, the following relation holds:

$$\dot{m}_0 \pi r_0^2 = 2\pi \int_0^R \dot{m} r dr = 2\pi \dot{m}_m \int_0^R \frac{\dot{m}}{\dot{m}_m} r dr \qquad (4)$$

where $\dot{m}_0$ is the mass flow rate per unit area at the nozzle exit and r_0 is the radius of the nozzle.

Substituting Eqs. (2) and (3) into Eq. (4) we obtain

$$\dot{m}_m = 5.62 \dot{m}_0 (\frac{r_0^2}{R^2}) \qquad (5)$$

3. Analysis of Cleaning with Stationary Waterjets

Cleaning by stationary waterjets involves in coating material removal by a waterjet at a fixed nozzle position and orientation (without traveling). Experimental observations have shown that the cleaning width is not as wide as the jet width, and an optimal cleaning width exists in the main waterjet region. The variation of cleaning width as a function of standoff distance is governed by two factors. One is the jet structure. As the waterjet propagates with continuing air entrainment, the jet width grows linearly as the standoff distance increases. The other is the impact pressure. The impact pressure generated by water droplets decreases with increase in the standoff distance. There exists a critical standoff distance at which the coating can not be removed at all, due to the impact pressure which has become too small. The distribution of impact pressure has the shape shown in Fig. 1. The impact pressure is the strongest at the center of each jet cross section and decreases to zero at the jet edge. Beside standoff distance the impact pressure is also a function of water pressure and nozzle radius. Due to the jet structure and impact pressure distribution, the maximum cleaning width occurs somewhere between the nozzle exit and the critical cleaning standoff distance. At the critical standoff distance, the jet loses its capability to create an impact pressure high enough to perform any cleaning at all (Meng, et al., 1996).

When a liquid droplet hits a solid surface, the sudden deceleration of the droplet generates an impact pressure which induces a stress wave at the liquid-solid interface. By making some simple assumptions, Springer (1976) showed that when the droplet velocity is perpendicular to the surface of impingement, the stress on the surface is equal to the well-known water hammer pressure $\rho U \psi$, where ρ is the liquid density, U is the droplet velocity, and ψ is the sound speed in liquid. Although the real droplet impact situation differs from his assumptions, this relation provides a good characterization of the average impact stress. For the case of a droplet impinging on the surface of a coating, he also showed that the impact stress on the coating surface is equal to $\rho U \psi$ multiplied by a coefficient which is a function of the droplet size, coating thickness, densities of the liquid, coating and substrate, as well as speeds of sound in the liquid, coating and substrate. The value of this coefficient is 1 when the coating and substrate have the same material.

Based on fatigue theorems established for bending and torsion in solid mechanics, Thiruvengadam (1967) and Springer (1976) investigated the repetitive impacts of multiple liquid droplets on a solid surface. Material removal occurs due to fatigue at a certain number of stress cycles when the equivalent dynamic stress is between the ultimate strength and the endurance limit of the material. Material removal does not occur at all if the equivalent dynamic stress is smaller than the material's endurance limit.

We apply the above general results to coating material removal by water droplets. In stationary waterjet cleaning, the number of stress cycles is theoretically infinite. Since the impact stress is compressive, an appropriate equivalent dynamic stress is the amplitude of the fluctuating stress, which is one half of the impact stress (Shigley, 1977). Coating material is removed when the equivalent dynamic stress is higher than or equal to the endurance limit of the coating material. Mathematically, this translates to

$$\lambda \dot{m} \psi \geq S \tag{6}$$

where S is the endurance limit of the coating material, $\dot{m}$ is the mass flow rate of liquid droplets per unit area as before, and λ is a stress coefficient depending on the droplet size, coating thickness, and properties of the liquid, coating, and substrate material. Note that we have only considered failure of the coating material, and have not considered failure at the coating-substrate interface because of the lack of knowledge on the bonding strength.

3.1 Critical Cleaning Standoff Distance

Critical cleaning standoff distance is the shortest distance from nozzle exit at which the waterjet is unable to remove the coating material. Theoretically, cleaning at the critical cleaning standoff distance happens at a single point (with zero cleaning radius) which is the center of a certain cross section. Thus $\lambda \dot{m}_m \psi = S$ at the critical standoff distance. By the use of Eqs. (1), (5) and (6) together with the relationship $\dot{m}_0 = \rho U_0$, it can be shown that the critical cleaning standoff distance, x_c, relates to the cleaning parameters as follows:

$$\frac{U_0 r_0^2}{C^2 x_c^2} = \frac{S}{5.62\lambda\rho\psi} \tag{7}$$

The waterjet velocity, U_0, at the nozzle exit is related to the water pressure, P, generated by the pump or intensifier as follows:

$$U_0 = k\sqrt{\frac{2P}{\rho}} \tag{8}$$

where k is a coefficient which accounts for flow resistance in the waterjet system and is usually around 0.96~0.99. The critical cleaning standoff distance can thus be expressed as

$$x_c = 2.82\left(\frac{\lambda\psi k}{S}\right)^{0.5}\left(\frac{r_0}{C}\right)(P\rho)^{0.25} \tag{9}$$

3.2 Cleaning Width vs. Standoff Distance

If the coating surface is placed somewhere between the nozzle exit and the critical cleaning standoff distance, the cleaning width w can be shown to satisfy the following equation

$$\left(1-\left(\frac{w}{2Cx}\right)^{1.5}\right)^3 \frac{U_0 r_0^2}{C^2 x^2} = \frac{S}{5.62\lambda\rho\psi} \tag{10}$$

where x is the standoff distance. The above equation can be obtained by using Eqs. (1), (2), (5), and (6) and letting $r = \frac{w}{2}$. Substituting Eq. (7) into Eq. (10) results in

$$w = 2Cx\left[1-\left(\frac{x}{x_c}\right)^{\left(\frac{2}{3}\right)}\right]^{\left(\frac{2}{3}\right)} \tag{11}$$

As a check, the cleaning width at the critical cleaning standoff distance is 0, i.e. $w = w_c = 0$, when $x = x_c$, from the above equation.

The maximum cleaning width $w = w_m$ can be obtained by letting $\frac{dw}{dx} = 0$. Thus, by differenting Eq. (11) with respect to x and letting $x = x_m$, we obtain

$$\frac{x_m}{x_c} = 0.576 \tag{12}$$

Substituting Eq. (12) back into Eq. (11) results in

$$w_m = 0.912Cx_m = 0.525Cx_c \tag{13}$$

If the critical cleaning standoff distance x_c is known, the optimal standoff distance x_m can be calculated using Eq. (12), and the maximum cleaning width w_m can be calculated from Eq. (13).

3.3 Effects of Water Pressure and Nozzle Radius on Critical Cleaning Standoff Distance

To investigate the effects of water pressure and nozzle radius on the critical cleaning standoff distance, we start by noting that the maximum equivalent dynamic stresses at the critical cleaning standoff distances of two cleaning processes are the same, i.e. the two values of $\lambda \dot{m}_m \psi$ are the same. By the use of Eqs. (7) and (8), we have

$$\frac{\lambda_1 P_1^{0.5} r_{01}^2}{C_1^2 x_{c1}^2} = \frac{\lambda_2 P_2^{0.5} r_{02}^2}{C_2^2 x_{c2}^2} \tag{14}$$

where P_1, P_2, r_{01}, r_{02}, C_1, C_2, λ_1, λ_2, x_{c1} and x_{c2} represent the water pressures, nozzle radii, spreading coefficients, stress coefficients, and critical standoff distances of the two cleaning processes.

Strictly speaking, C and λ are functions of water pressure and nozzle radius. Since these functions are highly complex and unknown, we will assume them to be independent of P and r in predicting the dependence of critical standoff distance on water pressure and nozzle radius. We will show that the predicted dependence relations agree fairly well with experimental observations even with these assumptions. By assuming C and λ to be independent of P and r, Eq. (14) can be rewritten as

$$\frac{x_{c2}}{x_{c1}} = \frac{r_{02}}{r_{01}}\left(\frac{P_2}{P_1}\right)^{0.25} \tag{15}$$

With the consideration of the same nozzle radii, i.e. $r_{01} = r_{02}$, Eq. (15) becomes

$$\frac{x_{c2}}{x_{c1}} = (\frac{P_2}{P_1})^{0.25} \tag{16}$$

Also, with the same water pressures, i.e. $P_2 = P_1$, Eq. (15) becomes

$$\frac{x_{c2}}{x_{c1}} = \frac{r_{02}}{r_{01}} \tag{17}$$

Therefore, we have shown that the critical standoff distance is linearly proportional to the nozzle radius and is proportional to the one-fourth power of water source pressure. It should be noted that these relations are only "approximate" because of the assumptions on C and λ.

4. Experimental Verification

Cleaning experiments are carried out with an Ingersoll-Rand waterjet system in order to verify the derived analytical relations. The cleaning head in the waterjet system is mounted on a 5-axis gantry robot. The movement is controlled by an Allen Bradley 8200 series CNC controller. The water is pressurized by an intensifier using a hydraulically driven, double acting, reciprocating plunger pump and then carried through a stainless steel pipe to the cleaning head. A flat sapphire nozzle is inserted into a cleaning head for generating the waterjet. Figure 2 shows the schematic of the experimental setup

In all of the cleaning tests, the waterjet stream is perpendicular to the surface of coating. A number of trials of the standoff distance are made to find the critical cleaning standoff distance, above which the surface cannot be cleaned. After that, a series of tests was conducted. The variation in cleaning width is obtained with systematic increase in the standoff distance. For each standoff distance, the corresponding cleaning width is measured and recorded. There are two combinations of the coating and substrate: a yellow epoxy-based paint on a steel substrate and an oil-based paint on a steel substrate. The oil-based paint made by Paris Paint & Varnish is coated by hand brushing on the surface of the AISI1018 steel substrate, while the epoxy-based paint made by Krylon is coated by spraying the paint on the surface of the steel substrate. The measured thicknesses of the oil-based and epoxy-based paints are 0.098 and 0.082 mm, respectively. The water pressures used in the experiments include 104, 172, 242, and 311 MPa (i.e. 15,000, 25,000, 35,000 and 45,000 psi). Sapphire nozzle nos. 14, 12, 10 and 7 made by Ingersoll-Rand are used, which correspond to the nozzle diameters of 0.014, 0.012, 0.010 and .007 inches, respectively. The cleaning width is obtained by measuring the diameter of the cleaning spot using a caliper. Three measurements are taken and the average of them is used as the measured cleaning width. In same cases the cleaning spot looks a little like an ellipse due to nozzle imperfection and wornout. For such cases the mean of the major axis length and minor axis length of the ellipse is used as the cleaning width.

The examples of the experimental results on cleaning width vs. standoff distance under various water pressures are shown in Figs. 3 and 4, respectively. The charts show the removal of epoxy-based paint from the steel substrate. The waterjet spreading coefficient used in the calculation is 0.0335, which is obtained from regression of the experimentally obtained data using Eq. (11). Figures 5 and 6 show the variation of critical cleaning standoff distance vs. water pressure for the removal of these two coating materials with four different nozzles. The experimental data are compared with the analytical curves calculated using Eq. (16), again with the measured critical standoff distance with nozzle no. 14 at the water pressure of 311 MPa. In all of these figures, the analytical results agree fairly well with the experimental results.

5. Conclusion

A mathematical model of cleaning using stationary waterjets has been established by applying the theoretical structure of waterjet in air and considering that cleaning occurs when the equivalent dynamic stress due to water droplets is greater than or equal to the endurance limit of the coating material. The model relates the cleaning width to the standoff distance, water pressure, and nozzle radius. Based on this model, the maximum cleaning width is shown to be linearly proportional to the critical cleaning standoff distance, and optimal cleaning is shown to occur at 0.576 times the critical standoff distance. By assuming that the spreading and stress coefficients (C and λ) are independent of water pressure and nozzle radius, the model also predicts that the critical cleaning standoff distance is linearly proportional to the nozzle radius and is proportional to the one-fourth power of the water pressure. The quantitative relations have been verified by waterjet cleaning experiments with various water pressures, nozzle radii, coating materials, and standoff distances.

The derivation of equations presented in this paper is of practical importance to waterjet cleaning. Without the analytical equations, it would be necessary to perform many tests in order to obtain the optimal standoff distance for the maximum cleaning width for each cleaning situation (i.e. each set of water pressure and nozzle radius). The derived mathematical model makes it possible to determine the optimal standoff distances for various cleaning situations (i.e. different water pressures and nozzle radii) by measuring only one critical cleaning standoff distance for each combination of coating and substrate materials (with constant coating thickness).

We have only considered cleaning with stationary waterjets here. In most of real cleaning work, however, the waterjet is moving and not stationary. The effect of traveling would require a modification of the mathematical model of stationary waterjet cleaning derived in this paper. We will discuss cleaning with moving waterjets in a separate paper.

6. Acknowledgment

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8. Nomenclature for Symbols

C jet spreading coefficient
k flow resistance coefficient of water system
$\dot{m}$ water droplet flow rate at any point inside the jet
$\dot{m}_m$ water droplet flow rate at a point on the jet center line
P water pressure from the intensifier or pump
r distance of any point of consideration from the jet center line

r_0	radius of nozzle
R	radius of the jet cross section
S	endurance limit of the coating material
U	velocity of waterjet
U_0	velocity of waterjet at the nozzle exit
w	cleaning width
w_c	cleaning width at the critical standoff distance
w_m	maximum cleaning width
x	standoff distance
x_c	critical cleaning standoff distance
x_m	optimal standoff distance
ρ	density of water
λ	stress coefficient
ξ	dimensionless parameter defined by $\xi = \frac{r}{R}$
ψ	sound speed in water

Nozzle number is the nozzle diameter in thouthands of inch

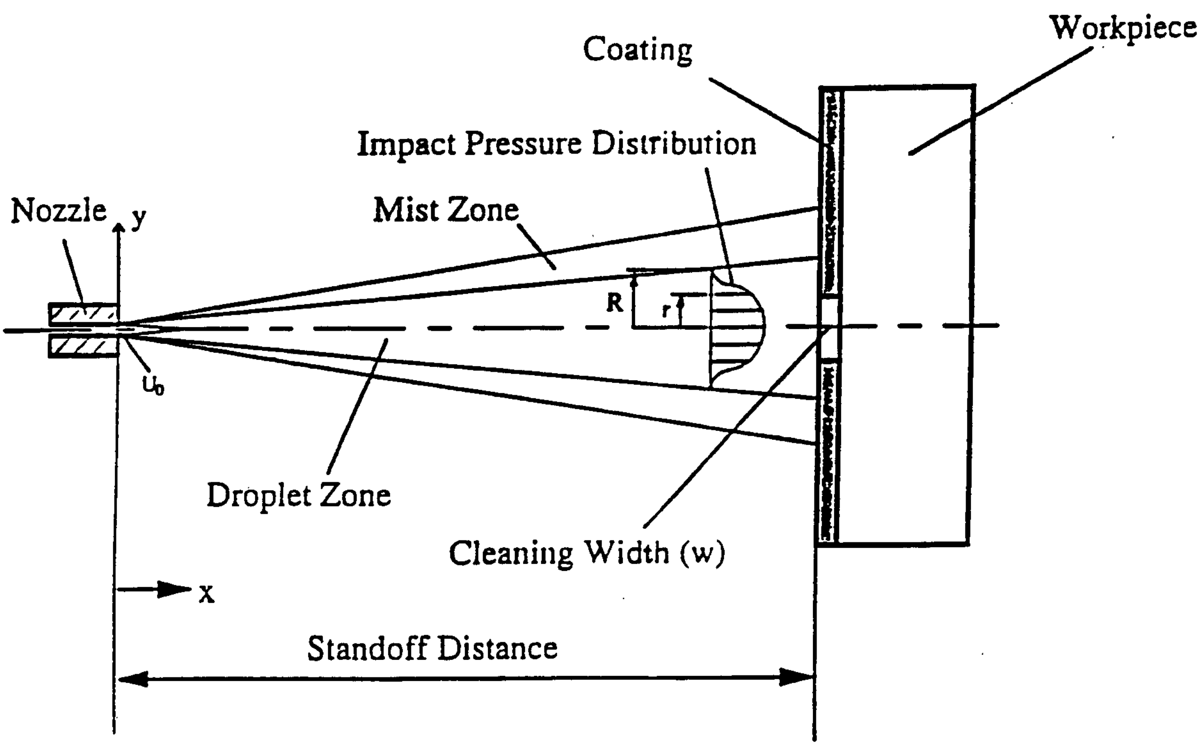

Fig. 1 Schematic of waterjet cleaning.

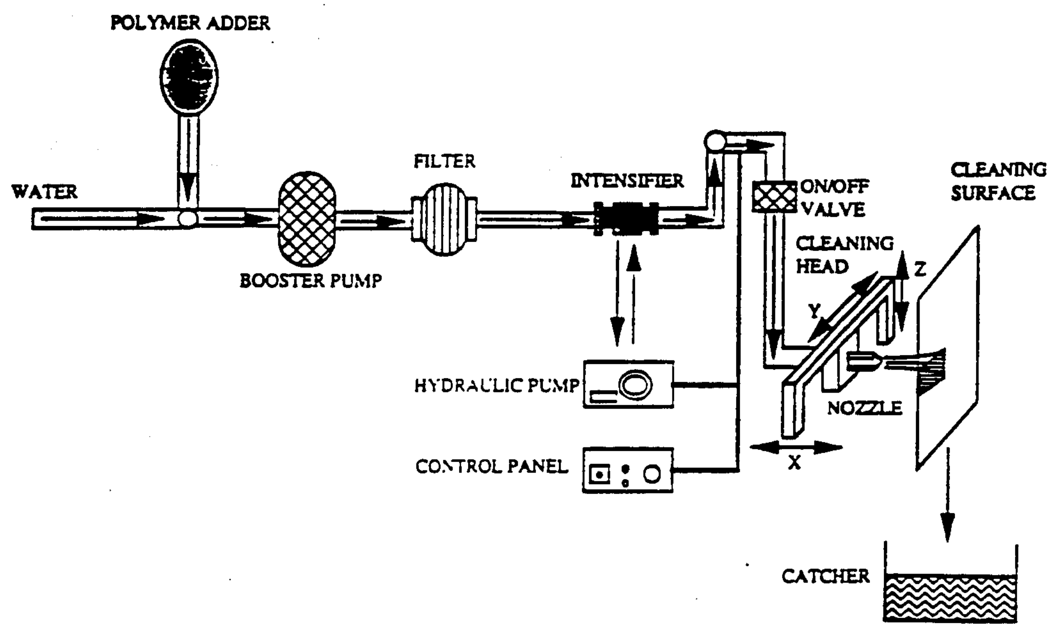

Fig. 2 Schematic of waterjet setup.

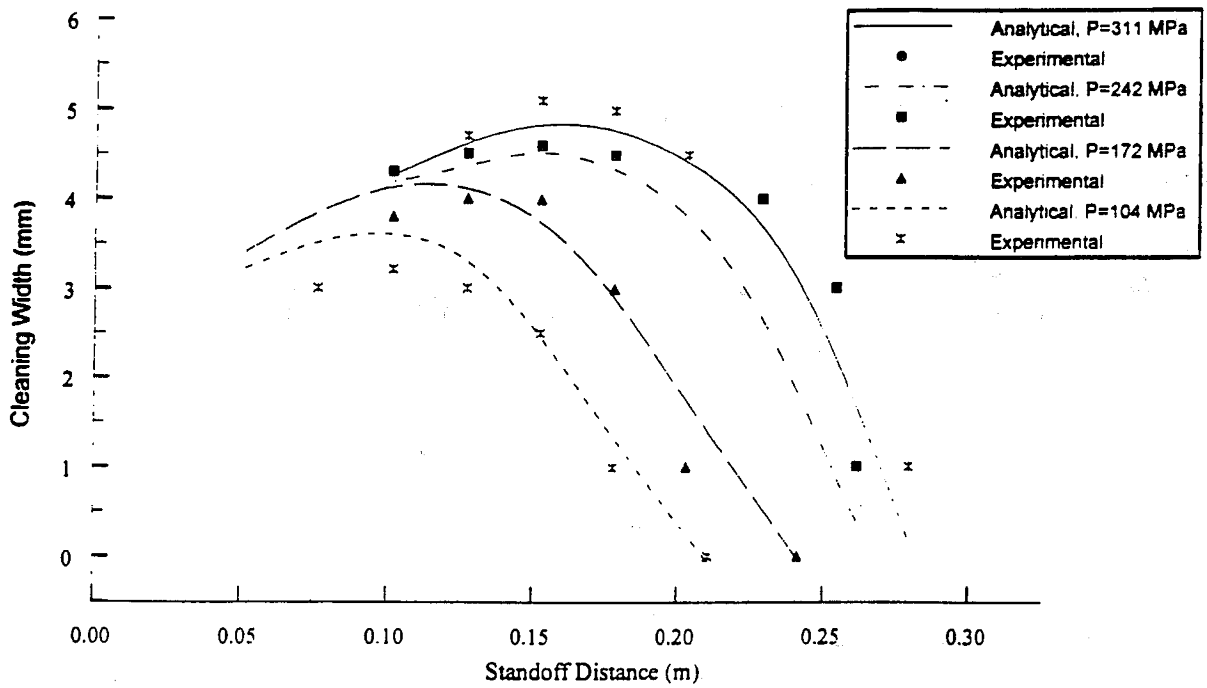

Fig.3 Cleaning width vs. standoff distance for stationary jet epoxy-based paint removal with nozzle no. 7 under four different water pressures.

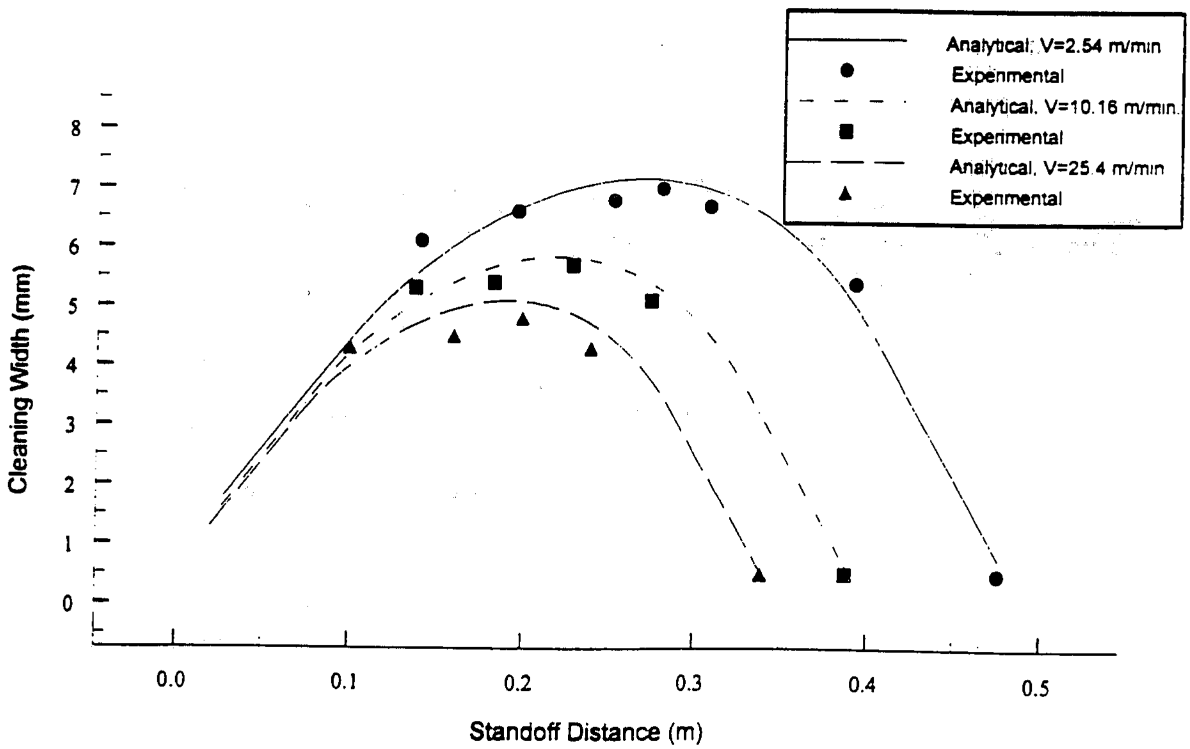

Fig.4 Cleaning width vs. standoff distance for moving jet oil-based paint removal with nozzle no. 14 at 276 MPa and three different travel speeds.

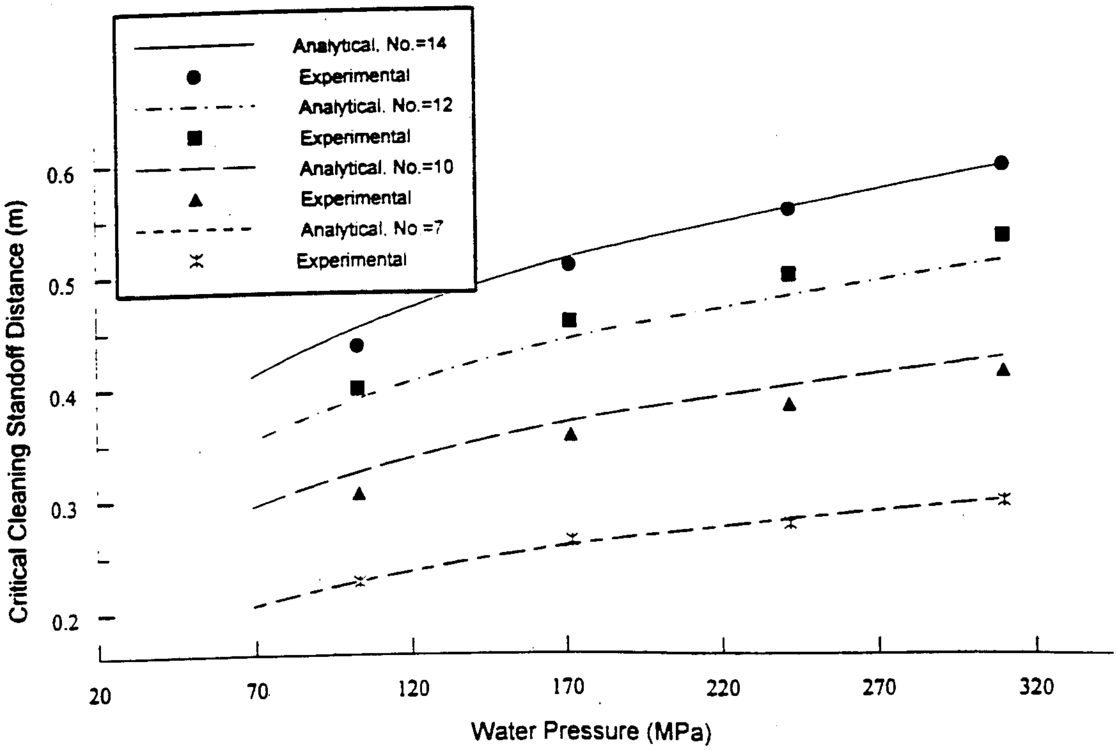

Fig.5 Critical cleaning standoff distance vs. water pressure for stationary jet oil-based paint removal with four different sapphire nozzles.

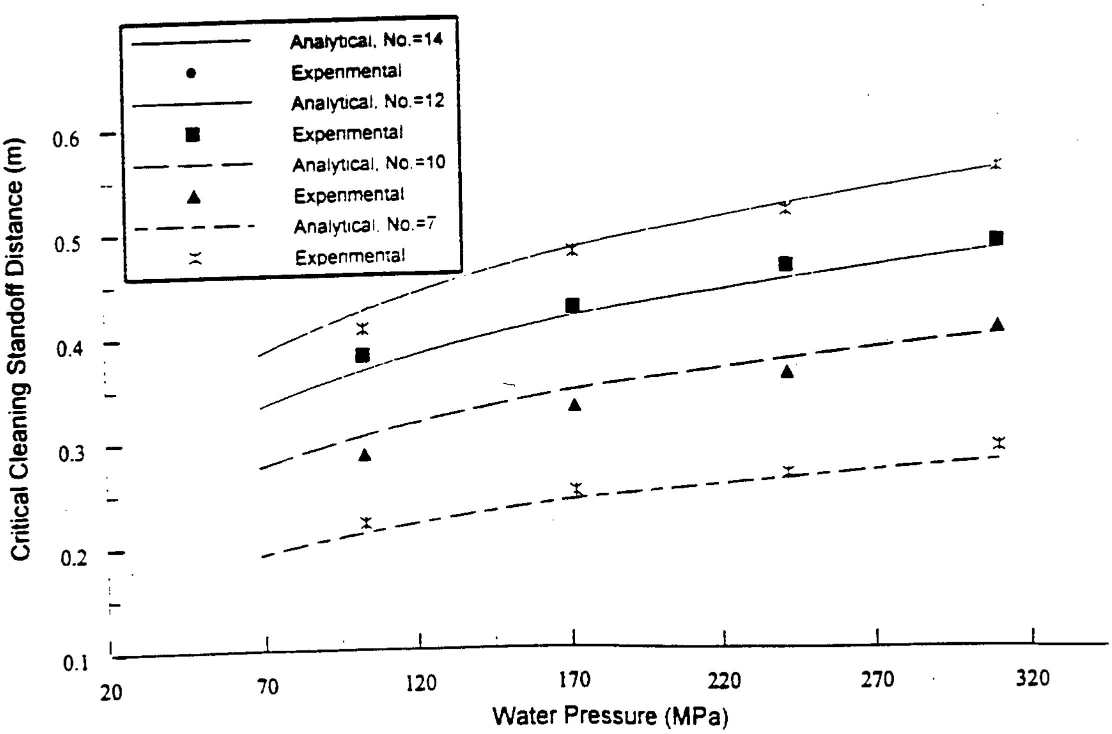

Fig.6 Critical cleaning standoff distance vs. water pressure for stationary jet epoxy-based paint removal with four different sapphire nozzles.

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Paper 38

A STUDY OF ROTARY JETS FOR MATERIAL REMOVAL

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ABSTRACT

Rotating waterjets have revolutionized the waterblast cleaning industry. Their capability and efficiency have greatly enhanced the use of waterjet technology. Over the last 15 years a large number of swivels and spinning nozzles have been developed. As a result, a wide variety of tools are available, with very different operating characteristics. Some of the differences are the result of optimizing the tool for different types of work.

This paper presents the results of testing to determine the influence of different operating parameters on jet performance and effectiveness. The parameters studied included: pressure, rotation speed, standoff, size of jets, angle of jets, and type of target material. Operating pressures of 35 to 140 MPa (5,000 to 20,000 psi) and flow rates of 15 to 170 lpm (4 to 45 gpm) were used.

The two target materials tested, concrete and rubber, have very different jetting characteristics. The concrete with small aggregate is hard and brittle. It erodes as grains and spalls in larger pieces. The neoprene rubber is pliable and very uniform without any fissures or boundaries of weakness. It requires the jet to cut and slice each piece removed.

Depth of cut and volume removed were the primary results measured and analyzed, while visual and subjective observations are included.

Organized and Sponsored by the Waterjet Technology Association.

1. INTRODUCTION

Rotating waterjet nozzles allow large surface areas to be covered quickly. High rotation speeds allow the jets to hit the surface multiple times, creating a high speed erosion process. The purpose of the research conducted for this paper was to determine the effectiveness of various rotation speeds in two materials with widely differing jetting characteristics, as well as the effect of rotation speed on jet quality, as pressures, flow rates and standoffs were varied.

The concrete and rubber chosen for the testing are representative of two very different material types that waterjets can remove. In the concrete, the jets act to erode the cement which binds the harder aggregate together and also pressurize microjoints and cracks in the concrete. Because the concrete is brittle, large pieces are broken and spalled off by the jet action. This is the typical effect of waterjetting on materials with a grainy structure. The rubber is more homogeneous and pliable. While the jets can cut and erode this material, each piece removed must be completely cut free by the jet, as any ribs left between jet passes will remain attached.

The pressures, flow rates, standoff distances and rotation speeds selected for these tests are representative of realistic, full scale conditions. The jet path diameters chosen are small compared to what is typically used for surface cleaning, but considered valid for material removal and predicting larger diameter performance.

2. TEST PROCEDURE

The test samples of concrete and rubber were placed on a stand providing fixed standoffs. A high pressure water swivel was fitted with nozzle arms and jets, and rotation was provided by an air motor and belt drive. The rotating head traversed along a rail, chain driven and powered by an electric motor, at a fixed traverse rate of 3.3 m/min (11 ft/min). This arrangement is shown in Figure 1.

The concrete test samples consisted of 30 cm (12 in.) square x 5 cm (2 in.) thick blocks, with 1 cm (3/8 in.) minus aggregate in a 3000 psi mix. The rubber test samples were 18 cm (7.3 in.) square by 5 cm thick, 60 durometer neoprene. A photo of each after testing is shown in Figure 2.

For the concrete cutting tests, the nozzle arms were fixed at a 90° angle to the concrete surface. Two diameters of jet path were tested, 13 cm (5 in.) diameter and 22 cm (8.6 in.) diameter. Configurations of 2 and 4 jets were also compared. Standoff distances were tested at 2.5, 11.5, and 25.4 cm (1, 4.5 and 10 in.). Rotation speeds of 125 to 3000 rpm were evaluated.

The rubber cutting tests were conducted with 2 jets in a 13 cm (5 in.) diameter jet path. Jet angles were varied from 45° to 90°, at a fixed vertical standoff distance of 15 cm (6 in.). Rotation speeds of 250 to 3000 rpm were evaluated.

In both materials, pressures and flows were selected to allow equivalent power output thru the jets. The concrete cutting was tested at water pressures of 35, 70, 100 and 140 MPa, (5,000, 10,000, 15,000, and 20,000 psi) while the rubber cutting was tested at pressures of 70, 100 and 140 MPa

(10,000, 15,000, and 20,000 psi). Nozzle diameters from .5 to 2.8 mm (.021 to .109 in.) were selected to result in power outputs of 33.6 and 93.2 kW (45 and 125 hp). Round tapered carbide nozzles 1.5 cm (.6 in.) long with a Cd of .9 and vane flow straighteners were used for all tests. Earlier testing had confirmed that this nozzle design was equal or superior to any commercially available nozzle.

Upon completion of each test, the blocks were measured to determine the maximum depth of cut and the volume removed. The rubber blocks were weighed before and after the cutting pass to determine the volume removed. The struck sand method was used to determine the volume removed from the concrete blocks. This method of measurement involved the filling of the removed area on the block with fine sand and then weighing this volume of sand and converting the weight to a volume. A total of 42 tests were conducted in rubber and 204 in the concrete. The data was broken down using a factorial analysis, where at each condition to be studied an average was taken of the data points relating to the analysis.

3. RESULTS

3.1 Concrete Material Removal

3.1.1 Effect of Pressure

The effect of increasing pressure on efficiency of concrete removal is shown in Figure 3. While a pressure of 35 MPa (5,000 psi) could begin to remove small amounts of the cement, an increase in power by increasing the flow rate had little effect. The jets did not penetrate the cement enough to allow the aggregate to be broken free, which blocked further erosion of the cement binder. The energy required at 70 and 100 MPa (10,000 and 15,000 psi) is less than at 140 MPa (20,000 psi), which demonstrates that once a pressure above the threshold for the material is reached, it is more effective to apply power through increased flow rate than through increased pressure for maximum volume removal. The critical pressure at which this occurs is dependent on the material, as is demonstrated by a comparison to the rubber removal results.

3.1.2 Effect of Rotation Speed

The analysis of volume removed versus rotation speed at pressures of 70 MPa (10,000 psi) and above is shown in Figure 4. These are values averaged for the three standoff positions, as well as the three pressures.

For the two jet power curves shown in the graph, the rotation speed for the most effective material removal was between 500 and 2000 rpm. At the diameter the jets were rotating in, the linear nozzle speed was between 3.4 m/sec and 13.4 m/sec (11 and 44 ft/sec) respectively. In this speed range, the efficiency was twice that at 125 rpm, and 45 percent better than that at 3000 rpm.

When the rotation speed was increased to 3000 rpm (66 ft/sec) the overall effectiveness of the jets was decreased. This appeared to be due to the degradation of the jet as it moved through the air at higher rotation speeds. This is especially true for smaller jet sizes. The specific energy of the lower power curve with smaller jet diameters increases at a much greater rate than that at the higher power, which has larger jet diameters.

The poor efficiency at 125 rpm was partially due to the ribs of material left between jet passes, as illustrated in Figure 5. Another contributing factor to the lower efficiency of volume removal at the slower speed was due to the decreased depth of cut. Normally one would suppose that a slower speed would allow a deeper depth of cut; however, in rotary material removal the higher rotation speed with successive passes of the jets permits the harder and unjettable aggregate to be removed, allowing the jets to penetrate deeper by removing the easily eroded cement binder. A comparison of the maximum depth of cut to the rotation speed, illustrated in Figure 6, shows that the maximum depth of cut occurs at a rotation speed of around 1000 rpm, which corresponds with the maximum volume removal. The maximum depth of cut at 125 rpm was less than the maximum depth of cut at higher speeds, showing that the jets were more effective in this material in making multiple high speed shallow passes rather than single slow cuts.

3.1.3 Effect of Standoff and Rotation Speed

An analysis of the specific energy for material removal at standoff distances of 2.5, 11.4 and 25 cm (1, 4.5, and 10 in.) shows the degradation of the jets due to high rotation speed, as illustrated in Figure 7. The jet performance decreased by approximately 50 percent over this standoff range at speeds of 500 to 2000 rpm, while at 3000 rpm the jet performance decreased by 70 percent over the standoff range.

The volume removed as a function of standoff distance was also plotted relative to jet power at standoffs of 2.5 and 25 cm (1 and 10 in.) (Figure 8). For 34 kW (45 hp) at 500 to 2000 rpm the specific energy increased by a factor of 2.5 at the 25 cm (10 in.) standoff, but at 3000 rpm the specific energy increased by 4.5 times at the 25 cm (10 in.) standoff. At 93 kW (125 hp), the specific energy was doubled from 500 to 2000 rpm, and increased by 2.5 times at 3000 rpm over the standoff range of 2.5 to 25 cm (1 to 10 in.) This shows that jets from smaller nozzle orifice sizes are more susceptible to degradation from higher rotation speeds, just as they are to increased standoff distance.

3.1.4 Effect of Four Jets Compared to Two Jets

These tests divided the flow used previously in two larger jets into four smaller jets of equivalent flow. When efficiency of material removal was compared, the effect was nearly the same between 500 and 1000 rpm, but when the rotation speed was increased to 2000 rpm, the four jet combination had a reduced efficiency of 20 percent. Refer to Figure 9. This decrease was due to the smaller nozzle orifice size, which allowed the jets to be degraded at the higher rotation speed. The advantage to the use of four jets as opposed to two jets would be in surface preparation, where four jets would reduce the amount of streaking between jet paths at the same rotation speed as two jets, if the standoff distance was kept to a minimum.

3.1.5 Effect of Increased Jet Path Diameter

In this series of tests, the jet path diameter was increased by 72 percent, from 13 to 22 cm (5 to 8.6 in.). At the larger jet path diameter, the linear velocity of the jets ranged from 5.8 m/sec (19 ft/sec) at 500 rpm to 23 m/sec (75 ft/sec) at 2000 rpm. With the larger jet path diameter the maximum depth of cut was decreased by 20 percent, but the larger area covered allowed the volume removed to increase. The effect on specific energy at 93 kW (125 hp), shown in Figure 10, was an increased efficiency of 25 percent over the smaller diameter jet path effect at a rotation speed of 500 rpm, but at a rotation speed of 2000 rpm, the specific energy of material removal by the 22 cm (8.6 in.) diameter was only 10 percent less than that of the 13 cm (5 in.) diameter path.

At 34 kW (45 hp), the specific energy of the 22 cm (8.6 in.) diameter jet path was twice that of the 13 cm (5 in.) diameter jet path at all rotation speeds. Again this was due to the higher linear speed of the jets created by the larger diameter, and the degrading effect of this speed on the smaller jet orifice size.

3.2 Rubber Material Removal

3.2.1 Effect of Pressure and Flow Rate

The effect of increasing pressure on efficiency of material removal in the rubber is shown in Figure 11. In this material the specific energy was decreasing as the pressure reached 140 MPa (20,000 psi), although between 100 and 140 MPa (15,000 and 20,000 psi) the curve has leveled, indicating that the optimum pressure for removal of this material has almost been reached.

3.2.2 Effect of Rotation Speed

In this series of tests, the angle of the jets was perpendicular to the surface, and only rotation speed was directly compared. At 250 rpm, the depth of penetration into the material was 25 percent deeper than at 1000 rpm, and 40 percent deeper than at 3000 rpm, as shown in Figure 12. This is in contrast to what occurred in the concrete, where the slower speeds did not cut as deeply as the higher rotation speeds allowed. However, as in the concrete, the maximum volume of rubber removed occurred at the higher rotation speeds, due to the ribs of material between slow speed deep cuts not being removed. At 1000 and 3000 rpm, the material was removed as a fine powder, with little evidence of jet path on the remaining material. The graph in Figure 13 compares the specific energy for material removal at 34 and 93 kW (45 and 125 hp) as a function of rotation speed. It can be seen that at the lower power the specific energy was lower at slower rotation speeds, while at the higher power 3000 rpm was more effective, although the curve has leveled off at this speed.

3.2.3 Effect of Jet Angle

For the rubber to be removed it requires that the jet completely cut pieces loose from the block. The jet angle therefore can be important to the removal process. In this series of tests an attempt was made to take advantage of the combination of greater depth of cut at slower speeds with the jets angled to the surface to remove as strips the ribs of material left between cuts.

Angles of 90, 75, 60 and 45 degrees were compared; these combinations are shown in Figure 14. The result of this series of tests is shown in the graph of Figure 15. The greatest effect occurred at 250 rpm, where the specific energy at 60 degrees was 36 percent less than the energy required at 90 degrees. At 1000 rpm, the greatest improvement in efficiency also occurred at an angle of 60 degrees, where the specific energy was 34 percent less than at the 90 degree angle.

At 250 rpm, the rubber was removed as crescent shaped pieces up to 3.3 cubic centimeters (0.2 cu in.) in volume. At 1000 rpm, the rubber was again removed as tiny chips. These two types of pieces are shown in Figure 16.

4. CONCLUSIONS

4.1 Effect of Pressure and Flow

In the two types of materials tested for this research, it was demonstrated that a selected material has a threshold jet pressure below which the material will not be affected by the jet, and an optimum material removal pressure above which an increase in power through increased pressure will have diminishing returns. When this point is reached the best way to increase material removal is to increase the power by increasing the flow rate.

4.2 Effect of Rotation Speed

Based upon the results of this preliminary study, an optimum jet tip speed range for removal of concrete was found to be between 6 and 15 m/sec (20 and 50 ft/sec). A degradation of jet quality occurred with jet tip speeds above 15 m/sec (50 ft/sec) in the power range of 34 to 93 kW (45 to 125 hp). For the rubber material removal with jets perpendicular to the surface, a jet tip speed less than 3 m/sec (10 ft/sec) was more effective in the 34 kW (45 hp) range, while speeds up to 18 m/sec (60 ft/sec) were more effective in the 93 kW (125 hp) range. Therefore, smaller jets need slower rotation speeds to maintain jet effectiveness.

If these speeds were to be extrapolated to a surface cleaner with a 60 cm (24 in.) diameter jet path, the optimum rotation speed range for maximum volume removal would range from 200 to 500 rpm. Above this rotation speed jet degradation would begin to occur, reducing jet effectiveness. However, if one wanted to evenly remove only a thin layer of material or softer coating, rotation speeds greater than 500 rpm would be desirable.

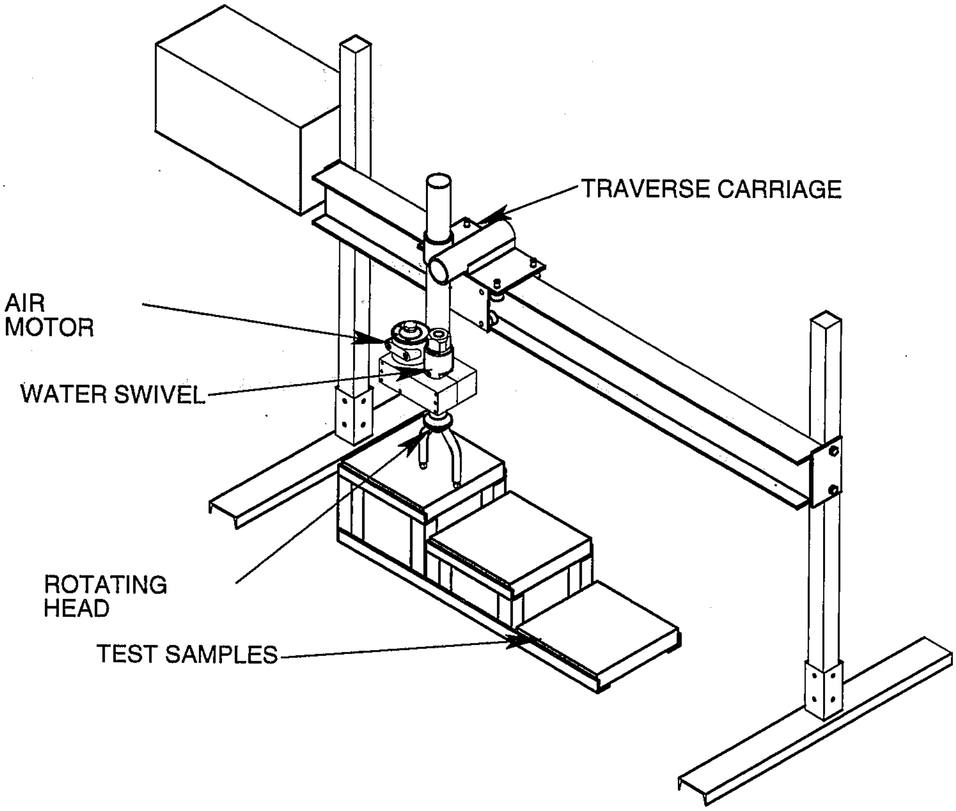
If surface removal without streaking is desired, the number of jets can be increased while maintaining the same flow as with the smaller number of jets. There was no effect on performance changing from 2 jets to 4 jets of equivalent flow at jet tip speeds below 7.5 m/sec (25 ft/sec), but above this speed degradation of the jets begins to occur and at 15 m/sec (50 ft/sec) the performance is reduced by 25 percent.

It is important to keep the standoff distance as small as possible at higher rotation speeds; a change in standoff distance from 2.5 to 10 cm (1 to 4 in.) at 3 m/sec (10 ft/sec) reduced the effectiveness by

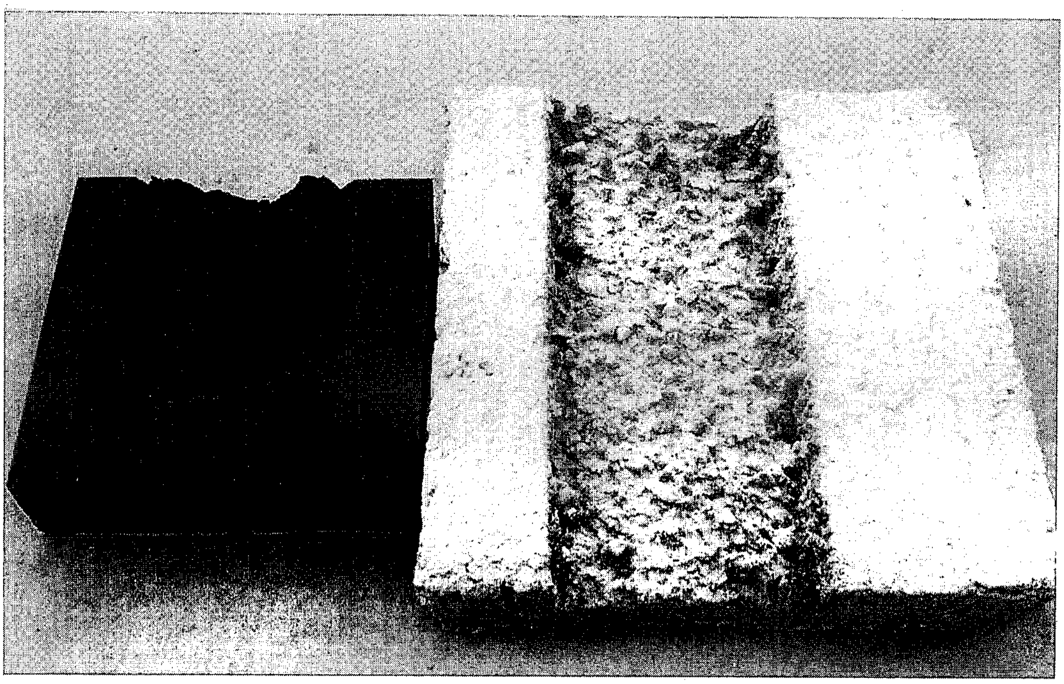
40 percent, while at 15 m/sec (50 ft/sec) the effectiveness was reduced by 55 percent. Other factors to be considered when selecting a rotation speed for operation are the increased wear and vibration with increasing speed on the rotating components and seals being used in the equipment.

4.3 Effect of Varying Jet Angle

The depth of cut in the rubber material was greater at slower rotation speeds; however, the sections between the jet paths remained attached to the block. By changing the angle that the jets strike the surface, it is possible to remove slices of the material between the jet paths. In this testing, the optimum angle was found to be 60 degrees, where material removal was doubled over that removed at a 90 degree angle. The improvement was greatest at the slowest speed, and would likely continue to diminish at higher rotation speeds.

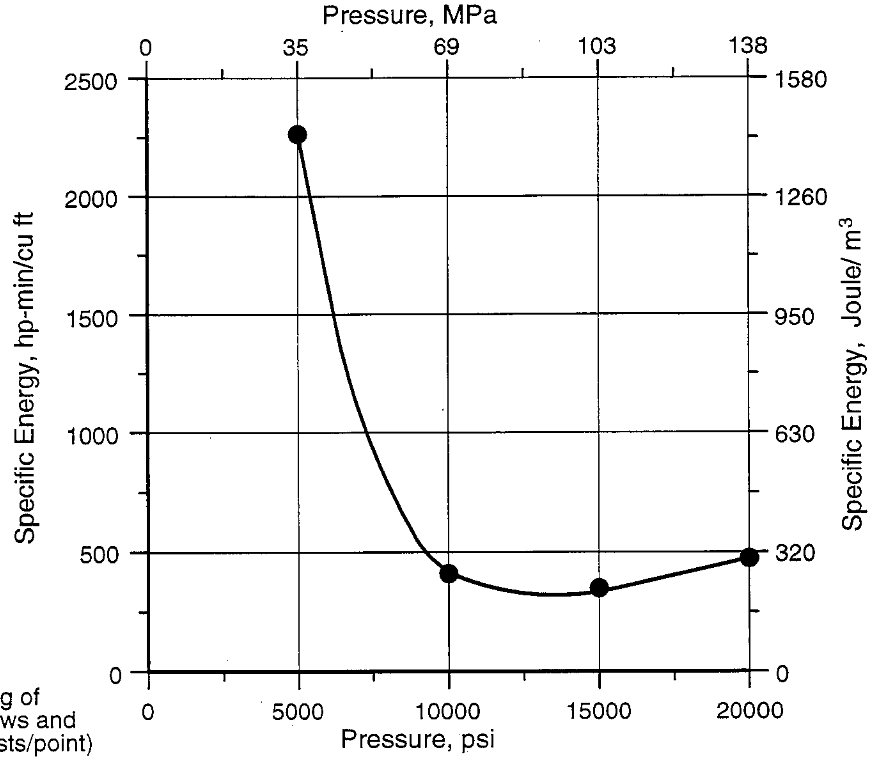


Test arrangement for rotary jet material removal
Figure 1



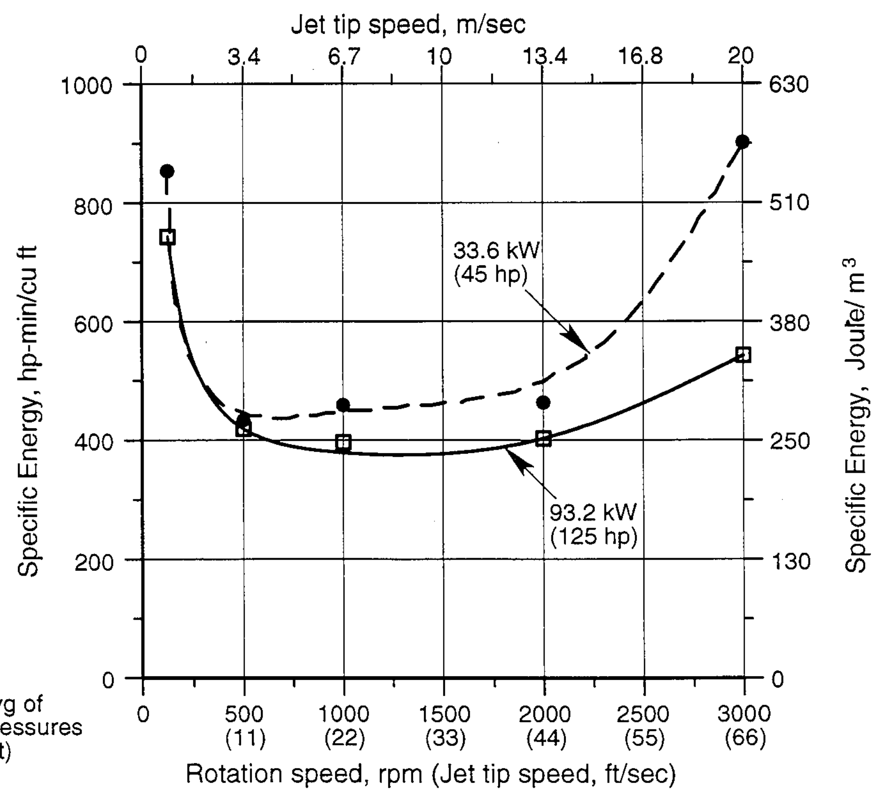
Photograph of concrete and rubber test samples

Figure 2



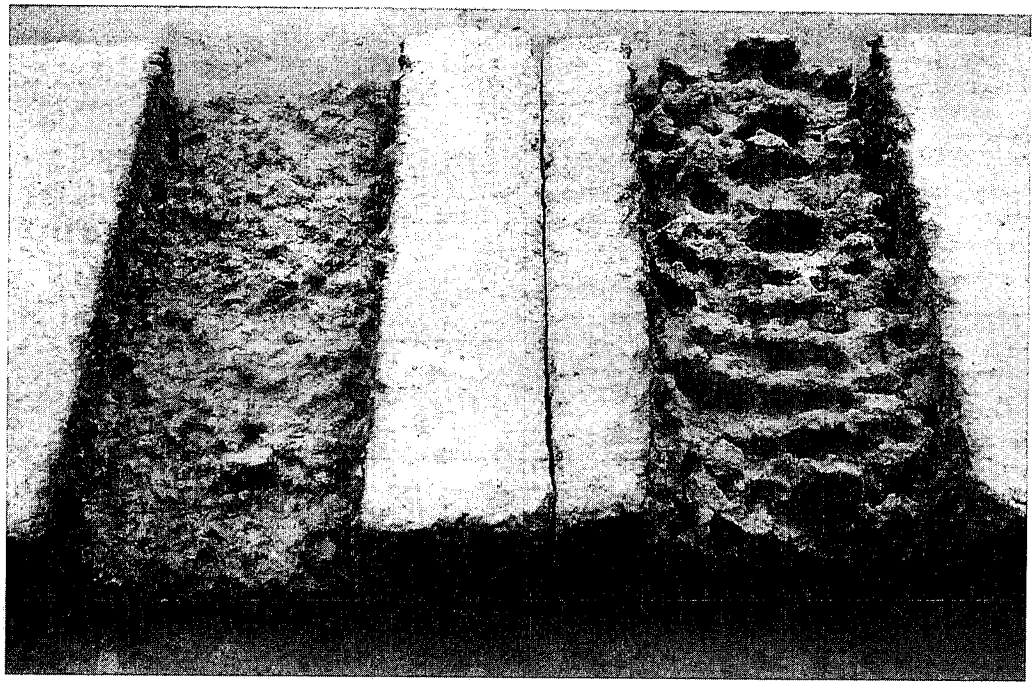
Concrete, avg of standoffs, flows and speeds (9 tests/point)

Effect of pressure on efficiency of concrete removal
Figure 3



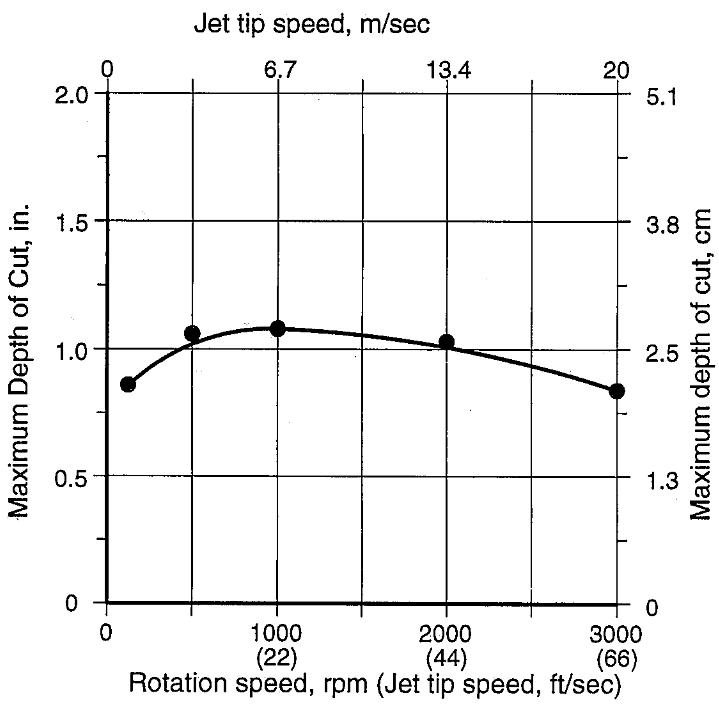
Concrete, avg of standoffs, pressures (6 tests/point)

Effect of rotation speed on efficiency of concrete removal
Figure 4

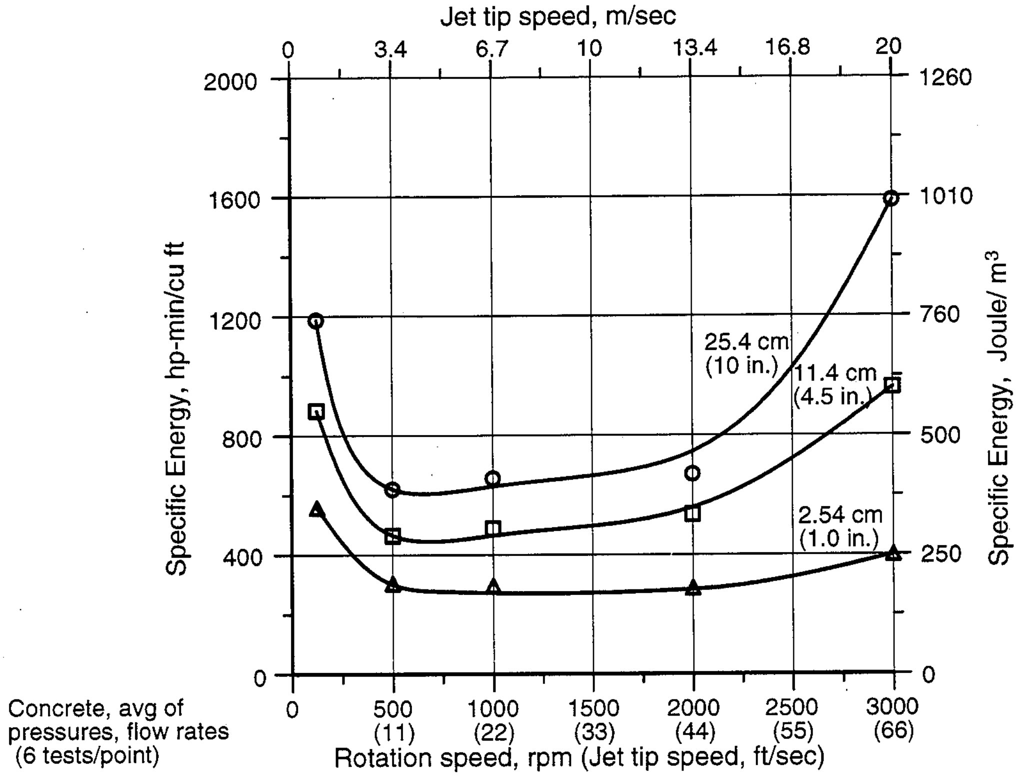


Photograph showing ribs of material not removed at 125 rpm compared to complete material removal at 1000 rpm

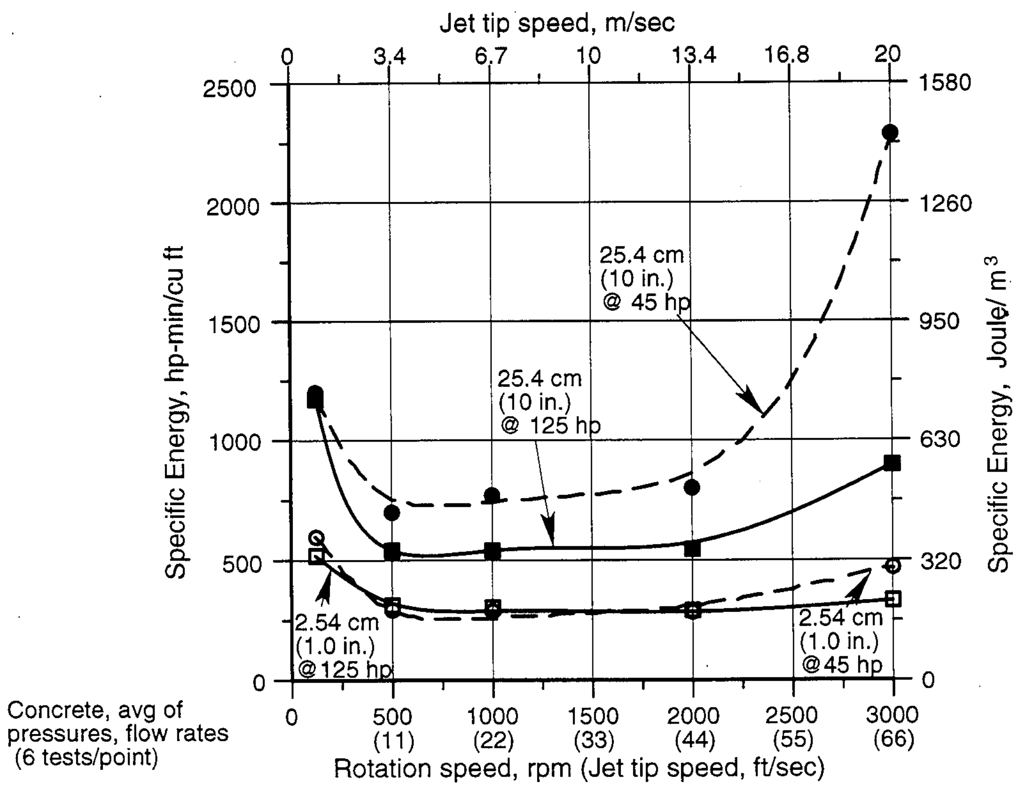
Figure 5



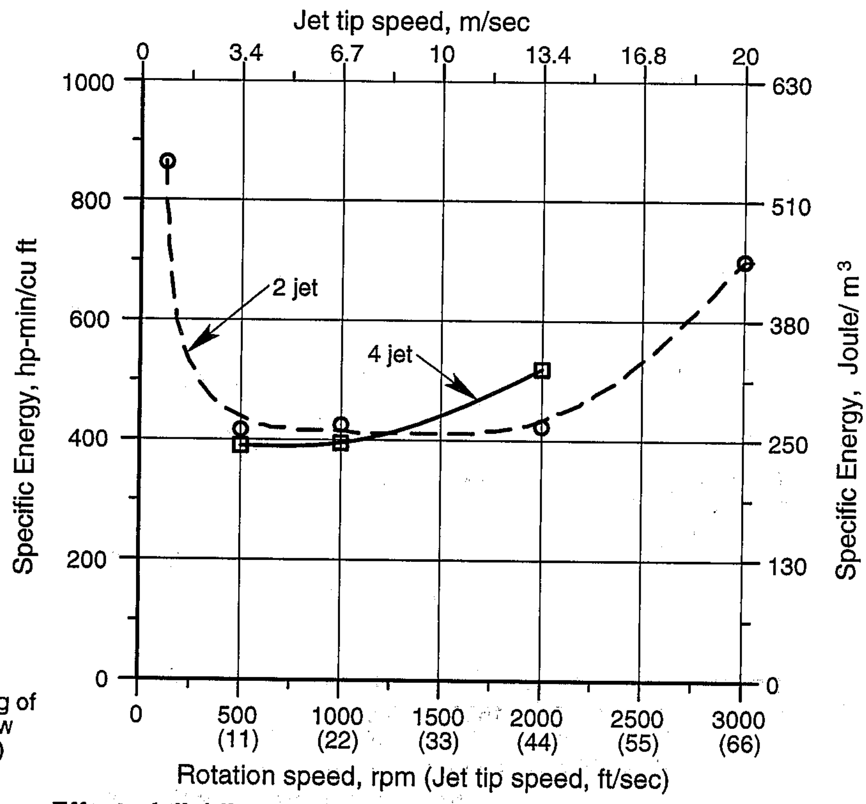
Effect of rotation speed on depth of cut in concrete
Figure 6



Effect of standoff and rotation speed on efficiency of concrete removal
Figure 7

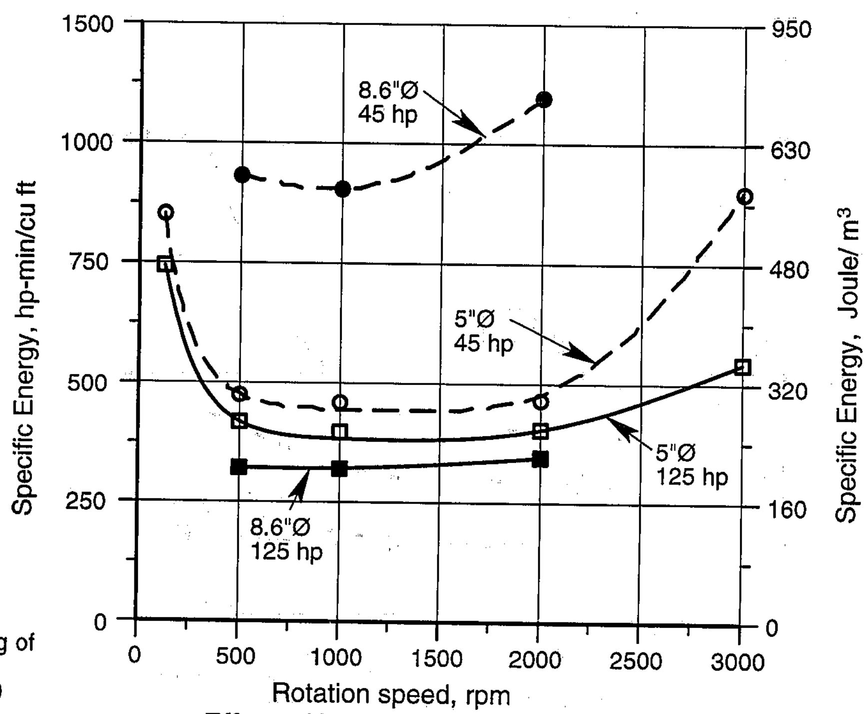


Effect of standoff at 45 and 125 hp on efficiency of concrete removal
Figure 8



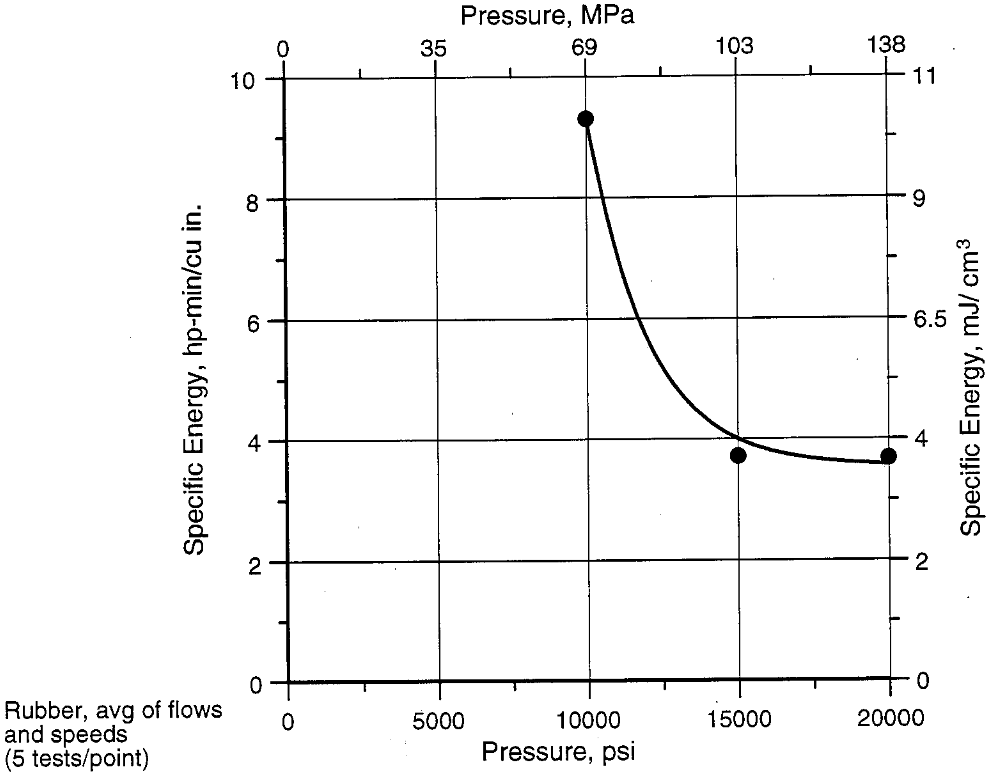
Concrete, avg of standoffs, flow (6 tests/point)

Effect of dividing flow into four jets compared to two jets
Figure 9

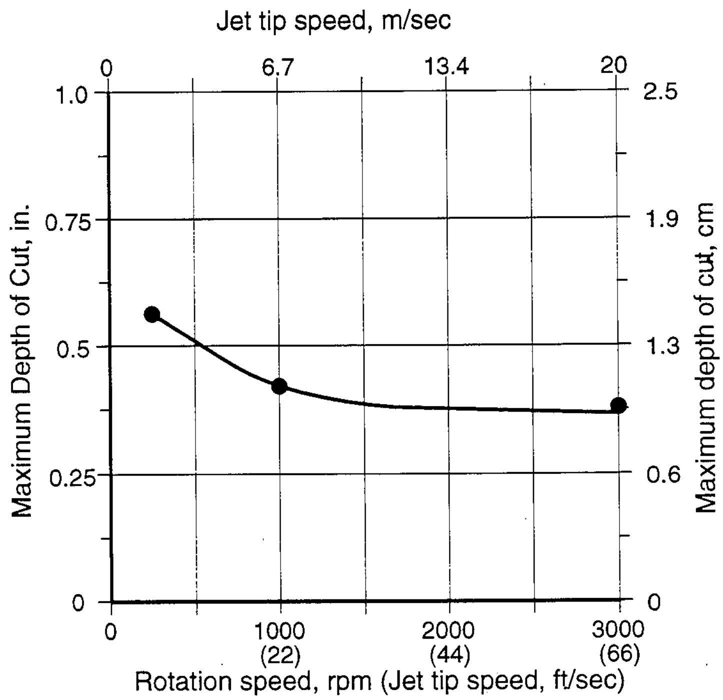


Concrete, avg of standoffs (3 tests/point)

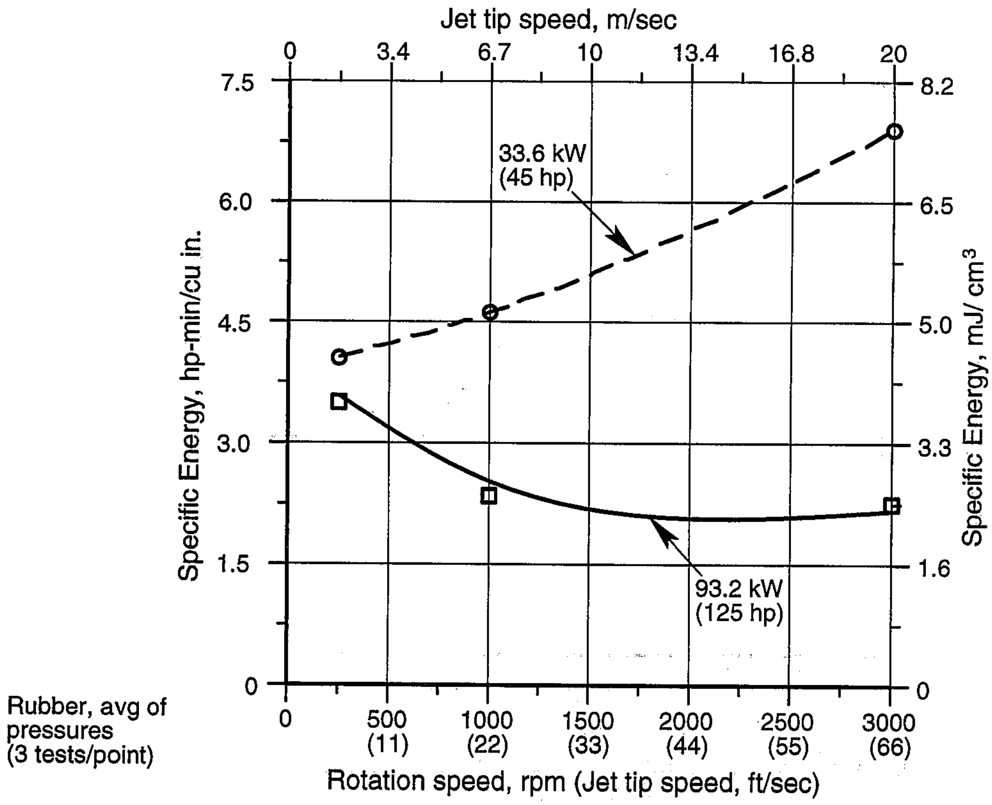
Effect of increased jet path diameter
Figure 10



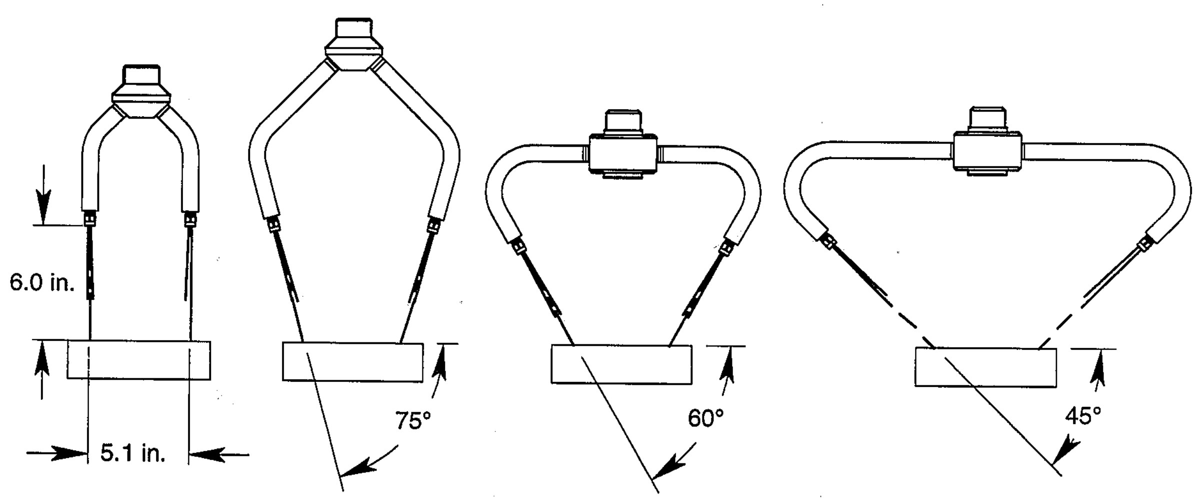
Effect of pressure on efficiency of rubber removal
Figure 11



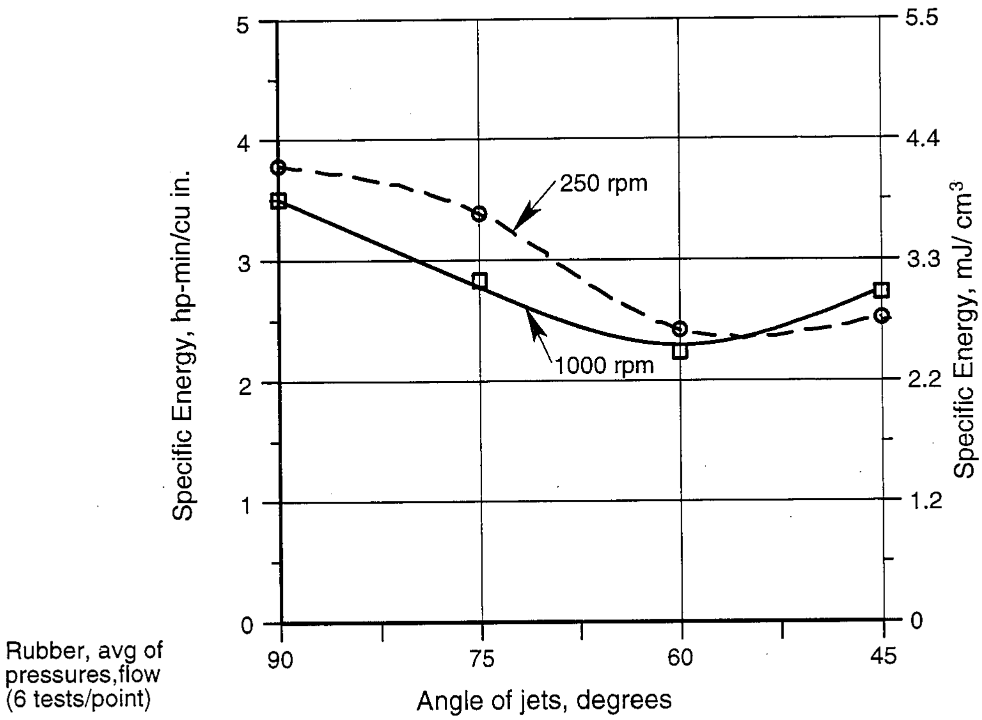
Effect of rotation speed on depth of cut in rubber
Figure 12



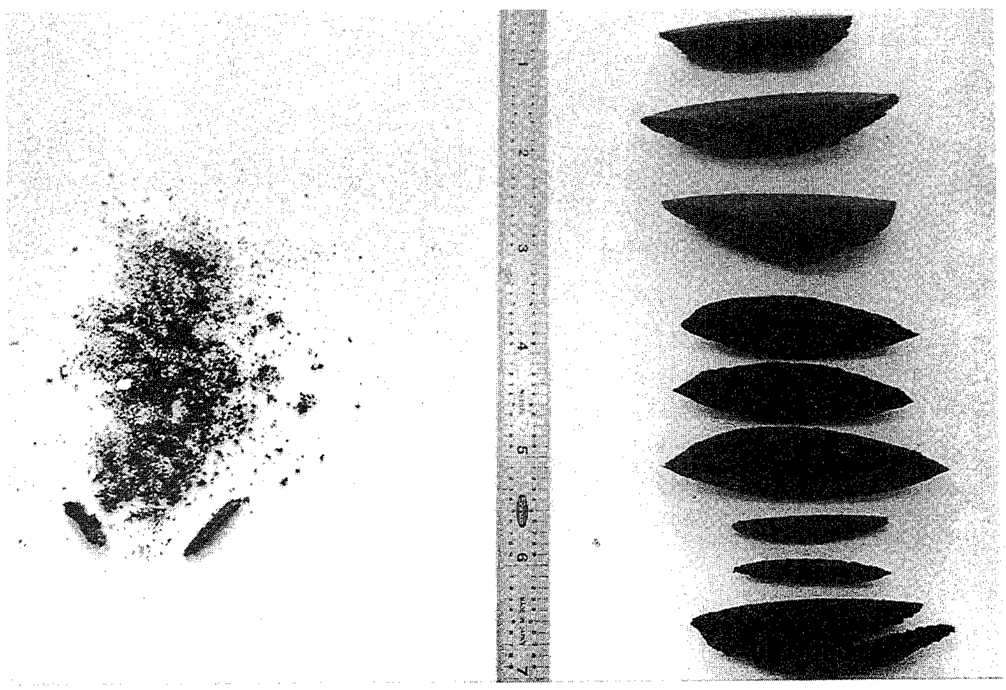
Effect of rotation speed on efficiency of rubber removal
Figure 13



Jet angles used in rubber removal
Figure 14



Effect of jet angle on efficiency of rubber removal
Figure 15



Photograph showing two types of material removal in rubber; sample on left removed at 1000 and 3000 rpm, sample on right removed at 250 rpm

Figure 16

9th American Waterjet Conference
August 23-26, 1997: Dearborn, Michigan

Paper 39

DEVELOPMENT OF A DYNAJET™ CAVITATING WATER JET CLEANING TOOL FOR UNDERWATER MARINE FOULING REMOVAL

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ABSTRACT

Current technology for cleaning of marine fouling from Navy ships involves the use of rotating brushes that remove part of the antifouling paint in addition to the fouling. This not only can damage the surface, but it also releases toxic copper compounds into the environment. This paper presents results of a study that has demonstrated the feasibility of efficient use of DYNAJETS™ cavitating water jets for marine fouling removal with little or no removal of the underlying paint. A cleaning tool based on these jets would be mounted on a new remotely operated Underwater Hull Maintenance Vehicle under development by the Navy.

Tests conducted on both fouled and unfouled painted panels quantified the removal rates as functions of the operating parameters and established desirable operating ranges for the system. Paint removal and damage were assessed both visually and by paint thickness measurements before and after jetting. Due to limited availability of fouled samples, a simulated fouling consisting of pebbles adhered to a rubberized undercoating sprayed onto metal panels was utilized for screening purposes. This simulated fouling had removal characteristics similar to actual fouling. Particular emphasis was placed on minimization of the power requirements due to constraints of the underwater vehicle design. Simulations were utilized to investigate different schemes for sweeping the jets across the surface. A self propelled rotating head was outfitted with pairs of DYNAJETS™ cavitating nozzles. The head assembly was tested at various rotation rates and arm radii on both simulated and actual fouling. The results of these tests demonstrated the ability of this DYNAJETS™ configuration to efficiently sweep out large areas for cleaning. Based on these results, a full scale cleaning tool could be designed to operate at 5 MPa (800 psi) or less. Tests of copper levels following jetting with the selected configuration showed no modification of the levels of copper in the effluent. This is a significant advantage over the existing method.

Organized and Sponsored by the Waterjet Technology Association.

1. INTRODUCTION

Marine fouling of ship hulls represents a serious problem (Preiser and Laster, 1980; Naval Ship's Technical Manual, 1986; Kalumuck, et al., 1996). This fouling takes the form of the deposition and growth of various marine entities such as grasses, slime, algae, barnacles, tubeworms and bivalves. Use of ion modified copper ablative antifouling (AF) paints has been found to significantly decrease but not eliminate such fouling. Fouling can significantly impact ship performance through increased drag resulting in increased fuel consumption, decreased maximum speed and range and increased frequency of required refueling.

Drydocking of a ship for overhaul is very time consuming and costly. By the use of periodic underwater cleaning and maintenance of the hull, the time between drydockings can be extended. Currently, underwater cleaning is accomplished with mechanical brushes mounted on an underwater diver operated vehicle (SCAMP). However, this cleaning has been found to remove not only the marine fouling but also a thin layer of the paint itself which releases particles of toxic cuprous oxide into the surrounding harbor water. Such a release is environmentally harmful and is subject to increasingly stringent regulatory restrictions. It is thus desirable to utilize a method of removal of marine fouling with minimal if any removal of paint.

Water jet technology provides an attractive and environmentally safe alternative to mechanical brushes. *Cavitating* water jets in which cavitation is deliberately introduced into the water jet produce a high degree of erosivity which translates into rapid cleaning. Various means can be used to induce the explosive growth of microscopic vapor filled cavities or bubbles within a liquid jet and their subsequent violent collapse in the high-pressure stagnation region of the jet on a surface. (See, for example, Chahine and Johnson, 1985 and Kalumuck, et al., 1996.) Because the collapse energy of each bubble is concentrated over a microscopic area, extremely high, very localized stresses are produced which provide the cavitating fluid jet with a great advantage over a steady noncavitating jet operating at the same pump pressure and flow rates. Cavitating jets offer an additional advantage. The velocity of the microjet formed during cavitation bubble collapse is affected by the properties of the surface against which it is collapsing. "Softer" surfaces lead to less violent collapse and less erosivity (Kalumuck, et al., 1995). This provides a mechanism for cavitating jets operating at low pressures to remove hard marine fouling without damaging the softer paint.

This paper summarizes the work performed in evaluating various DYNAFLOW cavitating water jet configurations, DYNAJETS™, for use as an underwater cleaning tool for ship hulls.

2. EXPERIMENTAL SETUP

Details of DYNAFLOW's cavitating jet technologies, DYNAJETS™, employed can be found in Kalumuck, et al. (1996). The jet configuration employed that exhibited the best results that are described here is that of the STRATOJET® (Chahine and Johnson, 1985; Chahine, et al., 1983). It creates cavitation in the submerged jet shear layer through interaction with the orifice geometry that consists of a straight throat followed by a sharp edged conical expansion.

2.1 Test Samples

Tests were carried out on three types of panels: unfouled panels painted with copper containing anti-fouling paint, panels fouled with marine growth adhering to various paint types, and panels coated with a fouling simulant. Fouled panels were stored in a tank with a stirrer and specified salinity. The fouled panels were utilized to assess the cleaning ability of each set of jet conditions. Potential damage to the paint was assessed by systematically jetting on the unfouled painted panels.

Due to a shortage of fouled panels available for testing, screening tests of various jet configurations were performed with a simulated fouling. Based on earlier work of Conn, et al., 1979, pea gravel affixed to steel plates with various adhesives was investigated. Various epoxies proved too brittle. A rubberized under coating was found to have the desirable removal characteristics which compared well with tests with fouled panels.

2.2 Tests with Translating Nozzles

Experiments were conducted in the DYNAFLOW Jet Technology Laboratory. The jet flow was driven by a Weatherford five piston positive displacement variable speed diesel pump. Samples were mounted in the Jet Translation Facility, a 1.5 x 1.8 x 1.1 m test cell with plexiglass walls on two sides and a variable speed hydraulically driven translating carriage shown in Figure 1a. Controlled translation speeds between 0.15 and 1.1 m/s were used. Jet pressures ranged between 2.8 and 21 MPa with standoffs between 1.3 and 9 cm.

Sample plates were affixed to a submerged test stand and the jet nozzle translated across the plate as shown in Figure 1b. The influence of pressure, flow rate and standoff distance was thus assessed. Two test configurations were employed. In the first, the sample panels were mounted in a fixture at a small angle to the horizontal resulting in a variation in standoff from the nozzle as the jet traversed across it. In the second configuration, the plate was held horizontally at a constant standoff. The first configuration enables obtaining a larger amount of data on a single run, but requires a relatively uniform target surface. Since marine fouling is generally not uniform, most tests were performed with a constant standoff for each run to enable averaging over a larger area. Fouled plates were inspected following testing and the cleaning assessed visually. Measurements were made of the clean path width. Results were recorded and documented photographically.

Initial evaluation of the paint surface disruption on the unfouled panels was made by visual inspection. More detailed evaluation was performed with the use of a Fischer Dualscope MP4C electromagnetic induction paint thickness measuring instrument. The paint thickness before and after jetting was measured to assess the amount removed.

2.3 Tests with Nozzles on a Rotating Advancing Arm

In order to achieve the desired surface coverage for cleaning, it is necessary to deploy an array of nozzles. A Mosmatic Turbo-Rotor Heavy Duty Swivel and T-bar were obtained and modified for this purpose (Figure 2). It consists of a freely rotating swivel joint with two radial arms having 90 degree bends at their ends onto which the desired nozzles are attached. The nozzles are inclined at an angle in the tangential (circumferential) direction to enable the nozzle thrust to produce the rotation. The angle of inclination and the length of the radial arms were varied to control the rotation rate and path width. The rotation rate was measured with a strobe. The swivel was attached to the carriage and translated across a sample at a desired rate.

3. RESULTS AND DISCUSSION

3.1 Threshold for Paint Erosion

Figure 3 presents example data showing the influence of the standoff and pressure on paint removal at a translation velocity of 0.6 m/s. *Even at 21 MPa the actual damage to the paint is quite minor, resulting in a removal thickness less than 25 microns (1 mil) for standoffs larger than 4 cm.* At a pressure of 5.2 MPa, there is no measurable paint removal, and at 6.9 MPa the removal is less than 13 microns at a standoff of 1.3 cm. This figure also illustrates that decreased standoff due, for example to a local surface protrusion, will not adversely affect the paint.

3.2 Fouling Removal Tests

Results of fouled panel tests are presented in Figures 4 to 6. Figure 4 presents a photograph of one of the fouled panels showing the cleaned paths for different jet conditions. In Figures 5 and 6, the influence of various parameters on this path width is presented. In Figure 5, the standoff was fixed at 4 cm while the pressure and translation velocity were varied. As can be seen, fouling is removed at pressures as low as 3.5 MPa with a slow increase in path width with increasing pressure and also with decreasing translation velocity. Figure 6 presents the influence of standoff at a translation velocity of 0.3 m/s (1 ft/s). The influence of standoff is very weak except at very low standoffs. Selection of a standoff as high as 7.5 cm would enable operation with little change in cleaning ability and would not cause damage as the tool went over typical hull surface profiles such as welds.

3.3 Operating Window

By combining the results of tests on fouled and unfouled panels such as those described above, an operating window can be obtained which provides the range in which one can operate to remove fouling without damage to the paint. This can be seen in Figure 7 which presents contours of the cleaned path width as a function of pressure and standoff. Superimposed on this is the region of damage initiation to the paint shown as the left thick black line in the center of the figure. The region below and to the right of this line is the region which was found to experience visual damage to the paint. Thus the region one wishes to operate in is that to the left and above this line. It should be pointed out that this is the line for the *onset of any visual change to the paint surface*. Thus operation at pressures less than approximately 5.5 MPa will produce no damage to the paint. If one is willing to accept a low level of paint removal, this line moves much further to the right resulting in a very large operating region. For example, the threshold for removal of 13 microns (0.5 mil) of paint is shown by the right thick black line. It is 9.7 MPa or larger for the entire translation velocity range of Figure 7.

It must be noted that these path widths are those for complete fouling removal. This 100% clean path is centered in a much broader path approximately three times as wide) over which varying percentages of the fouling were removed. This is illustrated schematically in Figure 8.

3.4 Tests For Full Scale Design

3.4.1 Cleaning Efficiency

We define the cleaning efficiency, η, as the ratio of the area cleaned per unit time to the power utilized in this cleaning:

$$\eta = \frac{Cleaning\ Rate}{Hydraulic\ Power} = \frac{(Path\ Width) \times (Translation\ Velocity)}{(Pressure) \times (Flow\ Rate)}$$

It is useful to consider the cleaning efficiency of both single nozzle components and of the tool as a whole - which would contain an array of nozzles. Our approach has been to select individual nozzle designs and operating configuration that maximize the cleaning efficiency of the individual nozzle subject to the overall system constraints. A laboratory tool was then constructed by deploying an array of these nozzles in such a manner that the system cleaning efficiency was maximized. Since both the clean path width and the power consumption increase with the pressure and flow rate, optimization consists of maximizing η.

The above expression for η could imply that one simply needs to maximize the translation velocity and the path width, and minimize the pump pressure and flow rate. While true, this statement is too simplistic since these parameters are not independent of one another. In fact, the path width is a function of the translation velocity, the pressure and the flow rate. Thus, results of parametric investigations need to be interpreted according to this efficiency relation when used for design purposes.

A critical design feature and factor in determining the overall tool cleaning efficiency is the method of covering the target area with an array of nozzles. A number of scenarios are possible. Based on analyses of path patterns and hardware simplicity, a set of rotating arrays was selected. The rotation means that if nozzles are located at various distances from the center of rotation, the outer edge of the pattern is exposed to the jets for a different time than the inner portion. There is also

$$\vec{V}_t = \vec{V}_a + \vec{V}_\Omega,$$

significant overlap with a rotating array. An example of this scenario for rotating heads having 2 nozzles at the same radial distance is depicted in Figure 9. The magnitude of the local translation velocity varies continuously along the jet path (and over the surface being cleaned) with its maximum value when the jet is moving forward relative to the vehicle travel and its minimum when the jet is moving backwards relative to the vehicle. The local instantaneous translation velocity of the jet relative to the surface being cleaned, V_t is then given by

Where V_a is the advance velocity of the rotating head (i.e., of the vehicle) and V_Ω is the tangential velocity of the nozzle rotating at a rate of Ω rpm at a distance R from the center of rotation given by

$$\vec{V}_\Omega = 2\pi R\Omega\vec{e}_\theta.$$

Each individual jet follows a helical pattern as it advances along the surface with the instantaneous magnitude of its translation velocity over the surface varying between two extreme values:

$$2\pi R\Omega - V_a \leq V_t \leq 2\pi R\Omega + V_a.$$

Use of jets at different radial positions would result in different sets of local translation velocities for each jet. Figure 9 shows the pattern achieved with 3 rotating heads having jets at a single radial position. The heads have been deliberately spaced apart to enable viewing of the individual patterns. In Figure 9a, two nozzles each located 180 degrees apart are located on each head. Figure 9b shows the pattern obtained if these nozzles are replaced by four smaller diameter nozzles located 90 degrees apart on each head with the same total flow rate. As can be seen, the gaps left are less suggesting that more smaller diameter nozzles present an advantage. By increasing the number of nozzles on a head, a faster advance speed can also be achieved as each nozzle's helical path will be offset from the others. The number of nozzles, number of heads, and rotation rate is determined by the desired vehicle advance rate and the limiting local translation velocities in conjunction with the desire to cover the entire path with minimal overlap.

For the case of n nozzles at the same radial distance each having a clean path width w, the condition for complete coverage is:

$$\Omega \geq \frac{V_a}{nw}.$$

3.4.2 Simulated Fouling Tests

Figure 10 presents a photograph of a simulated fouled panel after jet exposure showing the cleaned path for two different trials at a 7.5 cm standoff and a value of V_t = 1.1 m/s. In this figure, the left side of the panel provides a good view of the surface condition prior to jetting. Shown are the results of a single pass at 4.8 MPa and 20 l/min (left) and a single pass at 4.1 MPa and 21 l/min (right). This latter case was run as a control on each panel to account for potential panel to panel variation in the simulated fouling adherence characteristics.

Figure 11 presents photographs of cleaned panels for two rotating head tests on simulated fouling. The rotating head was translated across the panels at 0.3 m/s (to match the desired vehicle advance speed) from top to bottom in these photographs. In the top photo (conditions: 2.7 mm nozzle diameter, 30 cm head diameter, 4.1 MPa, 41 l/min total flow, 160 rpm) small arc shaped patches of uncleaned areas can be discerned. These are due to the rotation rate being too slow for the nozzle array to sweep over the entire area as it advances (as shown previously in Figure 9). This could be solved by an improved shaping of the rotating arm to minimize drag and/or with a different distribution of the jets on the rotating arm. In the bottom photo (conditions: 2 mm nozzle diameter, 41 cm head diameter, 6.32 MPa, 30 l/min total flow, 190 rpm) virtually complete cleaning is achieved with no apparent pattern to the few remaining pebbles.

Important conclusions from these tests include:

- A rotating head is a very attractive means of covering a surface of lateral extent much larger than that which could be covered by an array of the same nozzles fixed relative to the vehicle.
- The rotation exploits the ability of the jet to effectively clean at translation velocities relative to the surface being cleaned that are significantly larger than the vehicle advance speed.

Based on the results of these laboratory tests, we estimate that a cavitating jet cleaning tool could be designed and built with a cleaning efficiency, η, of 130 m^2/hr/kw.

3.5 Jet Effluent Copper Content

To provide additional confirmation of the ability of these jets to operate in a cleaning mode without need of filtering the effluent, a brief series of jetting tests were conducted on panels painted with copper based AF paint. The concentrations of copper were measured with a Hach 2000 Spectrophotometer before and after jetting. The results are presented (in micrograms per liter - i.e., parts per billion) in Table 1. Nozzles operating at the pressures of Table 1 were affixed to a lance and translated over the panel which was submerged in a 20 liter container.

The background concentration measured in the well water utilized for jetting was measured to be 25 - 35 ppb. Jetting at 4.1 and 6.2 MPa for 3 seconds at speeds comparable to that of the rotating head showed no increase above background levels. Jetting at 6.2 MPa for 30 seconds while dwelling at a particular point to produce visible removal of the paint resulted in a measured increase to over 200 ppb. These tests demonstrate that *the selected conditions for jet operation with the laboratory rotating arm test do not only efficiently clean the fouling, but they also result in no contamination of the effluent with copper from paint removal.*

4. CONCLUSIONS

This study has *demonstrated the feasibility of underwater removal of marine fouling from ship hulls with little or no damage to the underlying AF paint* utilizing cavitating water jets. Specifically, based on the data obtained a cleaning tool consisting of an array of cavitating jets could be configured to achieve a cleaning efficiency of 130 m^2/hr/kw while operating at jet pressures of 4.1 to 6.2 MPa. The jet nozzles could be arrayed on a set of self-propelled rotating heads that would sweep over the area being cleaned as the platform on which they were mounted advanced. Further increases in cleaning efficiency, and thus decreases in required power, should be able to be obtained through optimization of these nozzles and their deployment configuration. The ability of this cleaning tool to remove fouling without removal of the AF paint is extremely significant. Verification in prototype scale tests would substantially simplify and greatly reduce the cost of both construction and operation of an underwater hull cleaning vehicle since no filtration and handling system for the large quantities of water potentially contaminated by methods which release paint would be required.

5. ACKNOWLEDGMENTS

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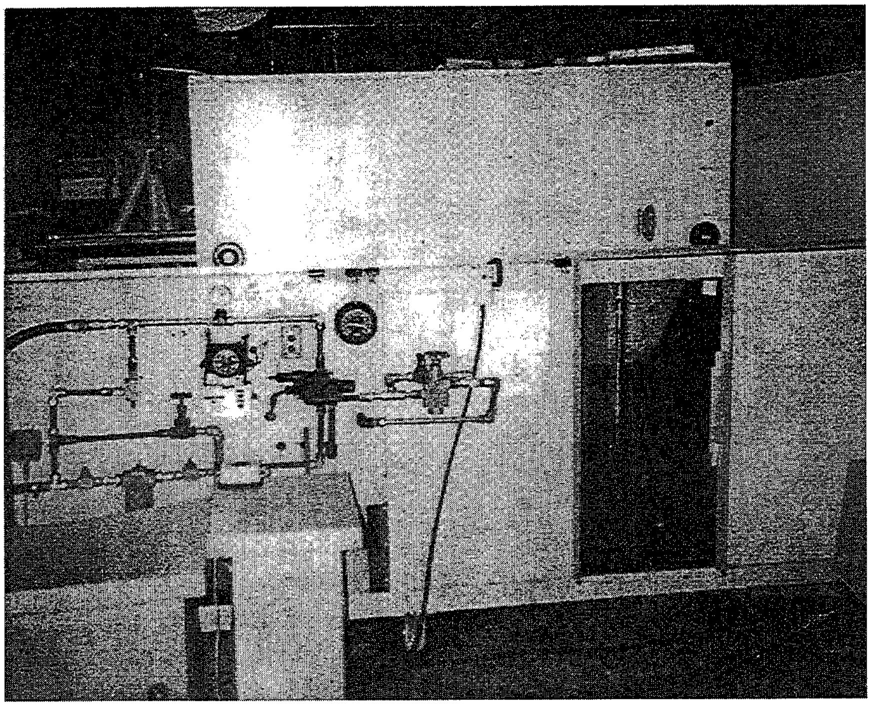
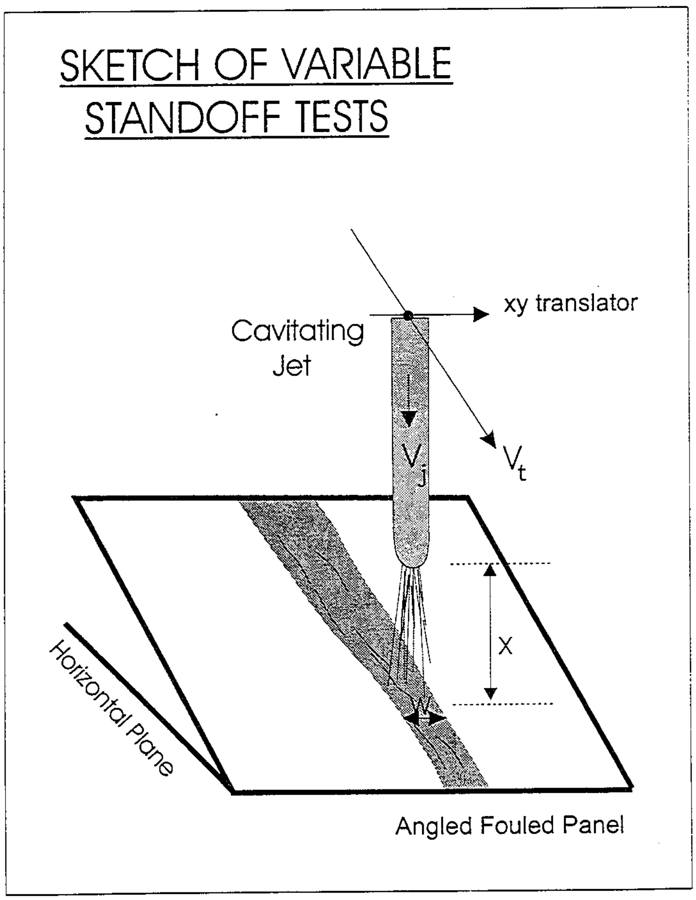
Table 1. Copper Concentrations in Effluents from Jetted Panels

Conditions	Concentration (ppb)	Comments
Background water	25-35	Well water
Jetting at 4.1 MPa	32	3 seconds exposure at speeds comparable to cleaning tool
Jetting at 6.2 MPa	28	3 seconds exposure at speeds comparable to cleaning tool
Jetting at 6.2 MPa	207	30 seconds exposure with dwelling to remove paint



a



b

Figure 1: Experimental setup for cavitating jet tests on sample panels. a) Test tank. b) Sketch of sample plate holder and translating nozzle.

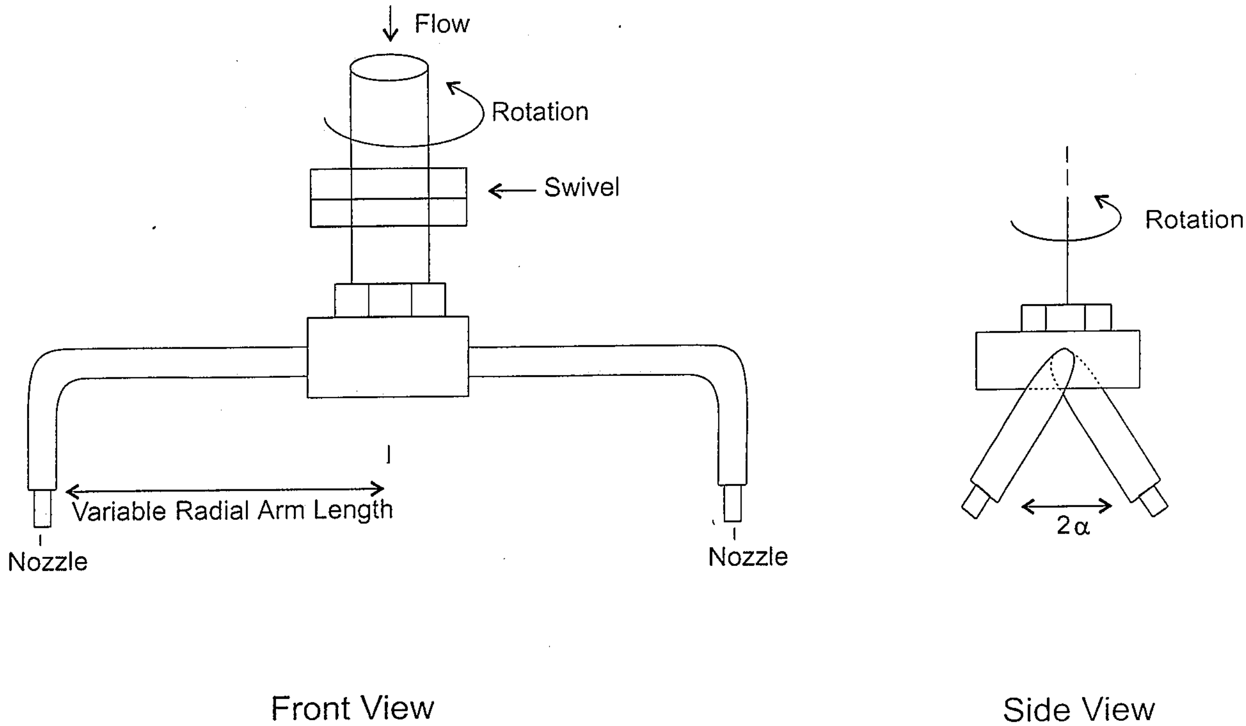


Figure 2: Sketch of rotating head configuration. Arm lengths tested were 7.5 – 20 cm.

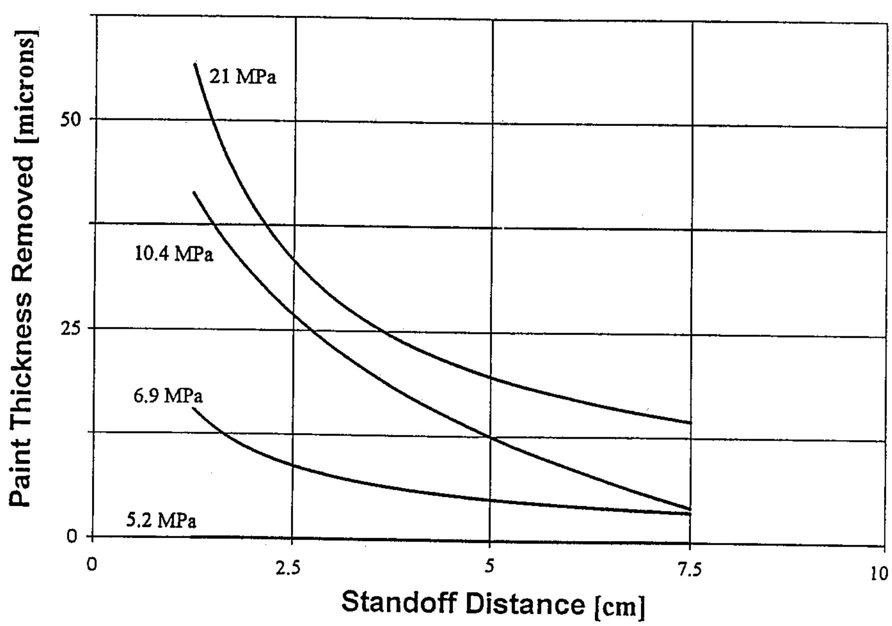


Figure 3: Curves fit to data showing influence of the standoff and pressure on paint removal at a translation velocity of 0.6 m/s.

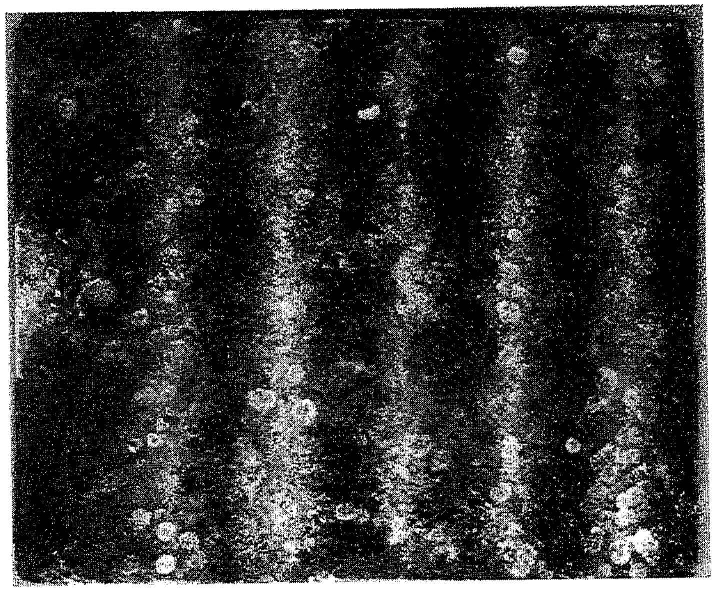


Figure 4: Photograph of a fouled panel illustrating cleaning following cavitating jet exposure at different conditions.

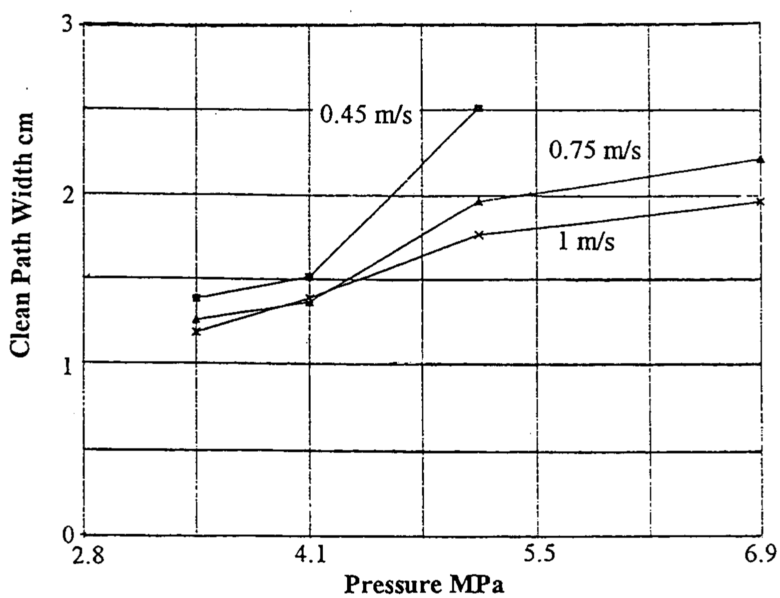


Figure 5: Influence of pressure and translation velocity on fouling removal at a fixed jet standoff of 4 cm.

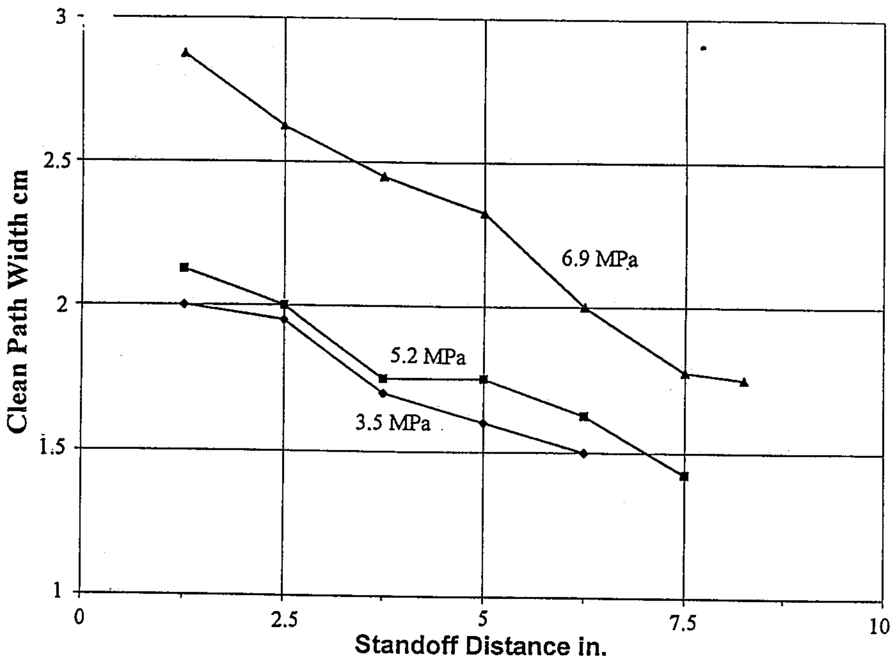


Figure 6: Influence of standoff and pressure on fouling removal at a translation velocity of 0.3 m/s.

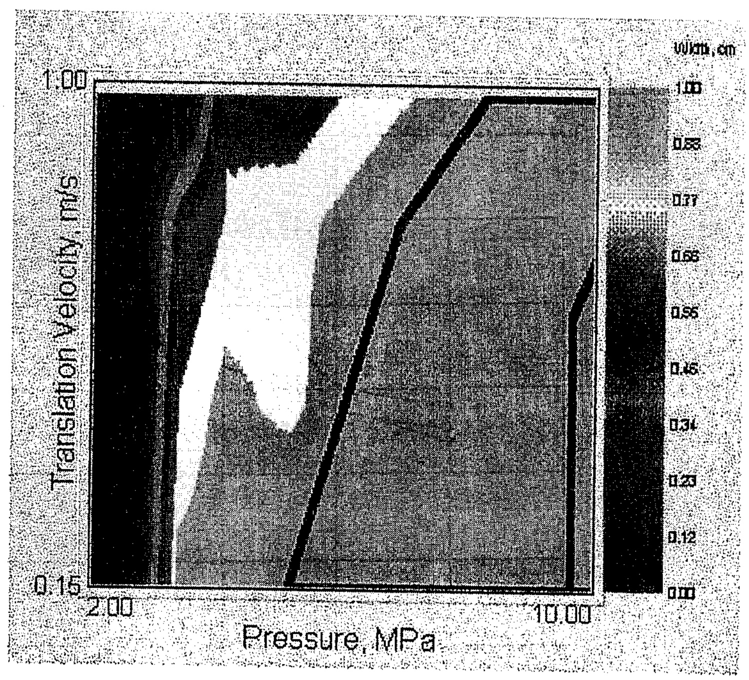


Figure 7: Contours of the cleaned path width as a function of pressure and translation veloccity at a 4 cm standoff. Desirable operating region for no paint removal is above and to the left of the left heavy black line which denotes the onset of paint removal. The second black line (on the right) denotes the threshold for removal of 13 microns of paint.

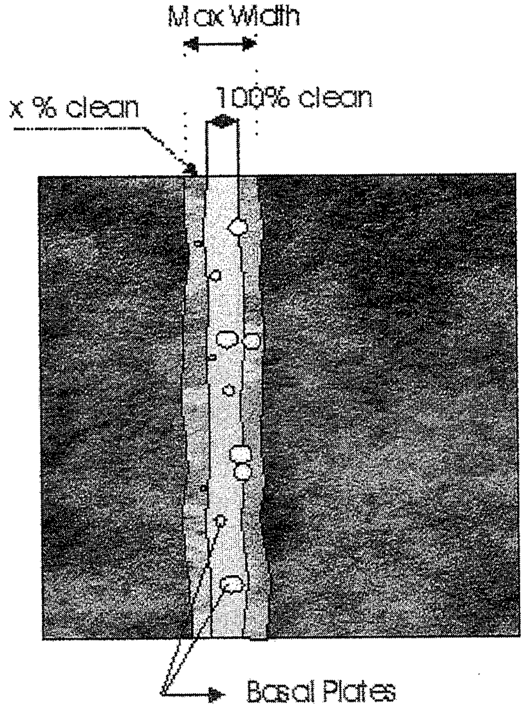


Figure 8: Schematic of typical pattern of fouling removal.

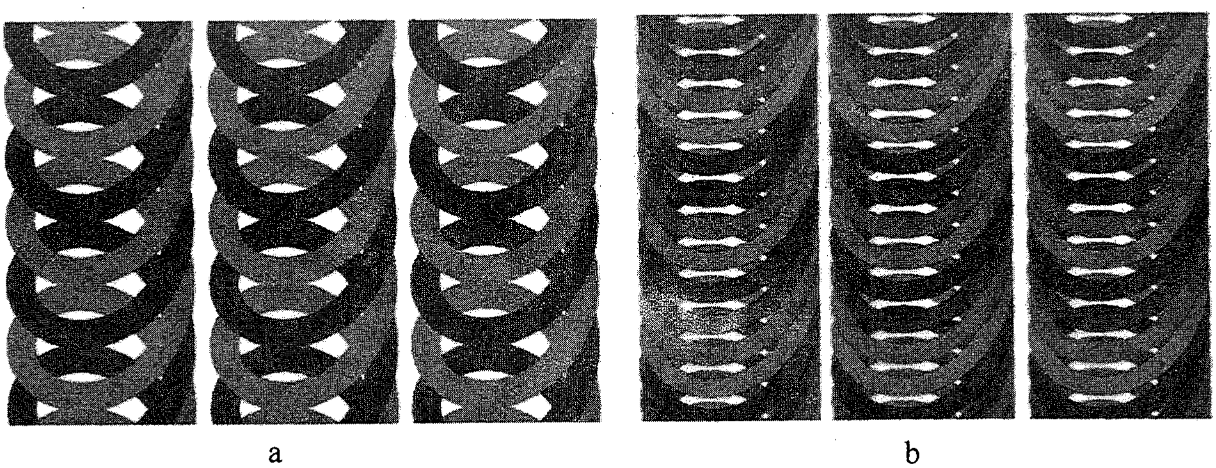


Figure 9: Sweep patterns for nozzles rotating at 160 rpm on 30 cm diameter heads as vehicle advances at 0.3 m/s. a) Two nozzles per head with individual clean path width of 2.5 cm. b) Four smaller nozzles per head with same total flow and individual nozzle clean path widths of 1.8 cm.

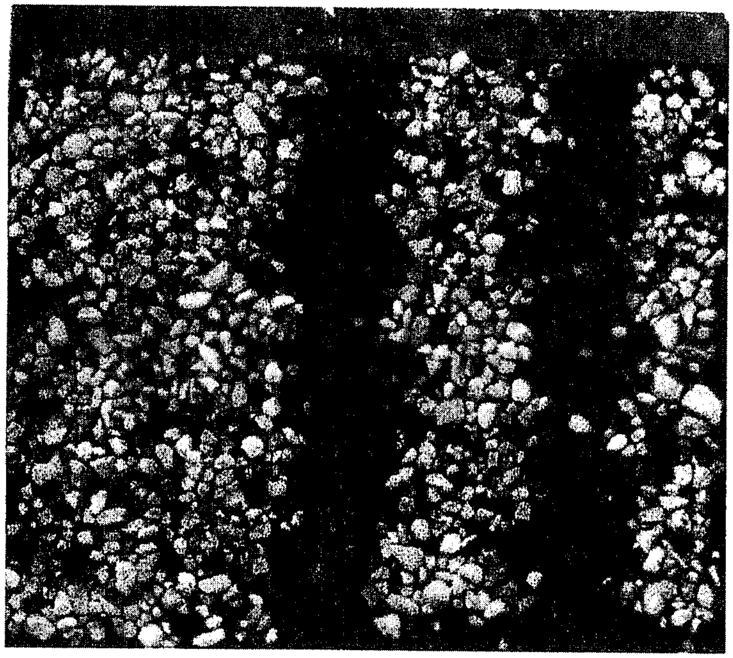


Figure 10: Photograph of panel with simulated fouling exposed to jetting. Left: 4.8 MPa. Right: 4.1 MPa.

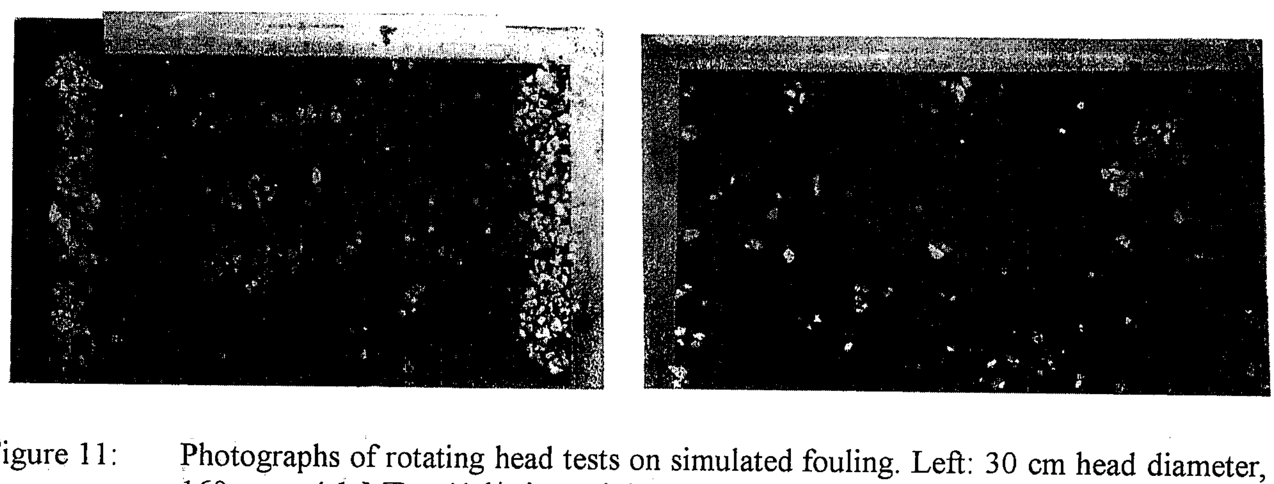


Figure 11: Photographs of rotating head tests on simulated fouling. Left: 30 cm head diameter, 160 rpm, 4.1 MPa, 41 l/min. Right: 15 cm head diameter, 190 rpm, 6.3 MPa, 30 l/min.

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Paper 40

RESEARCH ON THE EQUIPMENT FOR OIL PIPES INNER AND OUTER SURFACES CLEANING

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ABSTRACT

The process of boiling washings is being widely used for oil pipe cleaning in oil fields. While it is of great investment, it also has the disadvantages of high energy consumption, bad working condition and serious pollution. Test cleaning with high pressure water jet is done by the authors, and the result is very satisfactory. Under 70MPa pressure, all inner surface stain, outer surface paints and dirt accumulated on the screw are removed and the steel base is visible. In this paper, combining with the demands of oil fields, newly developed equipment for the cleaning of inner and outer surfaces of oil pipes is described. With jets from one rotating head and one swing rotating head acting on inner and outer surfaces respectively, the new process of oil pipes cleaning with clean water that has no pollution is achieved.

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1. REQUIREMENT OF OIL PIPE CLEANING

Oil pipe is also called oil well casing pipe. Because of the impurity in the crude oil, dirty will be adhesive to the surfaces of oil pipes after a period of use, these used oil pipes should be disassembled to clean. Generally, dirt on oil pipes contains bitumen, white wax and other organic matters that adhered tightly to the surfaces of oil pipe and is very difficult to remove. Because of this, special oil pipe factory must be set in every oil field to satisfy the cleaning requirement of disassembled oil pipes.

Traditional oil pipe cleaning is always with boiling detergent, that is, oil pipes are exposed in the open to be dried at first and then are put into a big pool that is filled with acid lye or washings to be boiled. Boiled oil pipes can be phosphorized directly or be mechanically cleaned with rotating reciprocating drill rod. Despite all this, cleaned oil pipes could not guarantee that its inner and outer surfaces are both clean. The reason is that the thickness of dirt is not the same, those large blocks seem to be dried, while still adhere to the surface, and thus are difficult to dissolve or separate entirely from the surface of oil pipe. Ratio of washings is also difficult to idealize, and with the decreasing of its concentration, its efficiency is also decreased. Thus uneven dirt still exists on surfaces of cleaned oil pipes in practice, it is more serious on the screw. Despite all this, this traditional process is still widely used in every oil field, because there is not a more ideal one to take the place.

In addition, there are many shortcomings that are difficult to overcome for oil pipe chemical cleaning. First, poison gas will volatilize from boiling washings, make the air be hazy, this is very harmful to the health of the workers, lower visibility affects the dragging of oil pipe. In some oil fields, mechanical drill rod is used to clean oil pipes after detergent boiled, it is very easy to hurt the inner surface of oil pipe, also the labor is very heavy. Besides, dirt is distributed everywhere, and while replacing the washings, dirt accumulated in the pool is very difficult to get out. So it is very necessary to improve the process of oil pipe cleaning.

The difficulty to clean oil pipes with high pressure waterjet is that the dirt is very sticky and of high adhesive. While standardized size of oil pipes makes it easy to design special used cleaning line. The authors studied the cleaning of 2.5 in. oil pipe which is widely used in oil fields, its specific size is as follows: ID: 62mm, OD: 73mm and Length is 9.7m.

2. CLEANING TEST WITH HIGH PRESSURE WATER JET

High pressure water jet cleaning is widely used in industrial cleaning field. Either pipe line, tubing bunch, vessel or plane could be cleaned with water jet depending on its normal striking and tangential stripping. However, to the specialized sticky dirt layer, many tests should be done to determine the power of water jet and optimize its technological parameters.

Striking force of high pressure water jet is always "useful for hard material and useless for soft". The authors tested different dirty oil pipes from Huabei oil field, Tuha oil field and Zhongyuan oil field. The pressure is 70MPa, power of cleaning machine is 55kW and 110kW respectively. With these two machines, under 70MPa pressure surfaces of oil pipes are cleaned satisfactorily, that is, the inner surfaces appear its even black base, white paints adhered tightly to outer surfaces are removed completely, all screws are white and shiny. The difference is cleaning velocity is higher when working with 110kW machine set than 55kW set.

For inner surface cleaning, rotating head and fixed multi-jet head are tested respectively. With rotating head, cleaning is even and there has no dirt left, while rotating head may stop rotating because of accidental external effect(such as bumping, adhesion, etc.)With fixed multi-jet head, only several clean grooves are left on the inner surface. Another important result is that jet contacts the surface with a fixed angle is better than perpendicularly. This shows the importance of tangential action of jet, similarly to the drill rod, it is the best way to let the jet rotate.

It could be concluded from tests that the 70MPa, 110kW(flow rate $4.2m^3/h$)high pressure waterjet cleaning machine assisted by rotating jets is the new technology for oil pipe cleaning, with this new process, oil pipe could be cleaned satisfactorily and only clean water at normal atmospheric temperature is needed. In order to realize the cleaning velocity(because the tested samples of oil pipe are short), rust removal test with jets under the same parameters is done by the authors, velocity reaches 2m/min., steel plate after rust removal appears to be white, and it exhausted only 4s for the outer surface cleaning of a 1m long oil pipe(power of cleaning machine is 55kW).

3. RESEARCHES OF CLEANING EQUIPMENT

The design principle of oil pipe cleaning equipment is taking advantage of rotating jet, rotating head is used for inner surface cleaning and swing rotating head for outer surface cleaning. Two jetting heads rotate relatively to the oil pipe and the oil pipe could be cleaned completely after only one stroke.

Sketch of oil pipe cleaning equipment is shown in Fig 1. The equipment consists of two 70MPa, 110kW high pressure reciprocating pumps, control table, executing mechanism and oil pipe feeding mechanism.

High pressure pump is the main part of the equipment. In order to guarantee its reliability and life of easily wear out parts, the high pressure reciprocating seal is designed to be a kind of combined seal of gap and packings with cone shaped sleeve and packings pressed together indirectly. Material of cone shaped sleeve is copper-beryllium. In this kind of seal, the hard and the soft help each other, also the pressing force do not transmit directly. The packings could remedy the sleeve's seal defects caused by the machining and wearing during operation, thus the seal life could be prolonged. The transport medium could be used directly for cooling and lubricating of the sealing pair.

The safety valve is used for over-load protection, and is of spring-cone valve structure. The pressure regulating valve is used for adjusting jet pressure to satisfy the requirement of cleaning operation. The control valve could relief the pressure. During the interval of cleaning, the control valve could be opened hydraulically or pneumatically, jets stop and the pump returns to the atmosphere pressure, and water flows back to water supply tank. While the next oil pipe is put in place, shut the control valve immediately, cleaning operation begins again. The control table could start and stop the two motors, also regulate the motion of feeding mechanism and its reciprocating velocity.

The device for feeding oil pipe is based on the existing device in oil field. The rolling wheels in this device drive the oil pipe to move forward and back, its feeding speed can be regulated by regulating electrical mechanism. The time consumed in washing a pipe is designed within 3 min., that is to say, the pipe moves forward 10m in 1.5 min. and back to the original position in another 1.5 min. Each rolling wheel is driven by belt at the end, the pipe is lifted and laid down by the hydraulic and the total device is manually controlled and operated.

In order to clean the inner and outer surfaces synchronistically, the inner and outer revolving head must be fitted at the same position, their rotating speed must be in concord with the moving speed of pipe. All these can guarantee cleaning the two surfaces thoroughly.

The two revolving heads are the keys to this research and the successes of the new technological process. The revolving head has been one of the key problems to be tackled in water jet technology. The higher the pressure, the more technological problems we encounter in this research. Fig 3 shows the structure of inner revolving head. It has two nozzles mounted at a distance from axis. The two nozzles can generate the torque needed to make the head rotate. This is one of the features of self-rotating head. To ensure the reliability of rotation under such a high pressure, there must be the seal specially designed for this purpose. We adopt the material of Be-Bronze to make the sleeve-shaped seal. This kind of clearance throttle and non-contact seal makes it possible to work continually under the pressure of 70MPa. The two nozzles fixed opposite along the circumference can generate the tangential reacting forces to make the head rotate. But after the head starts to rotate, if the revolving torque is not reduced, the rotation speed will become more and more high and will be as high as 1000 to 2000 rpm. At this state, the water jet will be severely atomized and will have no strike force remained to clean pipe. To avoid this, we design the retard mechanism using viscous liquid in revolving head. During rotation of the head, the viscous force will force the rotation speed down to about 100 rpm and shape of the jet can be kept in good condition.

It is very important that the inner revolving head be placed at the center of pipe, otherwise its rotation will be likely stopped by outside force. To overcome this, we place support mechanism on lance behind the head. In this device, plastic made rolling wheels are used to ensure the revolving head to be placed at the pipe's center.

The outer revolving head (showed in Fig. 3a) is specially designed in the shape of ring to clean the outer surface of oil pipe. It has four nozzles evenly mounted along the circumference of the inner ring. Its notable feature is that it is driven to swing by outside force. Using the level gear transmission and changeover mechanism, we can control the ringlike head to swing and acheive the ringlike revolving high pressure water jet. This kind of head is the patent we specially design for this kind of cleaning purpose.
The ringlike revolving head 's rotation speed is determined by

$$T = \frac{2V_x}{b \cdot n} \quad \text{rpm}$$

where V_x is the moving speed of oil pipe(cm/min.), b is the width of water jet(cm), and n is the number of evenly mounted nozzles.

Fan nozzles are used in the equipment, it is made by cutting a shaped semi-hole across the nozzle hole on the end surface of the cylinder nozzle. It can generate a fan jet. During cleaning procedure, it can sweep a wide belt and improve the cleaning efficiency. The diameter of the main hole is determined by

$$Q = 2.683 d^2 \sqrt{P}$$

where Q is the flow rate(L/min.), d is the diameter(mm) and P is the pressure(MPa).

Considering that the water consumption of the two 110kW units is $8m^3/h$ and the cleaning procedure is not allowed to stop, we can install container to collect the used water in working place. The used water is first collected in this container, settled and scraped the floating oil and other dirt, then filtered and transport to clean water container for reuse.

4. CONCLUSION

The device for cleaning the inner and outer surfaces of oil pipes synchronistically we have designed integrate the technologies of pump, valve, seal, control and jet working under high or ultra-high pressure. Its research will acheive the new technological process of cleaning the inner and outer oil pipes' surfaces synchronistically using normal temperature high pressure water. Now, the cleaning set for washing the inner surface of the oil pipe has worked in Zhongyuan oil field at a pressure of 70MPa and power of 110kW and gained favourable comments of the users. We will continue to improve the reliability and convenience of the working set and work hard to spread this research more quickly.

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FIGURES

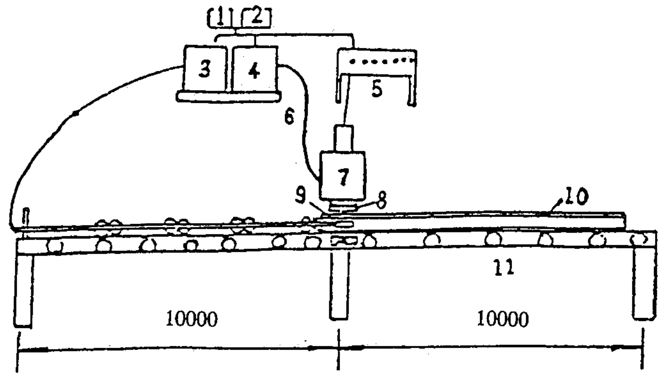

Fig 1 Sketch of Equipment for Oil Pipe Inner and Outer Surfaces Cleaning

1. Pressure Regulating Valve 2. Safety Valve 3. and 4. High Pressure Pump 5. Control Table 6. High Pressure Hose 7. Swing Rotating Device 8. Outer Surface Cleaning Head 9. 2-D Rotating Head 10. Oil Pipe 11. Feeding Mechanism

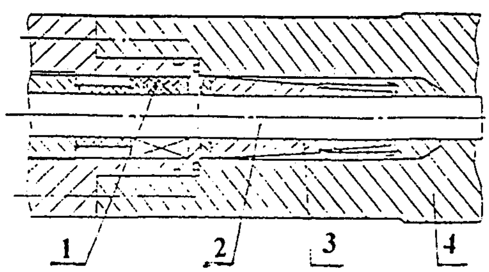

Fig 2 High Pressure Reciprocating Seal

1. Packings 2. Plunger 3. Sleeve 4. High-Pressure Cylinder

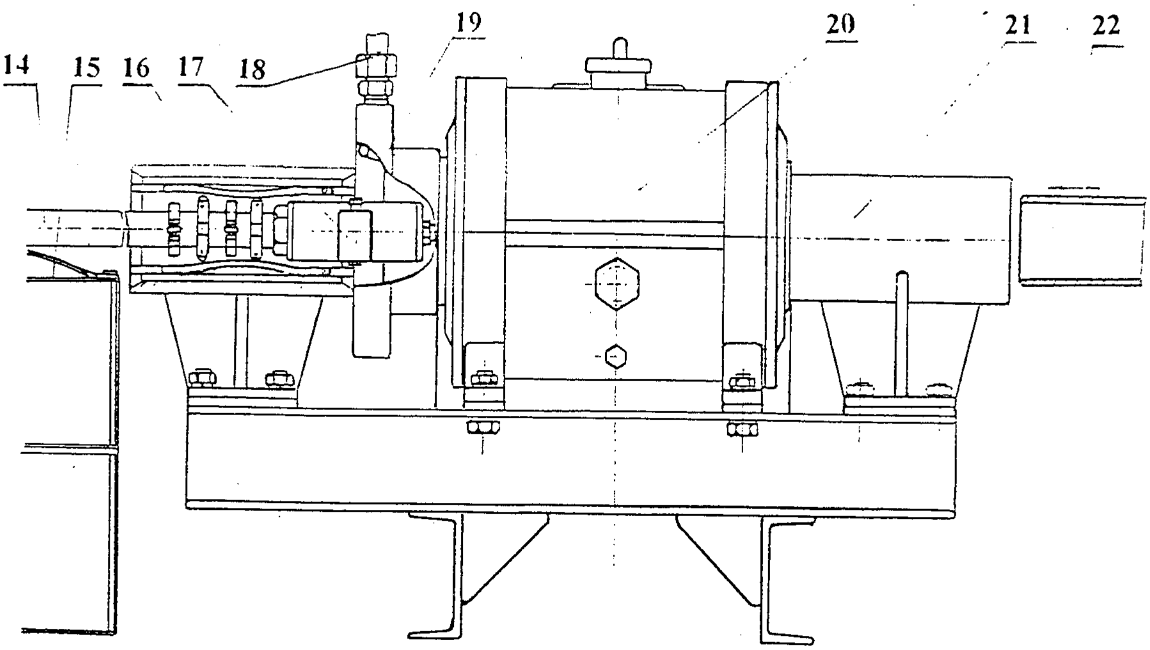

Fig 3 Rotating Head Device for Inner and Outer Surfaces Synchronistical Cleaning

14. Lance 15. External Support 16. Internal Support 17. 2-D Rotating Head 18. High Pressure Hose 19. Swing Rotating Head 20. Reversing Mechanism 21. Leading Tube 22. Oil Pipe

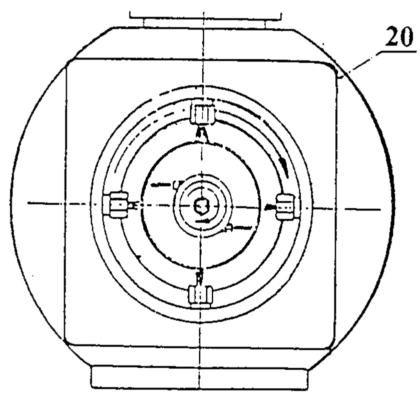

Fig 3a

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Paper 41

REMOVAL OF COATINGS WITH LOW PRESSURE PULSED WATER JETS

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ABSTRACT

Experiments were conducted to investigate the effectiveness of ultrasonically modulated high frequency pulsed water jets for removal of coatings. Several types of metallic samples coated with different types of paints (aircraft skins, automobile bumper castings, baked enamels, etc) were used in the investigation.

It was found that pulsed jets are very effective for removing several layers of coatings including the primer at pressures and traverse speeds in the range of 14 to 34.5 MPa and 0.3 to 3.0 m/min respectively. If interest is only in removing the paint without affecting the primer, the magnitude of pressure could be reduced to about 7 MPa. At such low operating parameters no damage to the metal substrate was observed.

Continuous jets, on the other hand, operating at pressures as high as 48 MPa, did not remove the primers. Based on these observations, it is concluded that pulsed jets have a great potential for commercial cleaning and removal of several types of coatings.

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1. INTRODUCTION

Defined in broad terms, coatings can be any substance that builds (generally undesirable) or, deliberately formed (desired protective coatings) on several metallic and non-metallic structures. Examples of undesirable coatings are: marine growth on sub-sea structures (Conn & Johnson, 1974), formation of tar and sulphur based deposits on coke oven doors (Brierley & Vijay, 1976; Conn, 1992), slags of several types in heat exchangers (Malaugh, et al., 1992), rust formation (Liu, et al., 1993; Jun, 1993), etc. Over a period of time, the protective coatings also loose their effectiveness and can be considered as undesirable. Several types of techniques including water jets (continuous, abrasive-entrained, submerged cavitating, etc) have been used to remove undesirable coatings from the structures. A few examples on removing some coatings with water jets are cited in Table 1.

It appears that removal of paints/coatings is a major concern worldwide (Foster, 1993; Gauthier, 1993; Hartley & Weeding, 1993; Holbein & Arnolds-Mayer, 1993; Kozol, 1993; Mooy, 1993; Smith, 1993 and Stein, et al., 1993). The major goal of the investigations reported in the literature is to replace toxic chemical and other environmentally unfriendly removal techniques (for example, dry sand blasting) with the safe and ecologically friendly systems. Therefore, a great deal of attention has been paid to various advanced techniques. These are: plastic media blasting (Christensen, 1993; Gillard, 1993; Pot, 1993 and Stoermer, 1993), lasers (Lovoi, 1993), ice particle-air blasting (Foster & Visaisouk, 1993), wheat starch blast media (Foster & Oestreich) and water jets (Brierley & Vijay, 1976; Conn & Johnson, 1974; Conn, 1992; Johnson, 1993; Jun, 1993; Liu, et al., 1993; Malaugh, et al., 1990; Scott & Hofacker, 1993; See, et al., 1993; Shengxiong, et al., 1992; Shengxiong, et al., 1993; Singh, et al., 1992; Volkmar, 1993 and Watson, 1993). Some of the novel techniques, other than pure water jets, appear to have more disadvantages than advantages. For instance, in the case of plastic media blasting, while hazardous chemical waste is reduced it is not entirely eliminated and, the possibility of damage to the substrate remains (Kozol, 1993). Therefore, in recent years, water jets have become quite popular for the removal of a variety of coatings (Conn, 1992; Johnson, 1993; Jun, 1993; Liu, et al., 1993; Malaugh, et al., 1990; Scott & Hofacker, 1993; Shengxiong, et al., 1992; Shengxiong, et al., 1993; Singh, et al., 1992; See, et al., 1993; Volkmar, 1993 and Watson, 1993). Examples listed in Table 1 demonstrate that water jets are capable of removing coatings of various thicknesses and hardness. With the exception of Conn (1992), all coatings removal operations have been carried out with continuous water jets and abrasive entrained water jets. The magnitude of pressure employed obviously depends on the type of jet, the coating and other factors such as the residual stress in the substrate. In order to eliminate the latter problem, it is highly desirable to use the lowest possible pressure. From this standpoint, low pressures (10 - 30 MPa) reported by Jun (1993) and Liu, et al., (1993) are quite attractive. However, they used large amount of abrasives (> 10 kg/min) which is generally not ecologically friendly. Holbein & Arnolds-Mayer (1993) also reported using low pressure water jets (< 50 MPa) which however required large amounts of nontoxic alcohol-based softening agents (in removing the paint from an aircraft, 2000 kg of alcohol was used). Although the softening agent is nontoxic, it contributes to the overall cost of the operation and may also pose some danger to the operator (for instance, continued inhalation may not be conducive to his/her health).

The focus in this paper is on the use of high frequency ***forced*** pulsed water jets for removing several types of paints from the metallic substrates. Note the stress on the word ***forced*** because this concept is radically different from the so-called servojets which are passively modulated water jets (Conn, 1992). The details on forced modulation and the ultrasonic nozzle device have been described by Vijay & Foldyna (1994) and Vijay, et al. (1995). Basically, by placing a vibrating tip in the nozzle (Fig. 1), a continuous stream of water is modulated to produce high frequency pulses (slugs) of water (Fig. 2; photograph taken with a Nd-Yag pulsed laser sheet light). Using this ultrasonic nozzle device, a series of tests on several types of coated metals was conducted. It is shown that even the hardest coatings can be removed with pulsed pure (tap) water jets at pressures $\leq$ 34.5 MPa. Furthermore, the technique offers the advantage of preparing the surface to required finish for recoating.

2. EXPERIMENTAL WORK ON PAINTED SURFACES

2.1 Experimental Facility

The experimental facility consisted of a Union pump, a 15 kHz ultrasonic nozzle (Fig. 1) with a fixed diameter (d_n = 1.70 mm) and a matching tip (d_t = 1.68 mm; $d_t/d_n \sim 1.0$) and a X-Y gantry (Fig. 3). The pump is capable of delivering 49 litre/min of water at 69 MPa. It should also be pointed out that a number of other variables (for instance, the distance 'a' indicated in Fig. 1) influence the characteristics of the pulses and hence the performance. However, based on the earlier work done in the laboratory (Vijay & Foldyna, 1994), the magnitudes of the variables selected in this investigation were close to optimum (that is, for which the area removal rate is considered to be maximum).

2.2 Materials

The characteristics of the coated metallic surfaces are as follows:

Aircraft Skins: The coating consisted of a well bonded primer coat compatible with a two-part finishing coating with two-part epoxy (yellow in color). It appears that these samples were taken from an old aeroplane.

Automobile Bumper Castings: The coating consisted of many layers of paints on aluminum comprising 25.4 microns of primer, 17.8 to 20.3 microns of base color coat and 38.1 to 50.8 microns of clear coat. The paint is solvent based low solids polyester melamine.

Hammond Aluminum Rack Panels: 3.2 mm thick aluminum panel treated with iron phosphate and then painted with a lead free alkyd paint that is impregnated with an etching agent to promote adherence to the metal. The painted panel is then baked in an oven at 176.7° C for 10 -15 minutes.

Steel Door Panel: The coating consisted of 25.4 microns of E-Coat baked on as the first coating followed by 25.4 microns of primer, 17.8 to 20.3 microns of base color coat, 38.1 to 50.8 microns of clear coat (127 to 152 microns total coating). The paint is solvent based low solids polyester melamine. The coatings were allowed to dry subject to certain specifications before baking in the ovens to achieve superior bonding characteristics.

Although this description is adequate to distinguish the types of coatings employed in the investigation, it is not, however, sufficient to fully understand the mechanism of material removal from the substrate.

2.3 Experimental Procedure and Results

2.3.1 Procedure

The experimental procedure was quite simple. Once the ultrasonic nozzle was assembled with the appropriate position of the tip (distance "a" in Fig. 1), it was mounted on the gantry (Fig. 3). The required pressure and traverse speed were then set and the nozzle was traversed over the sample to remove a swath of paint. In order to compare the performance of the pulsed jet with the corresponding (or, higher pressures) continuous jet, tests were repeated with no ultrasonic power input to the nozzle. In hand-held operations, the operator may use different angles of attack (see Fig. 4) or, may use swirling/oscillatory motions (see Fig. 5) of the gun over the surface to be treated. Some tests were conducted, without changing the operating parameters, in order to study the effect of the angle of incidence and the swirling motion on performance.

The performance of the nozzle design was evaluated using the rate of area removal (A_p) or, the specific energy (E_p) defined as the energy consumed (hydraulic power plus ultrasonic power input) per unit area of coating removed. Equations relevant to estimate these parameters are listed below (the variables are defined in the nomenclature):

$$A_p = W_p V_{tr} \qquad (m^2/min) \tag{1}$$

$$E_p = \frac{60(HHP + P_U)}{1000A_p} \qquad (MJ/m^2) \tag{2}$$

$$HHP = 0.013\varphi d_n^2 P^{3/2} \qquad (kW) \tag{3}$$

2.3.2 Results

First, a schematic diagram is illustrated in Fig. 6 to explain briefly a plausible mechanism of removal of the coating from the substrate. Quantitative data for the aircraft skin and the automobile bumper casting are depicted graphically in Figs. 7 to 17. In these figures, values of width of swath removed, rates of area removal and the specific energy are plotted as a function of the traverse speed (Figs. 7 to 11 for the aircraft skin and, Figs. 14 &15 for the bumper) and, the angle of incidence (Figs. 12 & 13 for the aircraft skin and 16 & 17 for the bumper) with the pressure or the standoff distance as parameters. The values of nozzle diameter and other parameters are as indicated in the figures (nozzle #: 067 implies that the diameter of the orifice is 0.067 in ≈ 1.70 mm; similarly MT#: F66 implies that the diameter of the tip, d_t, is 0.066 in ≈ 1.68 mm). It should also be stated that for the sake of brevity and clarity, detailed data for the rack panel and the automobile door are not presented.

Qualitative results, that is, appearance of the metallic substrates are depicted in Figs. 18 to 24. These are included to show the surface finish of the samples treated with pulsed water jets and, to emphasize the fact that continuous water jets, operating at pressures of the order of 69 MPa, were totally ineffective to remove the primers. These figures also confirm, to certain extent, the explanation given for the mechanism of coatings removal from the substrates.

3. DISCUSSION

3.1 Mechanism of Removal (Fig. 6)

How a coating is removed from a substrate depends upon the nature of the jet (pulsed, continuous, etc.) and the nature of the coating (brittle or ductile, thick or thin). It appears that the mechanism put forward by Erdmann-Jesnitzer, et al. (1978, 1980) and Foster & Visaisouk (1993) is applicable to coatings removal by pulsed jets. It should be noted, however, that the interrupted jet described by the former authors is not truly a pulsed jet because the length of the jet is far greater than its diameter. Fig. 2 shows that the pulsed jet generated by ultrasonic modulation consists of a chain of mushroom shaped slugs of water separated by short small diameter jets. These slugs are somewhat akin to the ice particles discussed by Foster & Visaisouk (1993). When these slugs of water impinge on the coating, depending on the magnitude of the dynamic (water hammer) pressure, the impact loading could be elastic (that is, coating is deformed, but not removed) or elastic-plastic (the coating is stressed beyond elastic limit).

On brittle coatings, at a pump pressure of the order of 7 MPa, the impact pressure (≈ 160 MPa) of the slug produces a compressive force that exceeds the strength of the top layer. This initiates a hemispherical crack (fracture) on the layer (Fig. 6b). With further impacts, the crack propagates radially through the layers to the bottom layer/primer interface (Fig. 6c). The thin stream of water then enters these cracks and peels off the coatings layer by layer. As the pump pressure is increased further ($7 \leq P \leq 34.5$ MPa), the unsteady impact forces exceed the cohesive forces (covalent bonds, ionic bonds or cross-linking; Foster & Visaisouk 1993) between the substrate and the primer. At this stage the thin streams will not only remove the primer but may start to erode the substrate (Fig. 6d). Thus, cracks generated by the frequent high unsteady impact forces imparted by the slugs and their intrusion by the radial flow of the thin streams appear to be the primary mechanisms by which the coatings are peeled off the substrate.

Evidence of the fracture mechanism of paint layer and erosion mechanism at the primer/metal interface came from microscopic examination of an aircraft skin surface subjected to pulsed jet impacts (see Figs. 19 & 20). These figures show that while the coatings were removed by fracture mechanism, the pits on the substrate were due to erosive mechanism. Cracking of the paint layers can be clearly seen in Fig. 22.

3.2 Quantitative Results

Figures 7, 8 & 9 (Aircraft Skin): As discussed earlier, the area removal rate (A_p) and the specific energy (E_p) are dependent on the width of the primer (paint) removed {Eqs. (1 & 2)}. In Fig. 7, widths of primer removed are plotted against the traverse speed at pressures and standoff distances as indicated. Magnitude of pressure indicated for a particular standoff distance is the safe operating pressure, (that is, it is the pressure at which no damage to the substrate occurred). As expected, the width of cut decreases as the traverse speed is increased. Using linear regression analysis, the following equations were obtained for the widths:

$$W_p = 10^{-3}(4.0356 - 1.1044V_{tr}) \quad \text{(m)} \qquad \text{(for } P = 34.5 \text{ MPa)} \tag{4}$$

$$W_p = 10^{-3}(3.9791 - 1.3571V_{tr}) \quad \text{(m)} \qquad \text{(for } P = 17.2 \text{ MPa)} \tag{5}$$

$$W_p = 10^{-3}(3.5067 - 1.5722V_{tr}) \quad \text{(m)} \qquad \text{(for } P = 13.8 \text{ MPa)} \tag{6}$$

As A_p is the product of W_p and V_{tr} {Eq. (1)}, an optimum traverse speed exists at which A_p is maximum. By substituting Eqs. (4, 5 & 6) into Eq. (1) and differentiating, it can be shown that the optimum traverse speeds are 1.83, 1.46 and 1.1 m/s respectively for the three pressures listed above. These values are in close agreement with the data plotted in Fig. 8. Similar reasoning shows that E_p will be minimum at the optimum traverse speeds (Fig. 9).

It is obvious from Fig. 9 that there is no need to use pressures greater than 14 MPa if the operation is to be conducted by a hand-held gun at traverse speeds in the range of $1.0 \leq V_{tr} \leq 1.5$ m/min (conceivably this is a comfortable range for the operator). However, pressures in excess of this value up to 34.5 MPa can be used if the operation needs to be carried out at higher traverse speeds ($2 \leq V_{tr} \leq 3$ m/min). In all the cases considered, continuous water jet was unable to remove the primer.

Figures 10 & 11 (Aircraft Skin): These figures on the area removal rates of the primer and, specific energy against traverse speed at a constant value of the nozzle pressure (P = 17.3 MPa) are included to emphasize the importance of standoff distance and other considerations. The main observations from these figures are:

- For a given pressure, there is a certain distance, called break-up length, below which the jet remains continuous. Therefore, the sample needs to be placed at a standoff distance greater than the break-up length (> 0.025 m in the plot) in order to expose it to pulsed water jets. Peak performance was obtained at a standoff distance of 0.0635 m. At this distance, well developed large pulses are formed (see Fig. 2). As the standoff distance is increased further, the pulses break up into small droplets and their effectiveness starts to decrease as evidenced by the data at S = 0.0762 m (for more details, refer to Vijay & Foldyna, 1994).
- The data refer to the rate of removal of the *primer*, not just the paint. Therefore, if only paint removal is of interest (that is, leaving behind a clean primer coating), it can be achieved at pressures much lower than the values indicated in this and all other figures.

- Continuous water jet operating at the same parameters as the pulsed jet was unable to remove the paint leave alone the primer.
- Once again, for a given standoff distance, the rate of removal of the primer peaks at a certain traverse speed which is the optimum value.
- It is interesting to note that when the standoff distance is optimum (≈ 0.0635 m), E_p is fairly insensitive to variations in the traverse speed in the range from 0.7 to 1.5 m/min (Fig. 11).

These results are encouraging whether the paint removing job is conducted with a hand-held gun or a robotically controlled system. In the case of a hand-held gun, the operator will have some flexibility in operating the gun (that is, varying the traverse speed or the standoff distance) without adversely affecting the area removal rate. Also, the fact that the work can be done at such low pressures indicates that the problem posed by reaction forces will be minimal (in the case of an operator, this will reduce the fatigue problems; for robotic systems, reliability will improve as their performance is quite sensitive to reaction forces).

Figures 12 & 13 (Aircraft Skin): In these figures the influence of the angle of impact (see Fig. 4 for definition) on the removal of coatings is depicted. Both figures show, for this paint and for the particular operating variables indicated, that increasing the angle from the normal direction has an adverse effect on the process of removal. This is probably due to the fact that at the pressure of 17 MPa, the magnitude of the normal component of force is less than the force required to initiate cracks in the paint. This observation implies that in hand-held operations, the operator should not deviate the gun from the normal direction by more than 5 degrees. Further work at higher pressures is required to find out if operating at larger angles of impact ($5° \leq \theta \leq 20°$) would enhance (or, keep intact) the performance (it would be very hard for the operator to keep the gun steady at a fixed angle for long periods of time). In all these tests, the area removal rate obtained with the continuous water jet was almost zero ($E_p \rightarrow \infty$).

Figures 14 & 15 (Car Bumper Casting): In these figures preliminary results obtained on removing multiple coatings from a car bumper casting are depicted. The magnitudes of the operating parameters (pressure, standoff distance, etc.) employed in these tests were based on the observations made above on the aircraft skins. It should be kept in mind that here many layers of paints were needed to be removed before reaching the primer.

In Fig. 14 area removal rates are plotted against traverse speed for a fixed standoff distance of 0.051 m at three distinct pressures (10.4, 13.8 and 17.2 MPa). Obviously at 10.3 MPa the primer is barely removed (this value can be considered as threshold pressure). At traverse speeds up to 1.5 m/min, the primer can be removed at 13.8 MPa. However, a slight increase in pressure to 17.2 MPa seems to have significant benefits at traverse speeds greater than 1.5 m/min. For instance, at the traverse speed of 3.0 m/min (≈ optimum speed), the area removal rate is almost 2.7 times the rate obtained at the pressure of 13.8 MPa.

Specific energy data are plotted in Fig. 15. The advantage of operating the nozzle at a pressure of 17.2 MPa can now be clearly seen. Not only does the magnitude of specific energy decreases as the traverse speed is increased, but it virtually remains constant in the range from 2.3 to 3.1 m/min. Once again, as in the case of aircraft skin, this affords the operator considerable flexibility in operating the gun without sacrificing the performance. Needless to state that no primer or the paint was removed with the continuous water jet.

Figures 16 & 17 (Car Bumper Casting): In these figures area removal rates (Fig. 16) and specific energy values (Fig. 17) are plotted as a function of the angle of incidence. Compared to the aircraft skin, these data show that the performance is not affected when the angle of incidence is increased up to 10°. A further increase to 20 ° has a slight adverse effect on performance. The reason for this behavior appears to be due to chipping of the paint which is quite brittle (see Fig. 22). Once the first layer of the paint is penetrated, the crack can easily penetrate through and between different layers of coatings. For changes in the angle up to 10°, there is sufficient energy in the jet to remove the primer without affecting the performance. In this case, the operator has some flexibility in operating the gun.

Obviously, the effect of angle of incidence depends on the type of coating. This observation is supported, to some extent, from the results reported on the removal of thermal spray coatings by Watson (1993) and Singh, et al., (1992). The former author found that the best results were achieved when the angle of incidence was 90°. The latter, on the other hand, stated that the 45° angle of attack was better. However, it should be noted that definition of the angle is different from the definition given in this paper.

3.3 Qualitative Results

Figures 18 to 24 (Aircraft Skin, Car Bumper Casting, Rack Panel & Car Door): These figures are included for qualitative discussion on the characteristics of the substrates exposed to both continuous and pulsed water jets. The most important point to keep in mind is that the substrate should remain intact after exposure to the jet (no deep pits, no water ingress and no residual strains such as warping etc.).

Figure 18 (aircraft skin) shows a comparison between the performance of pulsed (Test # 93) and the continuous jet (Tests # 94 & 95). It is clear that whereas the pulsed jet at a pressure of only 10.4 MPa removed the paint and almost the primer, the continuous jet required pressure in excess of 34.5 MPa to remove just the paint.

Figures 19 and 20 show the effect of standoff distance on the removal of paint from the aircraft skin exposed to pulsed water jet at 27.6 MPa. Both figures show evidence of surface erosion at this pressure. However, it is clear from Fig. 19 that the primer is not removed at many locations. This is probably due to the fact that at this standoff distance (0.152 m), the pulses have broken into droplets which are randomly distributed within the cross-section of the jet. A decrease in the standoff distance to 0.127 m results in uniform erosion of the substrate consisting of microscopic pits. This is not necessarily a negative effect because it provides the surface profile necessary for good primer cohesion and removes chemically bound corrosion products prior to re-coating. However, in some other situations, surface erosion can lead to serious problems of structural integrity especially if the metal is thin. Such problems can be avoided by setting appropriate operating variables for a given nozzle configuration.

For the car bumper casting, comparison of the performance between the pulsed and continuous jet is shown in Fig. 21 (Tests # 248 & 249 respectively). The pulsed jet, operating at a pressure of 17.2 MPa and a traverse speed of 0.305 m/min, removed all the layers including the primer. The continuous jet (Test #249), on the other hand, operating at the same parameters, removed the top coating only. Furthermore, the pulsed jet seems to retain its effectiveness even at the highest traverse speed (3.05 m/min; Test #254), albeit with a small reduction in the width removed.

Figure 22 (car bumper casting) shows that larger areas of the coatings can be removed by manipulating the nozzle motion over the surface. Obviously, the operator will use a combination of rotary (swirling or helix), oscillatory and linear motion over the surface to maximize the area removal rates. If a robotic system is employed for the application, rotary motion will maximize the area removal rate.

Figure 23 clearly shows the dramatic difference between the performance of continuous and pulsed water jet. The hard coatings including the primer on this metal panel was removed with the pulsed jet at a pressure of only 6.9 MPa (1,000 psi). The continuous jet, on the other hand, simply cleaned the surface at a pressure as high as 62 MPa (9,000 psi).

Figure 24 shows the results of tests done on the car door. These tests were conducted for demonstrating that pulsed jets can indeed remove hardest coatings. As discussed earlier, the coating on the door consisted of several layers bonded quite strongly to the metallic substrate. At a pressure of only 34.5 MPa (V_{tr} = 1.52 m/min), the pulsed jet removed all the coatings including the primer. The continuous jet, on the other hand, operating at the same pressure and a significantly reduced traverse speed of 0.305 m/min did not even remove the top coating. As discussed in the case of aircraft skin, the surface profile generated by the pulsed jet appears to be favorable for repainting.

4. CONCLUSIONS

A series of tests was conducted on removing various types of coatings with continuous and pulsed water jets. The high frequency (15 kHz) pulsed water jet was generated by an ultrasonic nozzle device. Conclusions from these results are:

- Even the hardest coatings, such as the one on the automobile door, could be removed with the pulsed jet at pressures of the order of 34.5 MPa. At this pressure, the standoff distance and traverse speed can be as high as 0.127 m and 3.0 m/min respectively.
- It is possible to significantly increase the area removal rates by manipulating the nozzle motion (rotary, etc.) over the surface.
- A favorable surface profile for strengthening the adhesion between the substrate and fresh coating could be achieved by employing appropriate operating parameters.
- The pulsed water jet technique appears to be technically competitive with the other advanced systems reported in the literature (plastic media blasting, etc).
- The pulsed jet technique uses only pure (tap) water and does not need any agents to soften the coatings. Lower pressures, elimination of agents, abrasives, etc., makes the technique not only economical but, user and ecologically friendly.

Based on this experimental investigation, the design and manufacture of a compact, economically attractive and portable pulsed water jet machine is in progress. The specifications, operating characteristics and performance of this new machine will be reported in a future publication.

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7. NOMENCLATURE

A_p Area removal rate, m^2/min
d_n Nozzle orifice diameter, mm
d_t Tip diameter, mm (See Fig. 1)
E_p Specific energy, MJ/m^2
f Frequency of modulation, kHz
HHP Hydraulic power input, kW
P Static pressure in the nozzle, MPa
P_U Ultrasonic power input, kW
S Standoff distance, m
V_{tr} Traverse speed, m/min
W_p Width of swath removed, m
θ Angle of incidence, deg (See Fig. 4)

Table 1. Summary of sample results on coatings removal applications reported in the literature.

Reference	Type of Coating(s)	Water Jet Technique	Parameters	Cleaning Rate
Brierley & Vijay (1976)	Sulphur, tar and carbon deposits on the walls of a gooseneck pipe in a steel mill (Stelco Steel Company in Canada)	Continuous	P = 41.4 MPa, d_n = 1.60 mm (two rotating orifices), HP = 41 kW	2.1 m^2/min
Conn (1992)	Carbon-like buildups in coke oven doors in a steel mill (Bethlehem steel)	Servojet (pulsed jets)	P = 69 MPa, d_n = 0.86 mm, HP = 14 kW	Not reported
Singh, et al. (1992)	Thermal Spray Coatings (two-wire electric sprayed 95/5 Ni-Al coating widely used to rebuild aircraft engine components). Bond strength can easily exceed 70 MPa (> plasma-sprayed coating). Thickness = 0.75 mm. Thickness of the coating in the JT8D burner can = 0.38 mm.	Ultra-High Pressure (rotating head)	P = 310 - 350 MPa, d_n = 0.35 mm, HP = 23.9 kW	0.108 m^2/min (JT8D burner)
Shengxiong, et al. (1992)	Ships rust	AWJ (abrasive water jet)	P = 70 MPa, Flow rate = 35 l/min, Sand (quartz sand grain = 0.3 - 0.5 mm) flow rate = 3.2 kg/min, d_n = 1.5 mm, HP = 39.4 kW	0.63 m^2/min
Watson, (1993)	Thermal Spray	Ultra-high Velocity	P = 379 MPa, d_n = 0.229 mm, HP = 9.48 kW	Cut width: 0.254 - 0.305 mm
Johnson, (1993)	Thermal Spray	Ultra-high Velocity	P = 248 - 414 MPa	Not reported
Liu, et al. (1993)	Ships rust	AWJ	P = 10 MPa, Flow rate = 30 l/min, Sand flow rate = 12 kg/min, d_n = 2.3 mm, HP = 5 kW	0.28 m^2/min
Jun, (1993)	Rust	AWJ	P = 10 - 30 MPa, Flow rate (per nozzle) = 10 - 16 l/min, Sand (size = 60 to 80 mesh) flow rate (each nozzle) = 2 to 3 kg/min, No. of nozzles = 6, Slurry pressure = 1.2 MPa.	0.8 - 1.0 m^2/min

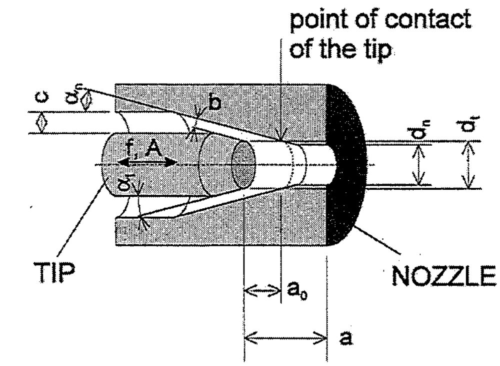

Fig. 1 Geometric configuration of the ultrasonic nozzle (Vijay & Foldyna, 1994).

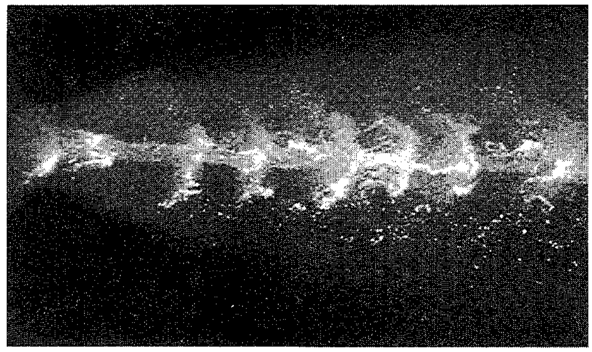

Fig. 2 Typical appearance of ultrasonically modulated pulsed water jet (Vijay, Lai & Jiang, 1995)

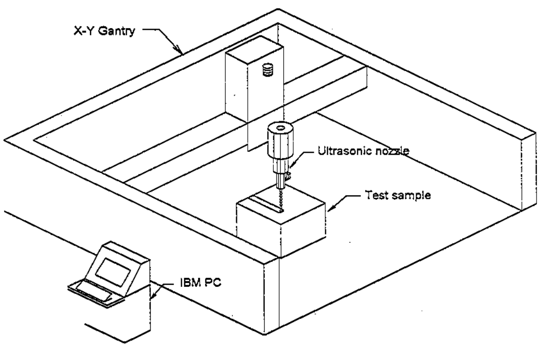

Fig. 3 A schematic diagram of the gantry showing the relative positions of the nozzle and sample.

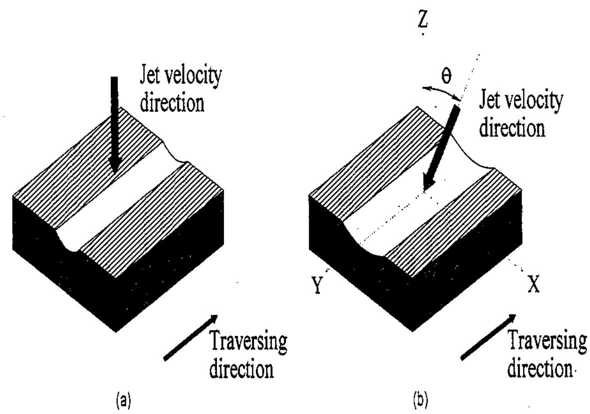

Fig. 4 Definition of the angle of incidence (θ) relative to the direction of traverse.

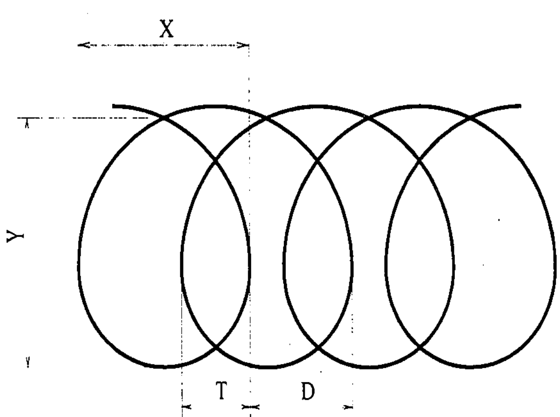

Fig. 5 Rotary (swirling or helix) motion of the nozzle over the painted surface.

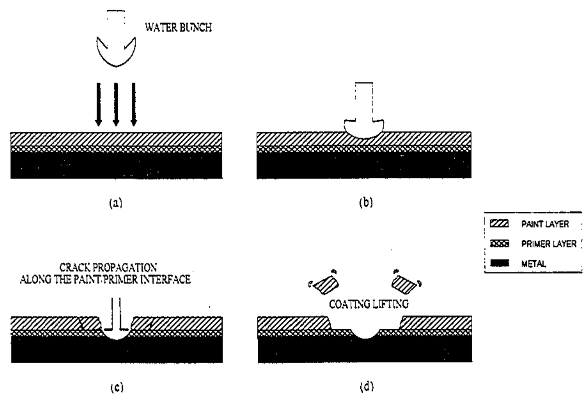

Fig. 6 A schematic diagram to explain the mechanism of removal of the coating from the substrate.

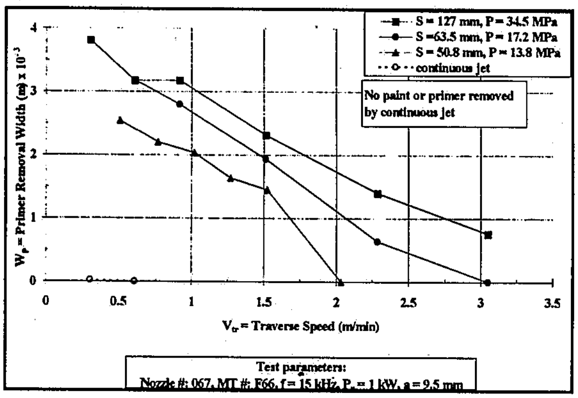

Fig. 7 Plot of W_p against V_{tr} at standoff distances (S) and pressures (P) as indicated (aircraft skin).

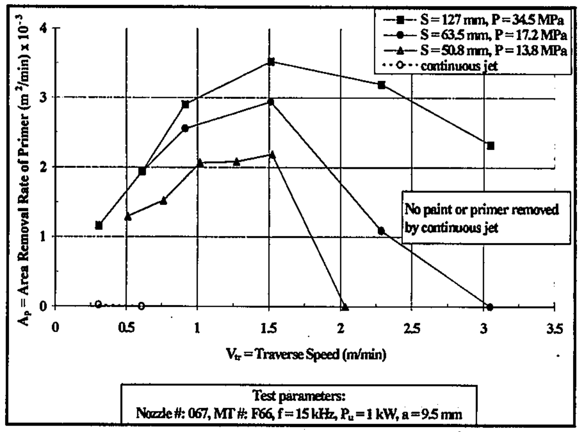

Fig. 8 Plot of A_p against V_{tr} at values of S and P as indicated (aircraft skin).

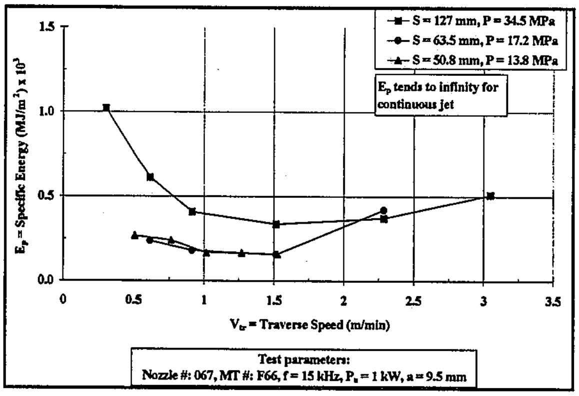

Fig. 9 Plot of E_p against V_{tr} at values of S and P as indicated (aircraft skin).

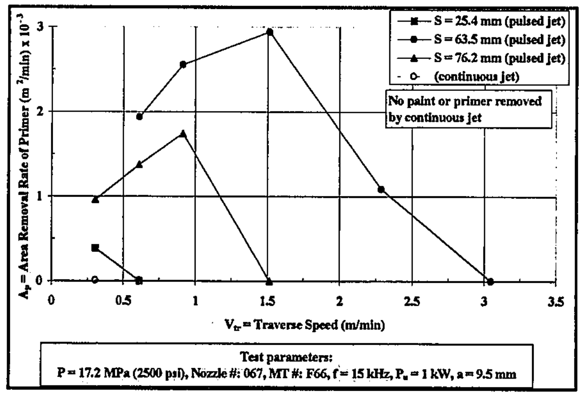

Fig. 10 Plot of A_p against V_{tr} at values of S and P as indicated (aricraft skin).

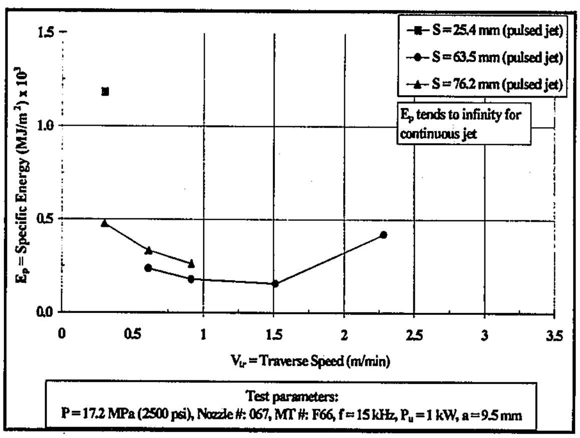

Fig. 11 Plot of E_p against V_{tr} at values of S and P as indicated (aircraft skin).

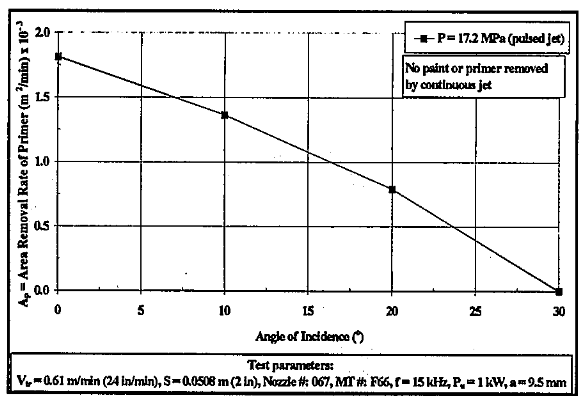

Fig. 12 Plot of A_p against the angle of incidence (θ) for aircraft skin. For definition of the angle, see Fig. 4.

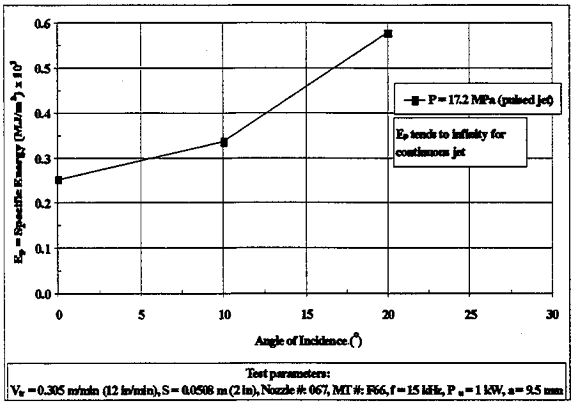

Fig. 13 Plot of E_p against the angle of incidence (θ) for aircraft skin.

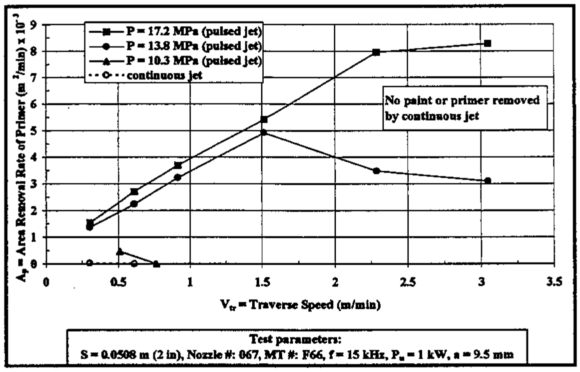

Fig. 14 Plot of A_p (removal of multiple coatings) against V_{tr} at pressures as indicated (car bumper casting).

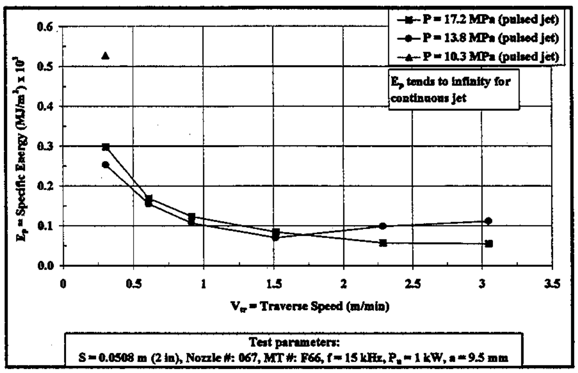

Fig. 15 Plot of E_p (removal of multiple coatings) against V_{tr} at pressures as indicated (car bumper casting).

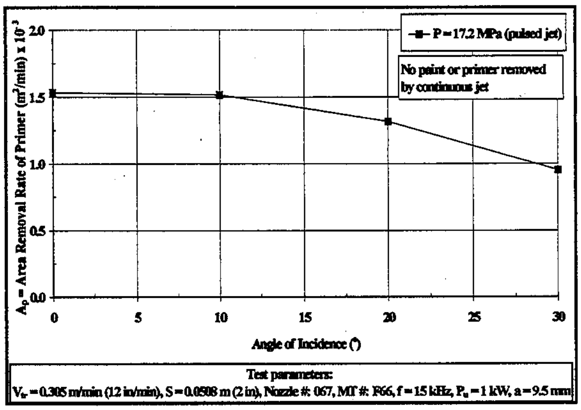

Fig. 16 Plot of A_p against the angle of incidence (θ) for the car bumper casting.

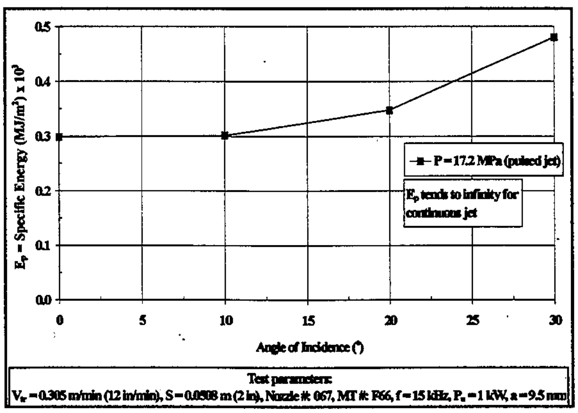

Fig. 17 Plot of E_p against the angle of incidence (θ) for the car bumper casting.

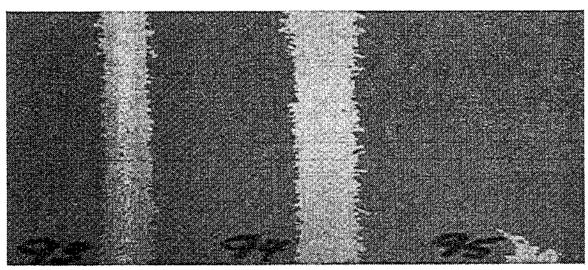

Fig. 18 Appearance of the surfaces of the aircraft skin showing the comparison between the pulsed jet (Test# 93; P = 10.4 MPa) and the continuous jet (Test# 94 at 48.3 MPa and Test# 95 at 34.5 MPa). V_{tr} = 0.254 m/min and S = 0.051 m**.

**Patented nozzle (Vijay, M.M., Ultrasonically generated cavitating or interrupted jet. U.S. Patent No. 5,154,347, 1992).

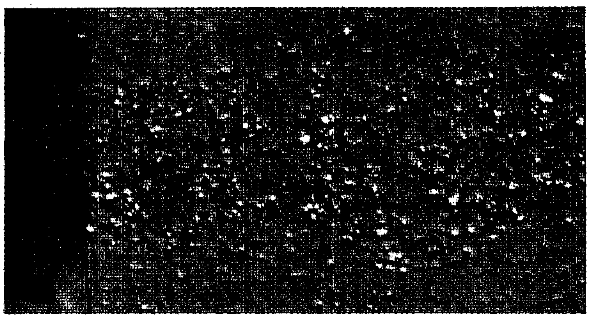

Fig. 19 Appearance of the surface of aircraft skin exposed to pulsed jets (Test# 91). Nozzle#: 067, MT#: 066, a = 9.5 mm, P_U = 1 kW, f = 15 kHz, P = 27.6 MPa (4000 psi), S = 0.152 m (6.0 in), V_{tr} = 0.305 m/min, Magnification = 18.

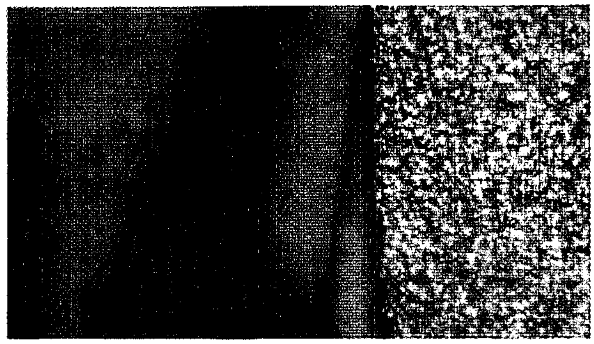

Fig. 20 Appearance of the surface of aircraft skin exposed to pulsed jets (Test# 79). Same configurational and operating parameters as in Fig. 16, except S = 0.127 m (5.0 in) and Magnification = 28.

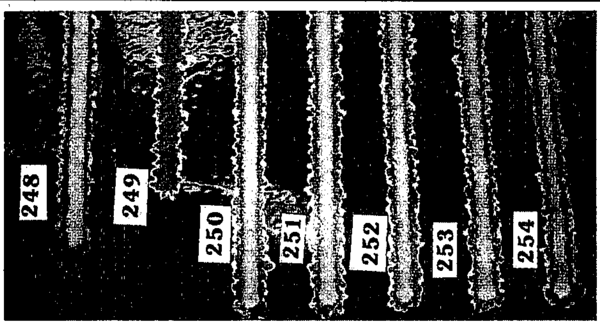

Fig. 21 Appearance of the surface of the car bumper casting showing the comparison between pulsed jet (Tests# 248, 250, 251, 252, 253, 254; V_{tr} = 0.305, 0.61, 0.914, 1.524, 2.29 and 3.05 m/min respectively) and continuous jet (Test# 249, V_{tr} = 0.305 m/min). P = 17.2 MPa, S = 0.051 m.

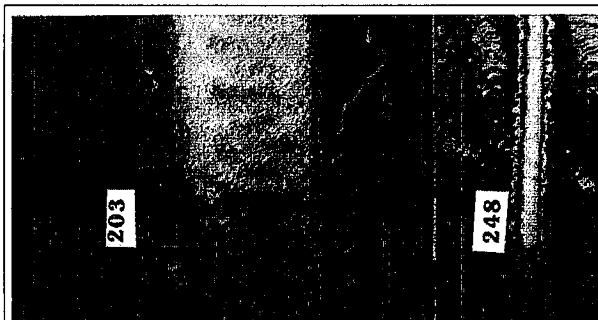

Fig. 22 Appearance of the surface of the car bumper showing the comparison between the rotational test (helix motion of the nozzle; Test#203 at P = 13.8 MPa, tangential speed = 1.52 m/min & V_{tr} = 0.254 m/min) and linear test (Test # 248 at P = 17.2 MPa & V_{tr} = 0.305 m/min). S = 0.051 m.

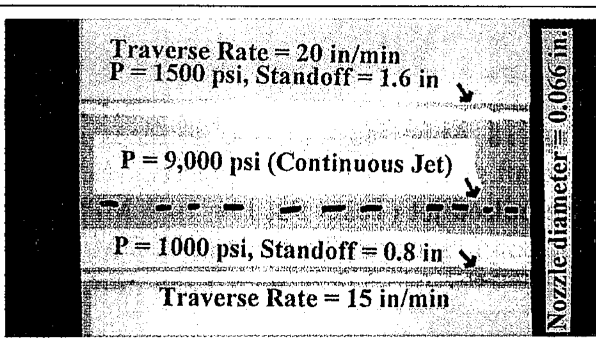

Fig. 23 Appearance of the surface of aluminum rack panel showing the comparison between pulsed and continuous water jet (shown by dotted ink line to indicate that no paint was removed) at conditions as indicated.

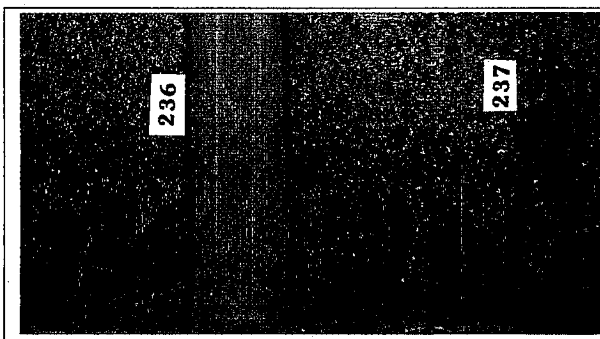

Fig. 24 Appearance of the surface of a car door panel showing the comparison between pulsed (Test # 236; V_{tr} = 1.52 m/min) and continuous jet (Test # 237; V_{tr} = 0.305 m/min). P = 34.5 MPa and S = 0.076 m.

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Paper 42

MOBILE FULL RECOVERY WATERJET STRIPPING SYSTEMS

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ABSTRACT

The marine refurbishment industry currently utilizes abrasive blasting for hull coatings removal. These processes generate extreme amounts of waste material, which must be contained and disposed of properly. The cost of containment, the hazardous work environment and the amounts of hazardous waste produced are all significant disadvantages of the existing processes. Additionally, environmental regulations and safety standards are being introduced which demand new techniques for marine coatings removal.

In light of these factors, Waterjet Systems. Inc. (WJS) was contracted by the U.S. Navy's Naval Surface Warfare Center - Carderock Division to develop an alternate paint and marine growth removal method, including complete effluent recovery at the source. WJS has successfully developed a complete line of Mobile Full Recovery Waterjet Stripping Systems. These systems, using only high pressure water, are semi-automatic and mobile. The systems can operate independently in a dry-dock without external utilities. The systems eliminate the current problems associated with coatings removal and reduce the overall operational costs.

Organized and Sponsored by the Waterjet Technology Association.

BACKGROUND

In today's demanding and competitive marine refurbishment industry, new technologies are needed to replace existing blasting methods (Figure 1). These methods are either too costly to continue or being totally banned or restricted by environmental regulations such as the Federal Water Pollution Control Act and the Water Quality Act of 1987, the Clean Air Act and the Clean Air Act Amendments.

Marine refurbishment, however, presents complex technical challenges and environmental issues because of the unique work environment.

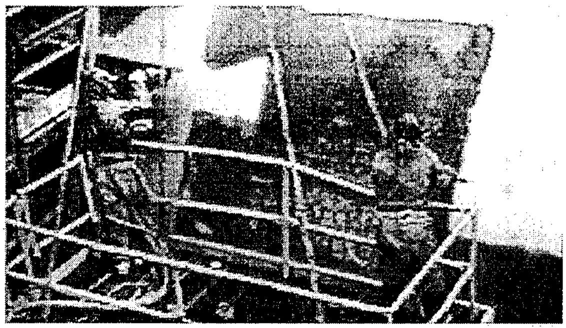

Figure 1 Typical Shipyard Hull Blasting

Environmental issues are working against the continued use of current grit and sand blasting technologies. These issues are primarily related to release into the air or water and disposal of the heavy metals used in marine coatings: copper, cadmium and lead.

The technical challenges are formidable in scale (encompassing both pierside and drydock operations) and in effluent containment (where virtually 100% containment is the only acceptable standard). To this end, WJS has produced a variety closed-loop waterjet stripping systems for use in Naval and commercial shipyards.

The goal of the Navy Project was to develop a prototype system to demonstrate complete removal and recovery of marine coatings. The prototype system was successful at acheiving this goal and is now being used for production work on active Navy vessels. The Navy has recently purchased multiple additional systems for continued production activities.

SYSTEM DESCRIPTION

The system (Figure 2) is totally mobile and self contained for drydock, shipyard or harbor operation. Basic system elements include a high-pressure water pump, a teleoperated transporter with a 5-axis telescoping arm, a 6-axis manipulator with specialized end effector, a recovery process trailer, and a system remote controle console.

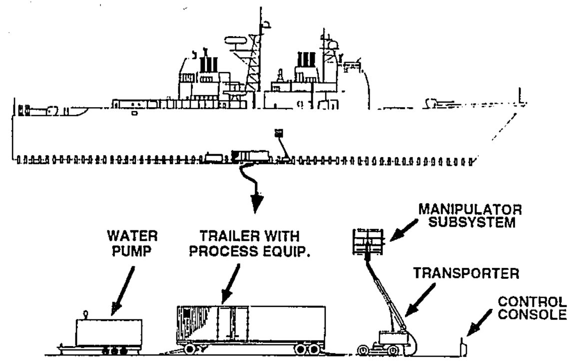

Figure 2 Coating Removal & Recovery System

The end effector incorporates a 6-inch-wide (15 cm) waterjet nozzle in a frame designed for precise application of the waterjet energy against the side of a ship. Stripping paths are mechanically guided by the frame. The end effector has the ability to "comply" with the various surface contour variations typically encountered on ship hulls. It also incorporates an effluent-containment shroud around the waterjet nozzle and a strong vacuum to completely contain all process water and coating residue and transfer them to the water reclamation unit.

For completely closed-loop operation, the system includes a modular water reclamation subsystem for water filtration and recirculation; the only waste product in waterjet processing is the removed coating and fouling. Finally, the entire system is completely mobile; it is transported on wheeled trailers.

System Advantages

The waterjet process is inherently superior to conventional marine coating removal methods, such as grit blasting, shot peening, sanding, chipping, scraping or brushing; it offers the major advantages listed below:

- Paint is the only waste product.
- No dust or airborne contaminants,
- Requires no containment structures,
- Does not subject workers or the environment to hazardous waste,
- Very effective removal of surface contaminates such as salts,
- Ability to *selectively strip* layers of a coating or *entire* coating in one pass.
- Eliminates the need for respirators or masking of mechanical equipment,
- Other operations can be performed in unison.
- Leaves surface clean and dry,
- Requires no cleanup after stripping,
- Lower manpower requirements and higher paint-removal rates,
- Allows repainting with no additional surface preparation, and

• Meets environmental concerns and has potential for large cost savings.

Subsystem Specifications

The patented Waterjet System (Figure 3) consists of an end-effector subsystem (nozzle, effluent-recovery shroud, nozzle rotation drive, and controls), a high-pressure pump, an effluent-recovery and water reclamation system, a manipulator and transporter, all on compact mobile trailers for maneuverability in shipyard areas.

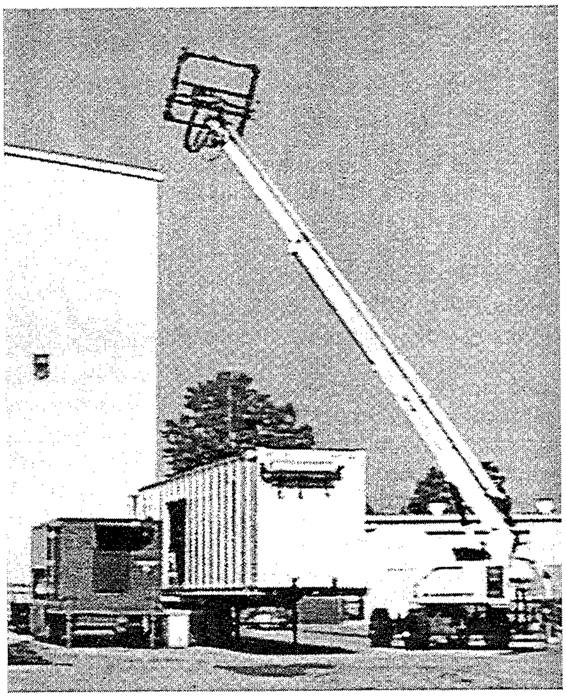

Figure 3 Mobile, Self-Contained System (11 Axes)

End Effector Subsystem

The end effector subsystem (Figure 4) is a self-contained nozzle and shroud assembly with a pneumatically controlled, 15-cm (6-inch) wide stripping nozzle. Controls are included for nozzle standoff distance and compliancy (mating to the coated surface contour) for complete effluent capture.

Nozzle. The patented Even-Energy™ nozzles contains more than 20 laser-drilled industrial-sapphires orifices, of varying sizes and placement; the sapphires provide long life, and the size and placement provide even energy distribution. The nozzle body does not wear out from water flow; the orifices in the nozzle body are the only consumables.

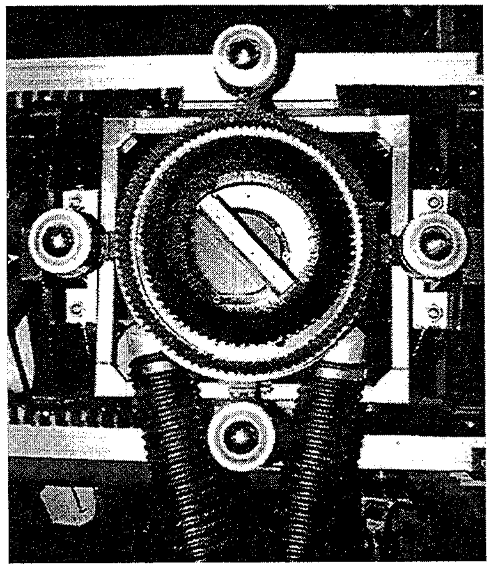

Figure 4 End Effector with Standoff Control Device

Vacuum Recovery Shroud. A unique vacuum recovery shroud designed to capture virtually 100% of the process water, the suspended paint particles and the fouling residue. The vacuum shroud quickly removes all effluent so as not to diminish the stripping efficiency of the nozzle as it progresses along a hull or other surface. As it removes the process effluent, it simultaneously dries the substrate, leaving a rust-free surface.

Manipulator Subsystem

The manipulator subsystem (Figure 5) provides the interface between the ship surface and the end effector, which moves back and forth across the manipulator's 1.37- x 1.98-m (4.5- by 6.5-foot) envelope at optimal standoff distance while maintaining contact so the vacuum recovery head can capture all effluents.

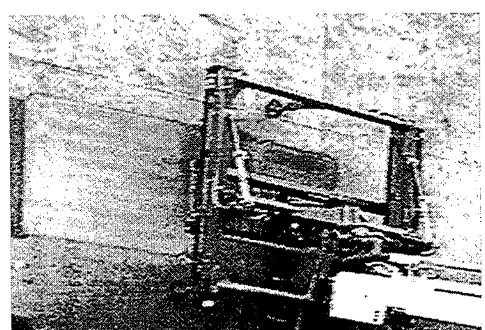

Figure 5 Manipulator and End Effector

Transporter Subsystem

A mobile, telescoping transporter subsystem (Figure 6) accurately positions and repositions the manipulator against the ship, barge or other surface to be processed. The transporters are capable of reaching 18.3-m (60-feet) high with 360° continuous rotation. Other transporters are available for reaching as high as 24.4-m (80-feet) or as low as 1.3-m (4 foot). The transporters are talso capable of stripping flight or cargo decks. All process hoses and cables are routed along the boom. An auxiliary power generator is provided on the tranporter for operation of the manipulator and the remote control console.

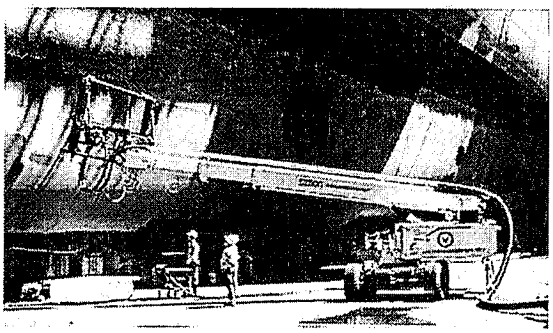

Figure 6 Transporter

Remote Control Console. A console (Figure 7) provides the operator a single point from which to control the transporter, manipulator, high-pressure pump and water reclamation unit. The console is mounted on a roll-around cart so it can be positioned for maximum operator convenience and visibility.

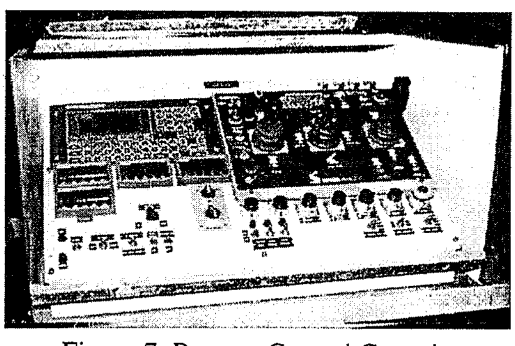

Figure 7 Remote Control Console

High-Pressure Pump Subsystem

A high-pressure water pump (Figure 8) is mounted inside a 6.1-m (20-foot) shipping container. The pump supplies water to the end effector at the required high pressure and volume for the stripping operation.

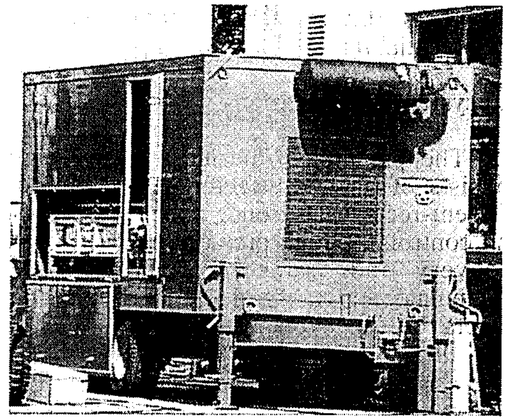

Figure 8 Mobile High-Pressure Water Pump

The pumping unit is self-contained, diesel-powered, and ideally suited to the task of stripping thick, tough coatings such as anti-foulant topcoat, marine growths, and epoxy primer. It is capable of supplying water to the end effector at up to 37.8 liters per minute (10 gpm) and 2482 bar (36,000 psi).

The operator controls the pump intensifiers and pressure from the remote control console, which can be wheeled around the dock for best operator visibility. The pump can also be manually operated at a control panel on the pump face. An automatic protection feature monitors critical pump functions and warns the operator if abnormal parameters are detected.

Effluent-Recovery Subsystem

The process water, paint and fouling residue are collected by the effluent-recovery system for filtering the paint and residue, removing leached ions (copper, cadmium, lead, etc.), microparticulates, chlorides, sulfates, nitrates and other contaminants picked up from the surface. This mobile subsystem is installed in a standard shipping container and chassis (Figure 9).

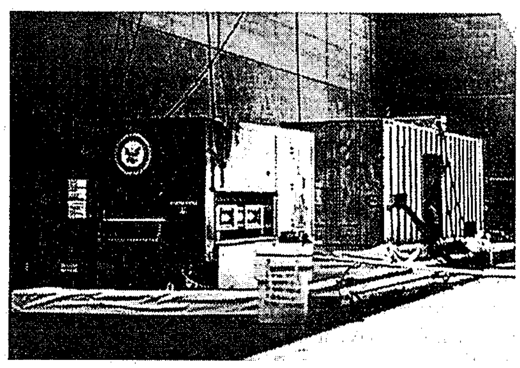

Figure 9 Pump and Recovery Subystem Trailer

The effluent first enters the recovery system through a 6-inch vacuum recovery hose attached to the shroud around the nozzle. A transfer pump removes the material from the vacuum and deposits it into a vibratory liquid/solid separator. The separator acts as a "shaker," removing most of the solid material and dumps the solids in 208-liter (55-gallon) drum. The liquid is then pumped to a micro-separator, which uses centrifugal force to remove materials heavier than water. A modular water reclamation unit (Figure 10) filters and conditions the used process water and returns it to the high-pressure pump. The water is passed through a coalescing tank (to remove oils and film), then through an ozone generator, charcoal filter, micro-filters and, finally, a deionization system with conductivity meter to ensure that the water recycled to the pump is Grade A deionized water.

Utility Trailer. To provide system mobility in the limited space of shipyards and dry-docks, the effluent-recovery subsystem is installed in a standard shipping container, which is approximately 12.2-m long x 4.1-m tall x 2.4-m wide (40- x 13.6- x 8-ft). The container can be placed flat on the drydock floor or supported at each corner by a dual-wheeled caster. The container can be moved on these casters with a forklift and towbar. A diesel-powered electric generator powers the vacuum unit, water reclamation unit, air compressor, transfer pump, liquid/solid separator and other trailer utilities.

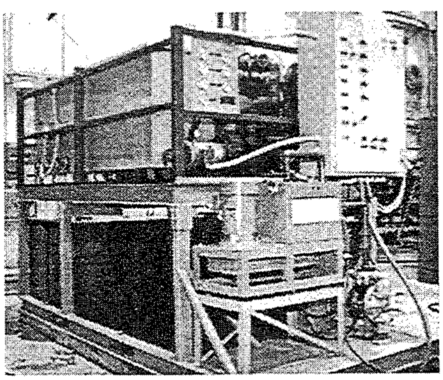

Figure 10 Water Reclamation Unit

NAVY SHIPYARD DEMONSTRATIONS AND USE

The first system was moved to Puget Sound Naval Shipyard on 18 July 1994. Its first test at the yard was the removal of about 46.5 m^2 (500 ft^2) of underwater hull paint from the USS NIMITZ (CVN 68). During this test, (Figures 11 and 12) the system showed its capability to remove all of the paint to bare metal and *selectively* strip layers of paint from the surface. The amount of material removed in selective stripping ranged from the first layer of antifoulant to the first layer of anticorrosive. This was performed by varying the water pressure and nozzle speed across the ship's hull.

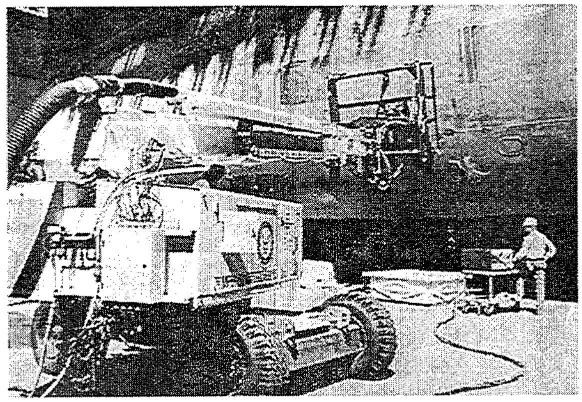

Figure 11 Stripping USS NIMITZ

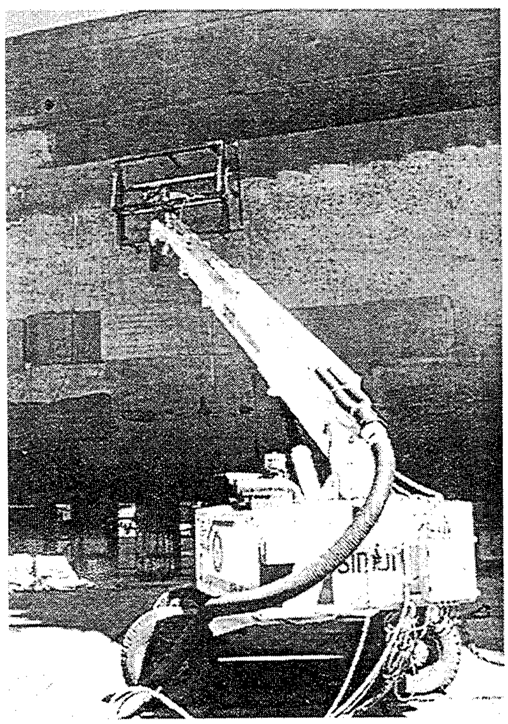

Figure 12 Manipulator on NIMITZ Hull

The typical coating systems on Navy underwater hulls have consisted of several primer layers, two coats of anticorrosive paint and four coats of antifoulant paint or topcoat paint. These coatings average between 30-40 mils thick, but can exceed 100 mils thick. Heavy marine growth and corrosion are also occasionally encountered.

The removal rates achieved with these systems have been in the range of 19-35 m^2/hour (205 -375 ft^2/hour). The systems are capable of stripping exterior hulls, freeboard and non-skid deck coatings with virtually 100% effluent capture.

After the paint is removed, the bare metal does not flash rust. This is because of the removal of the surface contaminants by the strong vacuum and the ~60 C (~140 F) heat of the water, which speeds evaporation.

The water and effluent were tested for trace metals as it entered and left the effluent recovery system. The measured values are listed in Table I.

Metal	Effluent (mg/L)	Recycled Water (mg/L)
Zinc	13.2	< 0.10
Lead	< 0.10	< 0.10
Barium	17.3	0.14
Arsenic	0.10	< 0.10
Selenium	0.20	< 0.10
Copper	19.7	0.11
Silver	< 0.10	< 0.10
Cadmium	< 0.10	< 0.10
Nickel	0.39	< 0.10
Chromium	0.39	< 0.10

Table I Analysis of Effluent

Most of the paint residue is pulled out by the liquid/solid separator and deposited into a 208-liter (55-gallon) drum (Figure 13). This waste was also analyzed, and results are listed in Table II.

Metal	Qty (mg/kg)
Zinc	6700
Lead	217
Barium	1950
Arsenic	< 20
Selenium	< 20
Copper	296.000
Silver	< 20
Cadmium	< 20
Nickel	329
Chromium	234

*Method: EPA 3050A & 6010A
Analysis Dates: 26 & 29 Sep 94

Table II Analysis of Solid Waste

Figure 13 Solid Waste Collected

The next test was removal of non-skid coating from the flight deck of the NIMITZ (Figures 14 and 15). Data was not collected on the coating thickness, but generally these coatings are around .64 cm (.25 inches) thick. The entire coating system was removed at a rate of 19 m^2/hour (205 ft^2/hour).

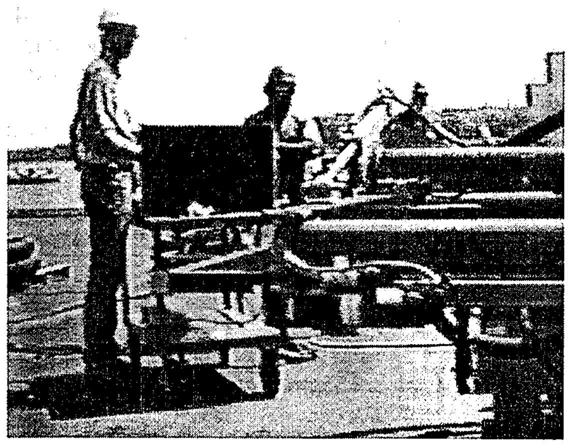

Figure 14 Setting Up for Deck Stripping

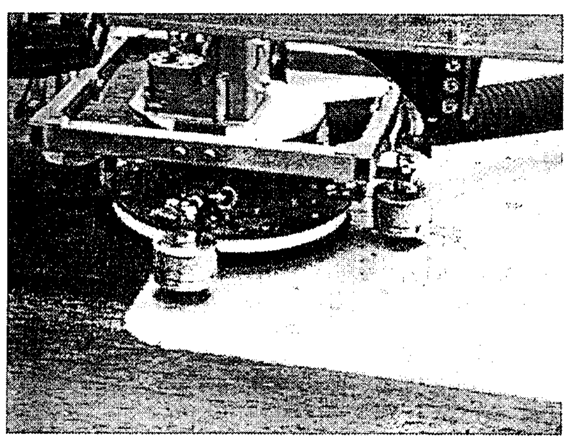

Figure 15 Stripping Non-Skid Deck Surface

The system was then moved to Drydock 1 at Puget Sound to begin testing on the USS STURGEON (SSN 637) (Figures 16 and 17). Several thousand square feet were stripped, demonstrating both selective stripping and complete stripping to bare metal.

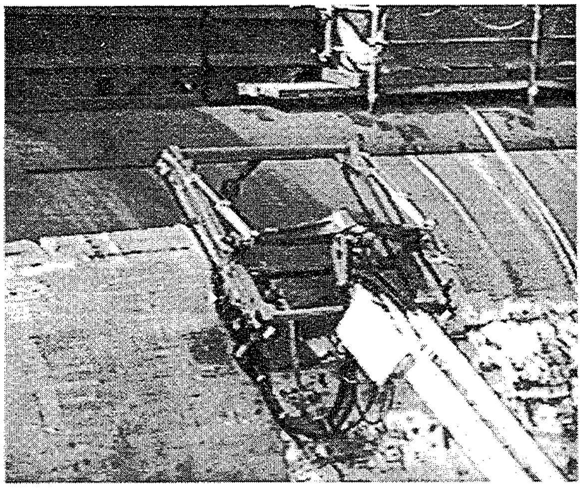

Figure 16 Stripping the USS STURGEON

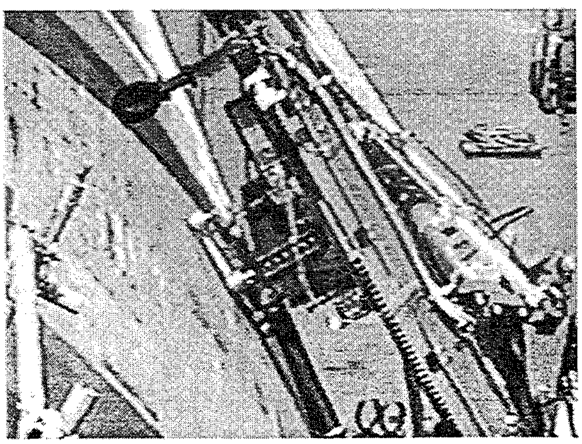

Figure 17 Side View of STURGEON

The surface was tested after paint removal to quantify the amount of chlorides remaining on the substrate. The Bressle Method Test Kit and Swab Kit were used and, in all tests, the readings were from 0 to 2 $\mu g/cm^2$. The vacuum recovery head performed well, and areas that were stripped to bare metal did not flash rust.

On 20 October, 1994, the system was shipped to Pearl Harbor Naval Shipyard (PHNSY) to remove 2322.5 m^2 (25,000 ft^2) of freeboard paint from the USS Leftwich (DD 984). Since the Leftwich had organotin on the underwater hull, dry abrasive blasting or open water blasting was not permitted on the freeboard until all the organotin was removed and the drydock was thoroughly cleaned. This sequential process would lengthen the LEFTWICH's time in drydock, so PHNSY requested the use of the Navy Waterjet System to see if it could remove the freeboard coating while the organotin was being removed thus reducing the ship's time in drydock. This was the first "production" test of the Waterjet Demonstration System, and it performed well, removing the 5-coat system at a rate of 19 m^2/hour (205 ft^2/hour). Waste reduction of 50:1 was acheived by using the closed-loop waterjet system. The only waste product generated was the removed paint coatings.

The Leftwich and other production jobs have provided the project team with valuable information that has been incorporated into the second-generation, production versions of the system. The work at PHNSY continued through January 1995. The equipment was then moved to Long Beach Naval Shipyard for further production work on the USS FOSTER (DD 964). Since that time the system has been used on several Navy vessels including submarines, floating dry-docks and the Abraham Lincoln Aircraft Carrier (CVN-72).

CONCLUSION

The Navy prototype waterjet system performed better than expected for a technology-demonstration unit. Production versions of the Mobile Full Recovery Waterjet Stripping Systems are currently being fabricated for the Navy and other customers. Waterjet Systems, Inc. is offering the shipping industry a complete line of versatile full recovery waterjet strippng systems for coatings removal from ships, submarines, barges, and large structures. There are significant financial and environmental benefits associated with this technology.

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Paper 43

WATER JETTING APPLICATIONS IN THE PETROCHEMICAL INDUSTRIES

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ABSTRACT

Production, reliability, process control, efficiency, productivity, safety and environmental concerns are but a few of the key issues in the refining and petrochemical industry. Water jetting plays an important role in maintaining operating efficiencies, throughput, and reliability in these industries to address these issues. This paper discusses water jetting applications and the trend to semi-automated and automated cleaning equipment and accessories to improve turnaround time and improve safety and efficiency.

Organized and Sponsored by the Waterjet Technology Association.

1. INTRODUCTION

Legislative restrictions and environmental concerns are resulting in the additional use of high and ultra high pressure water jetting in the Petrochemical and Refining Industries. Traditionally, these process industries have represented a major market for high pressure water blasting in a wide array of cleaning applications in all segments of the production process (see figure 1).

More recently, with the advent of strong state and national legislation and environmental regulations that either restrict, limit or prohibit use of certain materials and chemicals, water jetting is becoming the more preferred method of cleaning for maintaining the effectiveness of the process equipment. Applications that previously utilized sand blasting are converting to ultra high pressure water, which eliminates airborne contaminants and the need to collect and dispose of contaminated sand. Water jetting can also reduce the amount of collection and treatment required of chemicals used for cleaning and the rising costs associated with disposal of those chemicals.

Along with the increased utilization of high and ultra high pressure water jetting for maintenance of process equipment, comes the need and desire for faster and more productive cleaning equipment, increased safety of the operating personnel and ultimately reducing the downtime of the equipment or process being cleaned. This need has resulted in the availability of semi-automated and automated equipment, tank cleaning nozzles and other water jetting accessories that increase the cleaning efficiency and productivity of water jetting at all pressures.

Let's review the needs and applications for water jetting in the Petrochemical Industry.

Oil refineries convert crude oil into usable products including gasoline, LP gases, aviation fuels, diesel fuels, heating oils, greases and asphalt. Other products from refineries go to petrochemical plants for further processing into plastics, fertilizers, chemicals and consumer products. Both the refining and petrochemical processes include crude oil or petroleum by products that are a mixture of thousands of different chemicals. The crude oil is first subjected to distillation that separates the crude into fractions, or cuts, according to boiling point. These fractions are then fed to other processes within the refinery for additional processing where each process is designed to further refine or reform these "cuts" into useable products or by-products for additional refining. These additional processes include:

- Cracking to break these hydrocarbons into lighter components
  - Catalytic Cracking - using a catalyst to break down the hydrocarbons
  - Hydrocracking - using hydrogen to break hydrocarbons down
- Isomerization - rearranges molecules to form a desired product
- Reforming - converts fractions to products with a higher octane by rearranging the molecules of hydrogen and carbon
- Coking - severe thermal cracking of flasher bottoms in order to produce light gases, gasoline, naphtha and coke

In all of the above processes, precise amounts of heating and cooling of the various fractions is required in order to allow the process to take place. Sophisticated computer based control and monitoring systems are used to maintain correct process temperatures, pressures and other conditions.

As process equipment feed lines or reactors become coated with product build up and residues, the need for water jetting is apparent in order to restore the efficiency of the process equipment or promote effective heat transfer.

2. DISTILLING COLUMN CLEANING

The numerous distilling columns found in a refinery require periodic cleaning in order to maintain operating efficiency. After the crude oil has been heated in a furnace to approximately 750°F, about half of the crude oil changes to a vapor and the combination liquid and vapor is introduced to a tall distilling column. The distilling column consists of a series of trays with perforations that allow the vapor to rise through the tray bubble caps, which allow the vapor to flow through the liquid. Some of the vapor will condense and be drained off by a side draw while the vapors are allowed to further rise and repeat the bubbling process. Different products condense out of the crude oil and are drained off at the proper level. The various products are then pumped to other areas of the refinery for further processing.

A distilling column may include as many as 50 trays and each tray needs to be cleaned in order to maintain operating efficiency. A variety of methods may be utilized in order to satisfactorily clean the entire distilling column. A workman may perform blasting of the trays by removing the center portion of the trays and standing on a lower tray while manually cleaning an upper tray. This blasting is usually done at 5,000 to 8,000 psi using a hand lance. Often a two dimensional (2D nozzle) or a three dimensional tank cleaning head (3D nozzle) will be hung by cable in order to decrease the cleaning time or minimize worker exposure in the column (see figure 2). These nozzles and tank cleaning heads are capable of utilizing much greater water flows than an individual can handle and they are often able to reduce the cleaning times. Typical flows are 50 to 100 gpm.

3. HEAT EXCHANGER CLEANING

A water jetting application common to all phases of petroleum refining and petrochemical manufacturing involves the cleaning of heat exchangers. These devices are vital to the efficient condensation and collection of the various products being manufactured.

They generally consist of a tube bundle through which the product or coolant is passed and a "shell" through which the other is circulated. Over time the I.D. of the tubes, called the tubeside, and the O.D. of the tubes, called the shellside, or the space between the individual tubes, become fouled with product or residues and corrosion from the minerals in the coolant. When this happens their cooling efficiency declines thus reducing the throughput possible in the refining process.

There are several water jetting methods possible for cleaning the interior or tubeside of heat exchanger tubes. The simplest, but slowest, is hand lancing with rigid lances fabricated from high pressure tubing. Most tube lancing is done with pumps that produce at least 10,000 psi but 20,000 psi and 36,000 psi pumps are also used for difficult to remove materials. In hand lancing one or two men push the lance into the tube by hand. The pressurized water is activated with a foot control (see figure 3). Special care is necessary when starting each tube to avoid operator contact with water jets.

A similar method involves using a flexible lance or hose and hand feeding it into the individual tubes (see figure 4).

Heat exchanger tubes are sometimes cleaned in place using rigid or flex lances (see figure 5).

There are also various devices available for automating the tube cleaning process. Rigid lancing machines remove the operator from proximity to the tube bundle and provide a powered feed and rotation mechanism to speed the cleaning process (see figure 6). These sometimes also feed multiple lances to clean more than one tube at a time.

Flex lance machines also do the same thing but take up less space for use in confined areas. They can be as compact as small shop cart for a single flex lance machine (see figure 7) or a bit larger for a multiple lance machine (see figure 8). Both machines use a feeder drum or spool to coil and uncoil the flex lance. In both cases operator safety is enhanced because he doesn't have to touch the flex lance and both types of machines usually have a built in depressurization mechanism should a blocked tube stall the machine or the operator wishes to stop operation for any reason.

4. SHELLSIDE CLEANING

Once the tube bundle is removed from its shell or housing additional forms of cleaning take place. The exterior of the tube bundle and the spaces between the tubes must be freed of their product or condensate build up and the interior of the shell itself has to be cleaned.

The shell itself is often cleaned using hand held lances or with a pipe or stack cleaner depending on the diameter of the heat exchanger.

The tube bundle itself is very difficult to clean because of its configuration. The multiple tubes with voids between them collect material build up on their exterior. These build ups, particularly on tubes near the centerline of the bundle are very difficult to reach.

The other problem is that when heat exchangers are out of service for cleaning, the process they support has to be shut down. Therefore, time is usually of the essence. The result has been some highly specialized machines designed for the exterior cleaning of tube bundles.

The machines generally include a mechanism for moving the water jet nozzles over the surface of the tube bundle. Some also provide rotation of the nozzles for more effective cleaning (see figure 9). In addition to movement over the bundle, the bundle is also set on powered rollers to allow rotation of the bundle for complete coverage of the entire surface.

Some variations of these machines include versions that allow cleaning two bundles at a time (see figure 10) and others that incorporate a hydraulic arm for easy positioning of the nozzles as well as being able to self load the roller mechanisms (see figure 11).

The pumps used in these applications are usually a minimum of 250 horsepower to assure adequate flow as well as pressure to promote thorough cleaning. Flows of 50-100 gpm at 8,000 to 10,000 psi are generally utilized.

5. TANK AND REACTOR CLEANING

The petroleum refining and petrochemical processes of necessity require a great number of storage and holding tanks to store the unrefined crude oil and end products in their various forms.

Each time it is necessary to change from one product to another or product build-ups occur, they have to be cleaned. In the past, this was done by sending a person or crew into the tank with scraping tools or hand held water jet lances to clean down all surfaces of the interior of the tank. Needless to say, these activities were both time consuming and risky. Often, special staging, protective clothing and breathing apparatus were required. Special entry permits are also necessary when sending personnel into a tank (see figure 12).

Today, many of these concerns can be eliminated by the use of remotely operated lances and specially designed 3 dimensional coverage tank cleaning water jet nozzles (see figure 13). The tank cleaning head is lowered into the tank and high pressure water is directed to the nozzle. The water will power the nozzles which rotate in the axial plane and the gear driven nozzle head which will drive the body in a perpendicular plane, thus providing 360° coverage.

Obviously, in very large tanks a nozzle positioned in the middle of the tank would have very little cleaning effect because of lack of water impact on the distant side walls. Therefore, devices have been developed to allow repositioning of the tank cleaning head throughout the interior of the tank to assure adequate cleaning of all surfaces.

These devices can be as simple as a length of pipe made positionable by a ball and socket device attached to the tank manway to more sophisticated telescopic lances equipped with a mechanism to control extension as well as angle of attack within the tank or reactor (see figure 14) which is sometimes necessary due to tank baffles, coils and agitator blades.

The reactors used throughout the process are cleaned in the same way. Self rotating reactor/tank cleaning heads are used to free all types of deposits from reactor interiors. Even difficult to remove coke can be freed using high pressure water and 3D nozzles.

Sometimes the nozzles are even permanently installed on fully automated lances for between batch cleaning applications. These sophisticated devices are generally pneumatically driven into position and fully programmable for thorough cleaning. When not in use, the lance is retracted and the reactor/tank cleaning head housed in an isolatable housing above the reactor.

Another form of tank which requires special cleaning tools is the product transportation railroad tank car or tank trailer. These tanks must be cleaned each time the product being transported is changed or, in the case of a product like asphalt, when the product builds-up in the tank to the point where it reduces capacity, restricts flow or heat transfer in jacketed or "stream traced" tank cars.

One specialized device for cleaning these horizontal tanks operates on the same principle as a scissors jack. When collapsed it can be lowered through the manway at the top of the tank (see figure 15). It is then mechanically extended or retracted to position the 3D nozzle along the length of the tank.

Of course, all of these applications vary in terms of pumping capacity requirements. Difficult to remove materials like coke or asphalt may require as much as 10,000 psi and 40 gpm of flow while other easier to remove materials can be removed at lower pressures with less water.

Floors and tank bottoms are often cleaned using hand lances or grate and floor cleaners with rotating nozzles. Floors and tank linings can be cleaned of contamination or the linings themselves can be removed for replacement. Corroded or leaking tank bottoms can be cleaned and the surface prepared for repair or lining installation. Often 20 - 34 gpm at 10,000 psi is used to clean the tanks and 36,000 psi will be used for lining removal or surface preparation.

6. PIPE, TUBE AND STACK CLEANING

Refineries and petrochemical plants are a maze of pipes, tubes, drains and flare stacks that are used to convey the fluids and gases through the various processes. Water jet cleaning is often the best way to clean product residues or other materials which impede flow and reduce process efficiency. In many cases the same rigid and flex lance methods mentioned in the heat exchanger section can be used to clean these pipes and tubes. However, special care must be used in cleaning large diameter pipes with a flexible lance to be sure that it can't "turn around" in the tube and come back at the operator. The most common method to avoid this is to use a "stinger", or pipe, between the nozzle and hose or flex lance. The length of pipe should be longer than the diameter of the pipe.

When cleaning larger diameter pipes, drains and stacks some special water jetting nozzles and devices are often employed. These include special self rotating swivels with self centering skids or roller devices to allow thorough water coverage on the interior surfaces of a large diameter pipe or stack. These are rotated by the pressure and flow of the water and often the rpm may be adjusted for various applications by use of a built in braking mechanism.

7. ABRASIVE WATER JET CUTTING

Abrasive water jet cutting, often called cold cutting, has been very well accepted in the petroleum refineries. Adding abrasives to the water stream produces a jet capable of cutting steel at rates comparable to those of torch or saw cutting. When cutting with a water jet cutting system, there is no heat build up, thermal distortion or change in metallurgy. Water jet cutting leaves a smooth edge without slag thus reducing or eliminating secondary finishing.

A common application for water jet cutting is for cutting openings, called door sheets, in the large above ground crude or storage tanks. Often entry into the tank is required in order to remove sludge that has settled in bottom of the tank, to inspect/repair the tank for leaks and to generally clean the tank. A large water jet cut door sheet opening will permit easy access for crews or equipment in order to perform the necessary service. Obviously, strict safety precautions must be followed in cutting or opening the tank, ensuring the tank is properly ventilated.

Door sheets are cut using 20,000 psi water jets or above. The water/abrasive cutting nozzle is mounted on a linear tracking device that is secured either horizontally or vertically to the tank wall with magnets or pneumatic suction cups (see figure 16). The tracking system can include flexible sections that will allow cuts of virtually any radius. The track crawler and abrasive cutting nozzle is often hydraulically powered for smooth consistent cutting. Often the door sheets are cut with a beveled edge in order to facilitate welding the sheet back in place once the cleaning, inspection and repair process is completed.

Another common application for abrasive cutting is to cut and remove the top or dome from tanks or reactors in order to permit cleaning or repair. Occasionally, the top will be removed from a cat cracker reactor in order to repair a malfunctioning cyclone.

Water jet abrasive cutting is also used for removing pipeline sections for inspection, cleaning or replacement. In these cases, the hydraulically driven track crawler and abrasive cutting nozzle are secured to and follow a chain around the diameter of the pipe (see figure 17). This results in a clean straight or beveled cut that allows easy reinstallation of the serviced length of pipe.

Cutting rates for abrasive cutting vary with the thickness of the material being cut, the type of material, the amount of the abrasive being used, water pressure and the desired quality of the cut. Carbon steel pipe with a 1/4" wall is commonly cut at rates up to 14" per minute, 1" thick steel plate is often cut at 4-6" per minute.

There are numerous opportunities for abrasive cutting in refineries and petrochemical plants such as addition of lines and drains. They can easily and safely be added to tanks, vessels or other pipe lines without the risks of flame cutting.

8. SURFACE PREPARATION

Surface preparation or paint preparation to remove coatings, dirt, paint, rust and contamination offers many applications for ultra high pressure water jetting. Sand blasting or dry abrasive blasting results in airborne abrasive particles and dust that are harmful to mechanical equipment or contaminate the air and environment. As states enact legislation to ban or control the use of sandblasting, the need for water jetting increases. Water jetting does not result in airborne particles and is much easier and less costly to collect, filter or treat the effluent as required. The recent Joint Surface Preparation

Standard, NACE No. 5/SSPC-SP12 "Surface Preparation of Steel and Other Hard Materials by Water Blasting Prior to Coating or Recoating", issued by the National Association of Corrosion Engineers and the Steel Structures Painting Council, addresses the advantages and effectiveness of water jetting and its suitability for use in a wide range of industrial applications. Water jetting is also effective in removing salts and chlorides which can lead to premature paint or coating failure.

Surface preparation can be accomplished in a number of ways. Hand lancing is most common for structures and reinforcement members but can also be utilized for flat surfaces. A rotating cleaning nozzle can be utilized with an air or hydraulically controlled X-Y axis unit mounted on a telescopic boom or other lifting and positioning device. Other technologies are being explored that allow deployment of automated work modules on large vertical surfaces while eliminating scaffolding and safety equipment required to protect workers.

Flat horizontal surfaces are often cleared of paint and corrosion by using floor and grate cleaners with powered or self rotating nozzle arms for thorough yet fast coverage.

9. WELD INSPECTION

Cleaning of tanks or pipes is often performed, not only for surface preparation, but in order to inspect the weld or perform tests to determine the structural integrity of the vessel. Ultra high pressure water jetting at 36,000 psi will effectively remove paint, weld slag, rust and scale. The resulting white metal finish makes it possible to perform critical inspection tasks such as magna flux or integrity testing. Water is becoming the preferred alternative to sand blasting for weld inspection because there are no airborne particles or sparking to contend with (see figure 18).

10. CONCLUSIONS

The petrochemical and refining industries represent potential for virtually any type of water jetting from low pressure washdown to ultra high pressure cleaning and surface preparation applications. The industry trend is to use water jetting equipment incorporating greater water flows and/or higher pressures along with increased automation which results in increased worker safety, reduced downtime and improvements in cleaning efficiency. Water jetting, when compared to chemical cleaning or grit blasting, represents a more environmentally friendly alternative to avoid potential regulatory problems.

11. REFERENCES

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NACE/SSPC Joint Surface Preparation Standard NACE No. 5/SSPC-SP12, "*Surface Preparation and Cleaning of Steel and Other Hard Materials By High and Ultrahigh Pressure Water Jetting Prior to Recoating*".

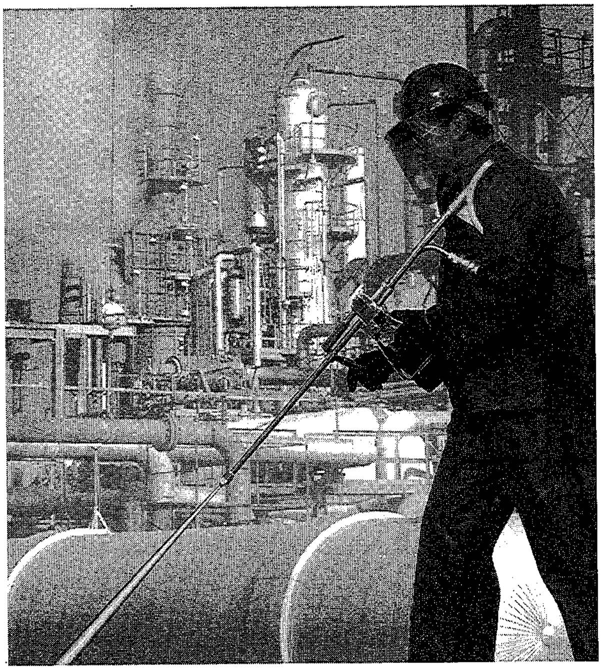

Figure 1. Water jetting is the most common cleaning method used in the petrochemical industry.

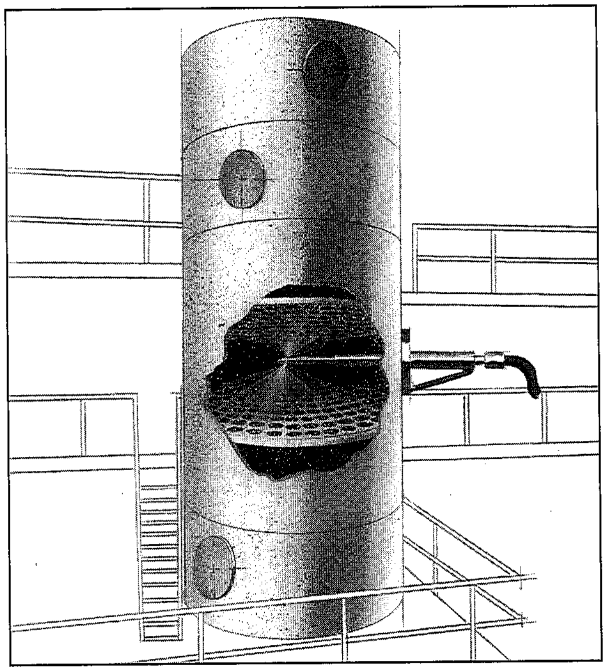

Figure 2. Distilling Columns are often cleaned using 3-D water jet nozzles to eliminate the need for personnel to enter the confined space.

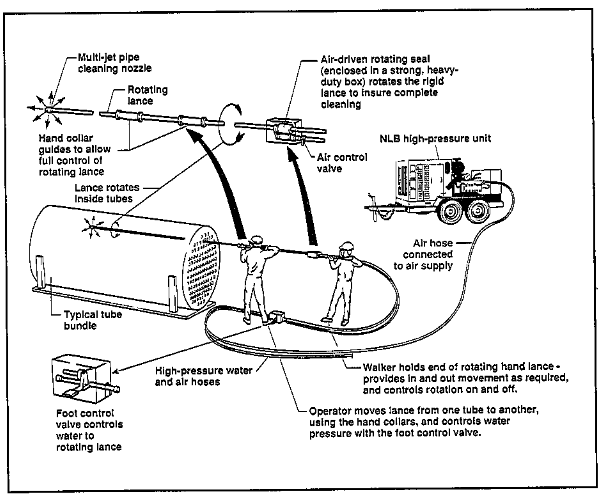

Figure 3. Rigid Lancing is a commonly used heat exchanger tube cleaning method.

Figure 4. Hand feeding a flexible lance is another common tube cleaning method.

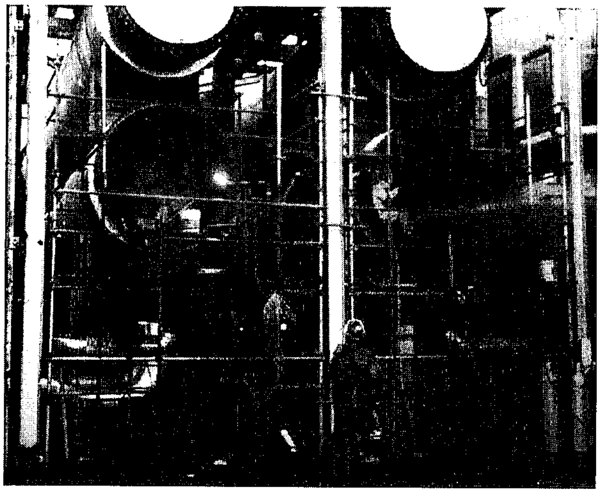

Figure 5. Heat exchangers are sometimes cleaned in-place with flexible lances.

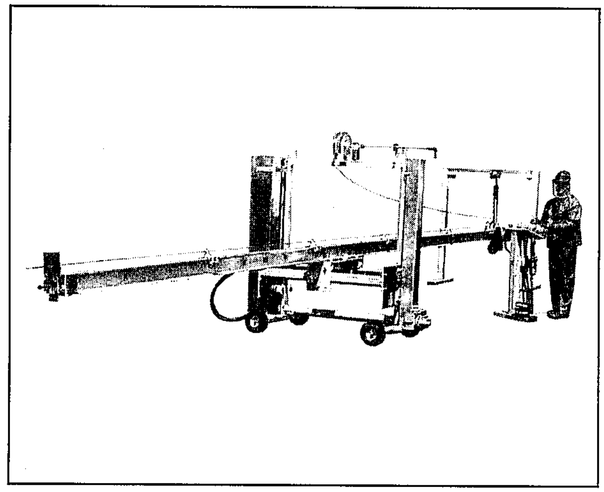

Figure 6. Special machines are available for rigid lancing to automatically feed and rotate the lance.

Figure 7. Small semi-automated flex lance machines take the lance out of the operator's hands.

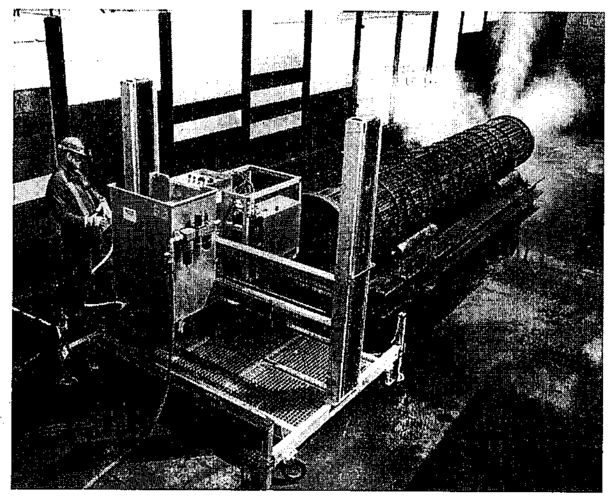

Figure 8. Fully automated machines clean multiple tubes at a time and further remove the operator from contact with the flex lance.

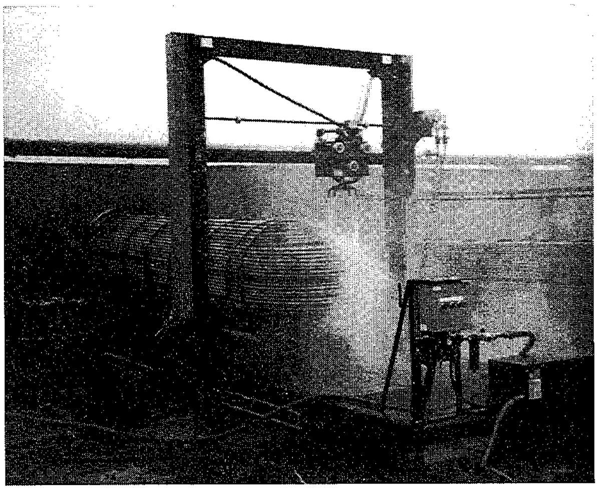

Figure 9. Rotating nozzles improve the cleaning efficiency of Shellside Cleaning Machines.

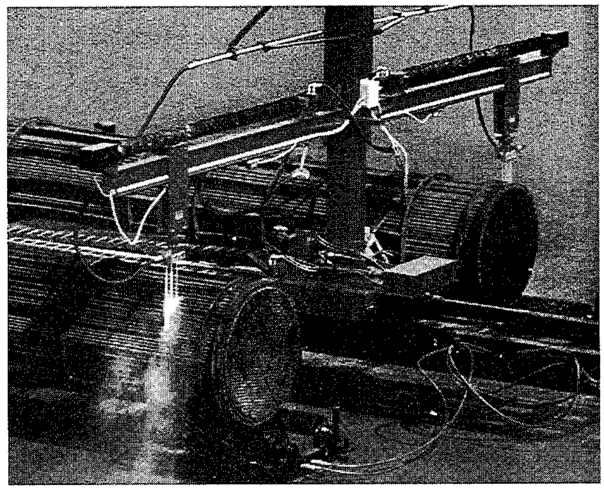

Figure 10. Some shellside cleaning machines are capable of cleaning two bundles at a time.

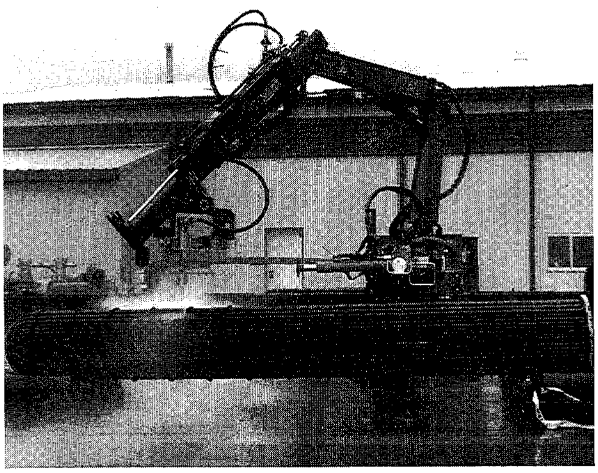

Figure 11. Articulated arm shellside machines permit precise nozzle placement.

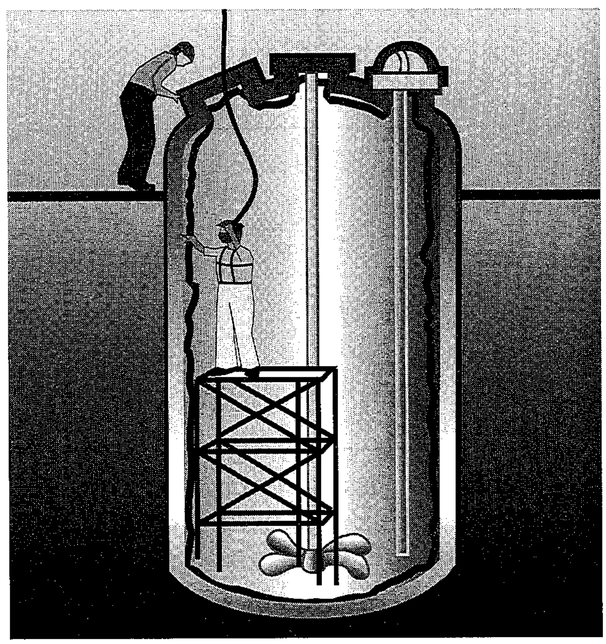

Figure 12. Hand cleaning methods require tank entry and elaborate preparations for cleaning.

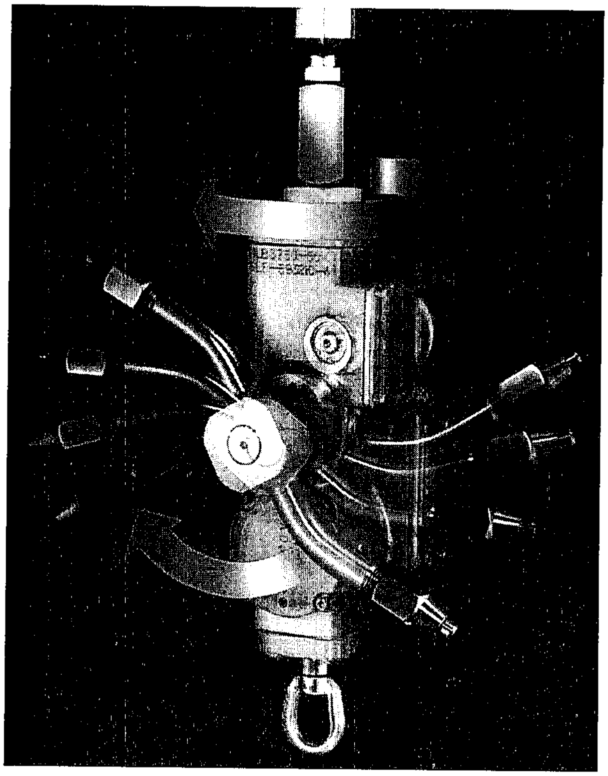

Figure 13. Three-dimensional tank cleaning heads rotate horizontally while their nozzles rotate vertically to give 360-degree coverage in all planes.

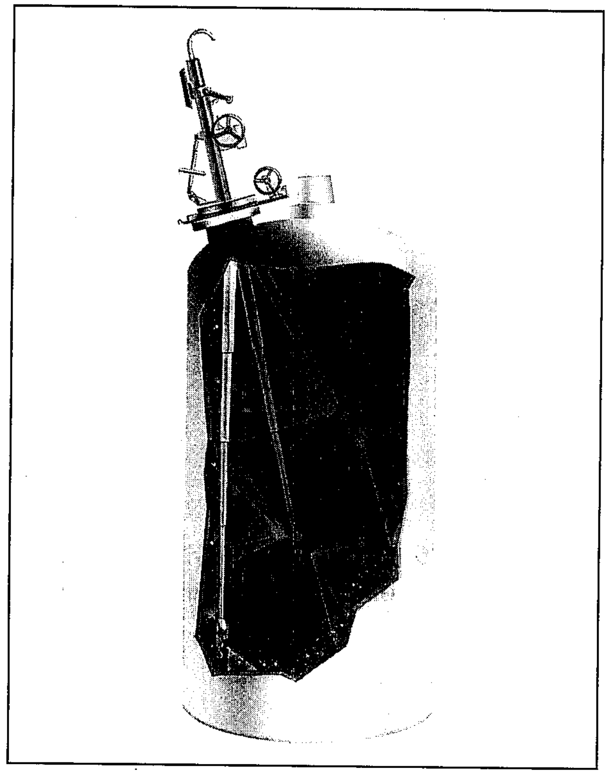

Figure 14. Telescopic lances often include capability to adjust extension, inclination and rotation in order to place the 3-D cleaning head in the proper working position.

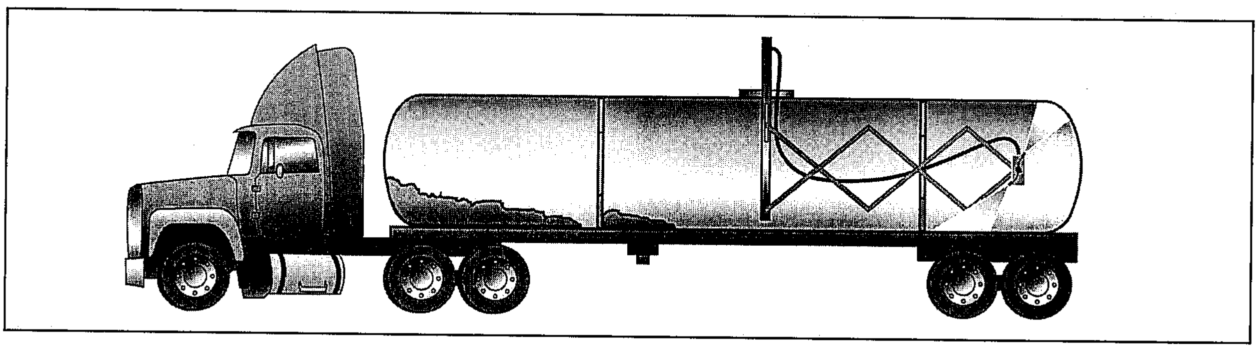

Figure 15. Illustration of tank car cleaning using a scissors-type mechanism for extending and positioning the cleaning head, permitting cleaning of the entire length of the tank.

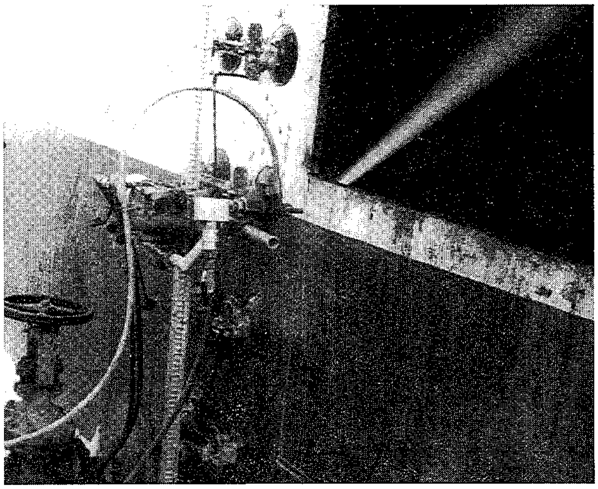

Figure 16. Abrasive cutting head and linear tracking device, secured to tank wall with pneumatic suction cups, cutting manway or door sheet for entry.

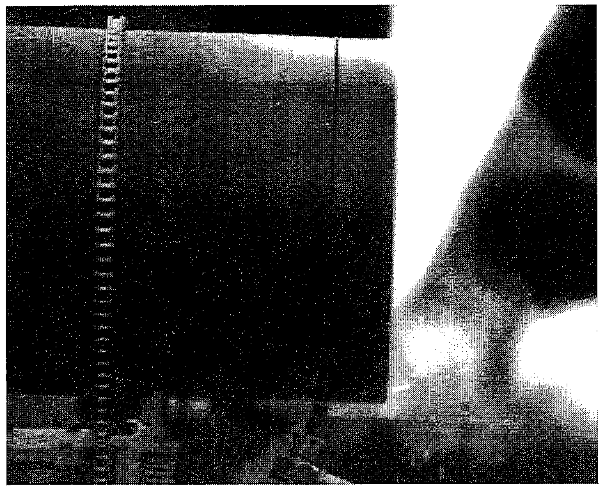

Figure 17. Pipe cutting using 36,000 psi abrasive cutting head. The pipe cutter rides along a guide chain secured around the pipe.

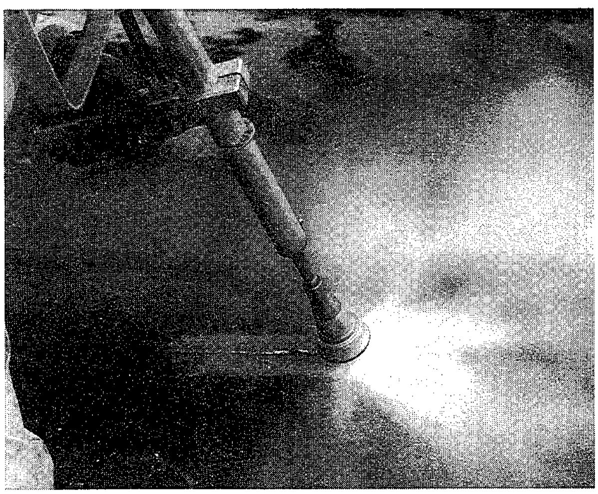

Figure 18. Weld inspection and testing is possible following paint and coating removal using 36,000 psi water, which produces a "white metal" surface.

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Paper 44

A STUDY ON DESCALING OF WATER INJECTION TUBING BY WATER JET

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ABSTRACT

Scale formation inside water injection tubing in oil fields causes low water injection efficiency and seriously injection failure. Conventional descaling methods, chemical treatment and mechanical scraping, for these tubings not only cost much money and time but also create tubing damage and environmental problems. This paper, upon the investigation into the formation and composition of calcium carbonate scale on water injection tubing in oil fields, describes the laboratory experiments and system development of tubing descaling by water jet. The effects of nozzle pressure and advancing speed on descaling efficiency are tested. The results show that the descaling efficiency increases as jet pressure increases, and, decreases as advancing speed increases. Two sets of descaling systems, stationary and mobile, are developed for scale operation of injection well tubing of oil fields with water jet technology. Preliminary field experiments have shown the feasibility and potential of the technique which is of low cost, high efficiency and no environmental pollution .

Organized and Sponsored by the Waterjet Technology Association.

1. INTRODUCTION

Scale formation inside water injection tubing and pipe in oilfields raises certain problems such as lowering injection efficiency as well as, seriously, leading to injection failure. The scale, mainly calcium carbonate deposit, is hard and tightly fastened on inner wall of the tubing, and is rather difficult to be removed.

There are two conventional ways--chemical treatment and mechanical scraping--to remove the scale(Patton,1986). The descaling efficiency and the cost are commonly concerned. Tubing descaling with chemical treatment, which uses chemical compounds to dissolve the scale, not only costs much money and time, but also creates environmental pollution and tubing surface damages. The mechanical descaling method which removes the scale mainly by scraping action of specially designed mechanical tools such as pigs is often effective in certain cases, but the high cost and inadaptability to different sized pipes limit its wide application. Water jetting descaling method which uses high pressure water jets exiting from the nozzles of a nozzle head to cut and remove the scale is an emerging technology(Sun,1992). By reasonably designing the nozzle head and controlling water jetting pressure and flow rate, this descaling method can be adapted to a large variety of pipe descaling and deposit removing applications with the advantages of low cost and no environmental pollution and pipe surface damages.

The authors, upon investigation into scale formation mechanisms and scale composition inside water injection tubings in Shengli Oilfield, conducted the experiments of descaling of the tubings with water jet and studied the effects of jet nozzle pressure and advancing speed on descaling efficiency. The results have served the development of both stationary and mobile descaling systems for indoor and on site descaling operation of water injection tubings in oilfields.

2. SCALE FORMATION AND COMPOSITION

2.1 Scale Formation

As is well known that both surface water and under ground water contain various kinds of dissolved chemical compounds. On certain conditions, some of the compounds can become undissolved in water. The deposits of these undissolved compounds are known as scale. The composition of these scale deposits in most oilfields in China is mainly calcium carbonate (Wang,1994).

The investigations indicate that scale formation is basically caused by the deposit of calcium carbonate because of high concentration of scaling ions in the underground water, and is influenced by the system temperature and pressure, PH value, salt content, and content of carbon dioxide in the water. While the concentration of carbon dioxide increases, the solubility of calcium carbonate in water increases and its deposit decreases; The higher the temperature, the more the crystallization; The higher the system pressure, the higher the fractional pressure of carbon dioxide. With the significant drop in pressure, carbon dioxide will get free from the solution, and the resulting rising in PH value will lead to increase in amount of deposit; With the increase in salt content in water, (not including calcium ion and carbonate root), the solubility of calcium carbonate goes up and scale deposit goes down.

Solubility product constant, K_{sp}, which is the product of concentration of various ions in a saturated solution at given temperature and pressure, is basically used to predict the tendency of precipitation of soluble salt in the solution. For the prediction of calcium carbonate scale formation in water, saturation index or stability index, which is defined as the logarithmic value of the ratio of ion product to solubility product constant, is often used. Langelier(1936) published an empiric equation to calculate the saturation index of water and noted that there would be scale formation in water when saturation index was over zero. Ryznar(1944) developed the concept of stability index, SI, to predict not only the tendency but also the amount of scale formation in water. Water is stable and without scale formation or corrosion when SI is within the range of 6 to 7; There exists a tendency of scale formation when SI is below 6 and the amount of scale formed increases as SI gets smaller.

2.2 Scale Composition

As is well known that the composition of common water scale is the mixture of carbonates, sulfates and phosphates of calcium, barium and strontium as well as oxidization of aluminum and magnesium. There are different types of scale formed by water in different oilfields including calcium carbonate, calcium sulfate, barium sulfate, and strontium sulfate, with calcium carbonate scale being the most common one. The scale from water in Shengli Oilfield in China, for instance, is gray, solid and tight one fastened firmly on the tubing wall. The composition of the scale sample is scaled with atomic absorbtion spectrophotometer and the result is listed in Table 1. As shown in Table 1, calcium carbonate is the prime scale component and silicate and iron oxide follow behind.

3. EXPERIMENTAL EQUIPMENT AND PROCEDURES

3.1 Nozzle Configuration

The nozzle head for the experiments is shown in Fig.1. According to the inner diameter and the area of the scaled tubings, the number and exit diameter as well as the jet direction of nozzle are determined so as to cut and clean the scale inside the tubing completely at certain advancing speed under the working nozzle pressure and flow rate.

For commonly used tubing of 62.2 mm inner diameter with calcium carbonate scale of about 10 mm thick, six-jet nozzle head with exit diameter of 1.6 mm each and direction angle of 75 degrees is used at jet pressure of 20 MPa and flow rate of 3.01/s.

3.2 Experimental Equipment and Procedures

The descaling tests of calcium carbonate scale tubing with water jet were carried out in Water Jet Laboratory, University of Petroleum. Test system is shown in Fig.2.

Two sets of triplex-plunger pump, each with rated pressure of 50 MPa and maximum flow rate of 1.5l/sec, are used to pump water through a flexible hose and a conductor tube to the nozzle head from which six water jet streams eject onto the tubing wall to remove the scale. Water jet pressure is controlled and adjusted by a pressure regulator. The tubing to be tested is fixed on a tubing holder. The advancing action of the nozzle head and the conductor tube inside the scaled tubing is controlled by a planing machine with variable traversing speed from 0.05m/min to 1.0m/min. The weight of the tubing with scale is recorded before testing. The tests are carried out at different nozzle pressures and nozzle advancing speeds. The tested tubing is weighed and recorded. The weight loss of the tubing is the amount of scale removed. And descaling efficiency, DE, is defined as the ratio of the amount of scale removed(weight) to the original amount of scale (weight) inside the tubing which is determined by the original weight of scaled tubing and the net weight of the tubing body, that is

$$DE = \frac{Wr}{Wo}$$

in which DE denotes the descaling efficiency; Wr represents the amount of scale removed (weight); Wo is the original amount of scale(weight)

4. EXPERIMENTAL RESULTS AND DISCUSSIONS

4.1 Effects of Nozzle Pressure on Descaling Efficiency

The descaling test results at different nozzle pressures and advancing speeds are listed in Table 2. Significant effects of nozzle pressure and advancing speed on descaling efficiency are observed. Fig.3 shows the relation between descaling efficiency and nozzle pressure at three different advancing speeds.

It can be seen in Fig.3 that, at fixed advancing speed, descaling efficiency increases greatly as nozzle pressure increase. Descaling efficiency increases from 0.70 to 1.00 as nozzle pressure increases from 15.0 MPa to 20.0 MPa with advancing speed fixed at 1.0 m/min. It can also be seen in Fig.3 that, at nozzle pressure of 20.0 MPa, descaling efficiency reaches 1.00 at three different advancing speeds tested. This definitely means that, for descaling of calcium carbonate scale inside the injection tubing in Shengli Oilfields, when working nozzle pressure is 20.0 MPa, the descaling efficiency can reach 1.00 with advancing speed up to 1.0 m/min. It can be inferred that the descaling speed would exceed 1.0 m/min at higher nozzle pressure than 20.0 MPa.

4.2 Effects of Advancing Speed on Descaling Efficiency

Fig.4 shows the relation between descaling efficiency and advancing speed at fixed nozzle pressures. It can be seen that the descaling efficiency decreases as advancing speed increases in varying degrees at different nozzle pressures. The descaling efficiency decreases more rapidly as advancing speed increases at lower nozzle pressures than at higher nozzle pressures. At nozzle pressure of 15.0 MPa, for example, descaling efficiency decreases by 22 percent from 0.95 to 0.70, as advancing speed increases from 0.2 m/min to 1.0 m/min. And at nozzle pressure of 18.0MPa, descaling efficiency decreases by 16 percent, from 0.96 to 0.80, as advancing speed increases by the same value from 0.2 m/min to 1.0 m/min. As nozzle pressure increases to a certain value, 20.0 MPa in this test, the descaling efficiency remains at 1.00 at different advancing speeds tested.

5. DEVELOPMENT OF TUBING DESCALING SYSTEMS

In order to meet the needs of descaling operation for tubings of injection wells in oilfields, two types of descaling systems, stationary and mobile, have been developed.

5.1 Stationary Tubing Descaling Systems

In oilfields, plenty of scaled tubings from the shut down injection wells are pulled out of the wells and are gathered in the work shop for descaling, detecting, and repairing if necessary. After these processes, they can be reused. A stationary descaling system for these injection tubings has been developed and fixed in the workshop, as shown in Fig.5, which consists essentially of pump section, control section, flowing and jetting section, tubing holding and conveying section, and water clarifying and circulating section. A motor- driven plunger pump, with rated pressure of 50 MPa and maximum flow rate of 215l/min, is used in this system. The working nozzle pressure is controlled by a pressure regulator.

Water is pumped through a flexible hose and then a ten-meter length of conductor tube, which is a little longer and thinner than the injection tubing to be descaled and is laid on the conveying belt, to a nozzle head from which six water jet streams eject. The scaled tubing is placed from the support belt onto the conveying belt by a mechanical grasper and is descaled as it moves forward on the conveying belt. After the tubing passes over the jet nozzle and the scale inside it is removed completely, it is withdrawn from the descaling operation for the next one so that the descaling operation can proceed.

The scale removed is collected and carried away, and the water is clarified and circulated through the settling pool and filtering unit to the water supply tank.

5.2 Mobil Tubing Descaling System

For the descaling of waterflood pipelines and injection tubings which are impossible or need not to be disassembled to the work shop, a mobile descaling system has been developed for the descaling operation on-the-spot.

The whole system is mounted on a truck. High pressure water stream is pumped through flexible hose to a nozzle head from which water jets eject to remove the scale. The nozzle head is so designed that water jets eject in a certain backward angle which not only impinge on the inside surface of the pipe to remove the scale but also create a drag force to move the nozzle head and the hose in the pipe. A hose-driven unit can be used so that longer pipes can be descaled in a single trip.

5.3 Preliminary Field Experiment

Preliminary field experiments in Shengli Oilfield have shown that water injection tubing can be descaled at higher efficiency and lower cost with both stationary and mobile water jet descaling systems, which costs averagely 0.20RMB yuan per meter of tubing with descaling speed of 1.0 m/min at jet nozzle pressure of 20.0MPa, compared to chemical treatment costing 0.35RMB yuan per meter of tubing at an average speed of 0.8m/min and to mechanical descaling which costs 0.40RMB yuan per meter at average speed of 1.0m/min. Field experiments have also demonstrated the advantages of no environmental pollution and tubing wall damages with water jet descaling method over chemical and mechanical ones.

6. CONCLUSIONS

(l) Nozzle pressure is an important factor affecting the descaling efficiency. Descaling efficiency increases greatly as nozzle pressure increases at the same advancing speed.

(2) Descaling efficiency decreases as advancing speed increases under certain nozzle pressure range, and the decreases in descaling efficiency are greater at lower nozzle pressures than at higher pressures.

(3) Pipe descaling with water jet has the advantages of low cost and no environmental pollution and damages to pipe surface, and can be widely applied for the descaling operations for pipes of boilers, heat exchangers, chemical plant, power plant, etc.

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Table 1 Composition of Typical Scale from Shengli Oilfield

Ingredients	CaO	SiO_2	Fe_2O_3	P_2O_5	MnO_2	BaO	Na_2O	Al_2O_3	K_2O
Content (%)	45.12	6.91	2.27	0.37	0.18	0.15	0.13	0.12	0.02

Table 2 Descaling Efficiency of Water Jet at Different Pressures and Advancing Speeds

Adv. Speed m/min \ Noz. Pres. MPa \ Desc. Effic.	13.0	15.0	18.0	20.0
0.2	0.88	0.90	0.96	1.00
0.5		0.87	0.93	1.00
1.0		0.70	0.80	1.00

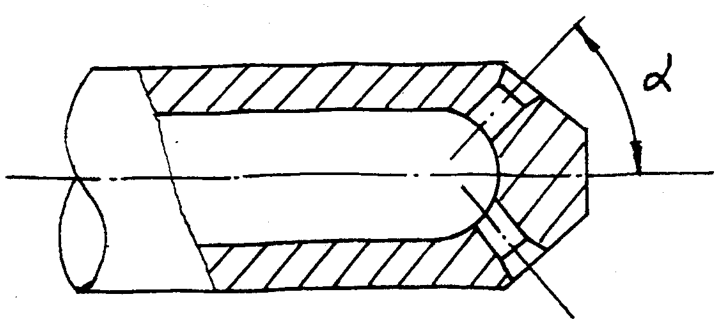
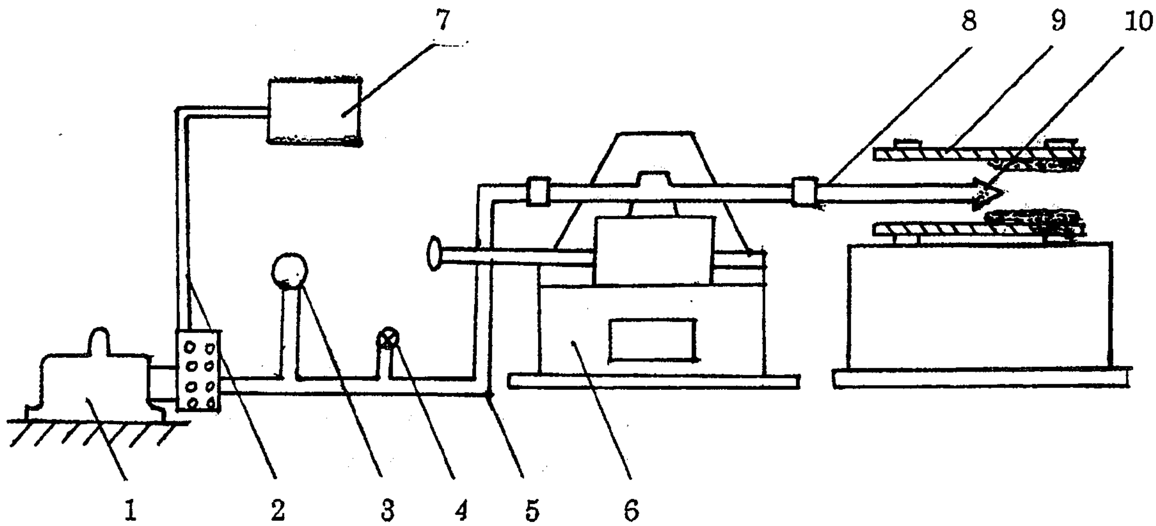


Fig.1 Schematic of Nozzle Head for Descaling Experiment



(1) High pressure pump; (2) Suction line; (3) Air accumulator;
(4) Pressure regulator; (5) Flexible hose; (6) Planing machine;
(7) Water tank; (8) Conductor tube; (9) Tubing; (10) Nozzle head.

Fig.2 Schematic of Laboratory Test System

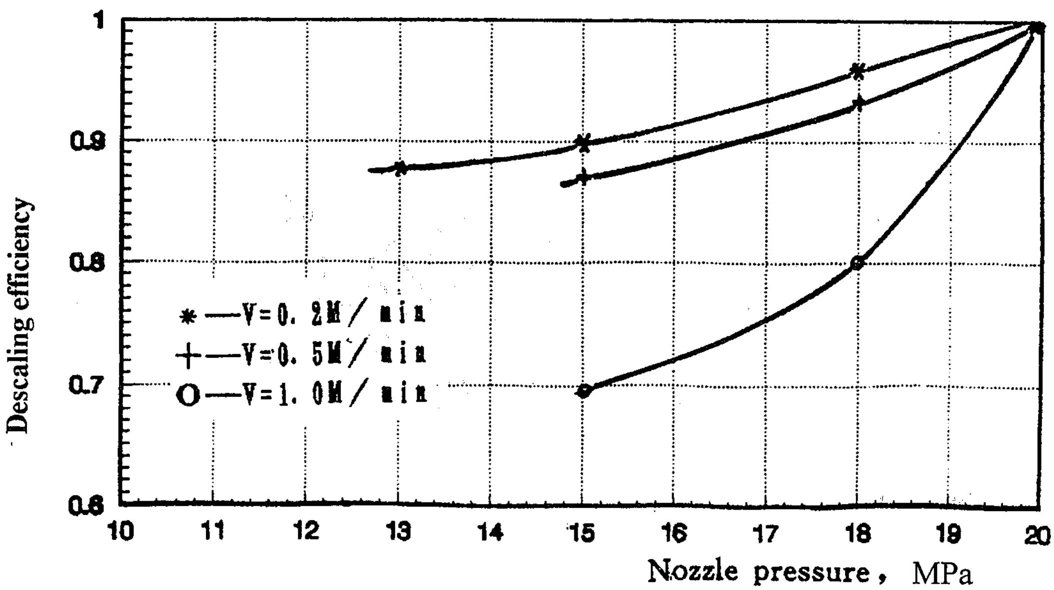


Fig.3 The Relation Between Descaling Efficiency and Nozzle Pressure

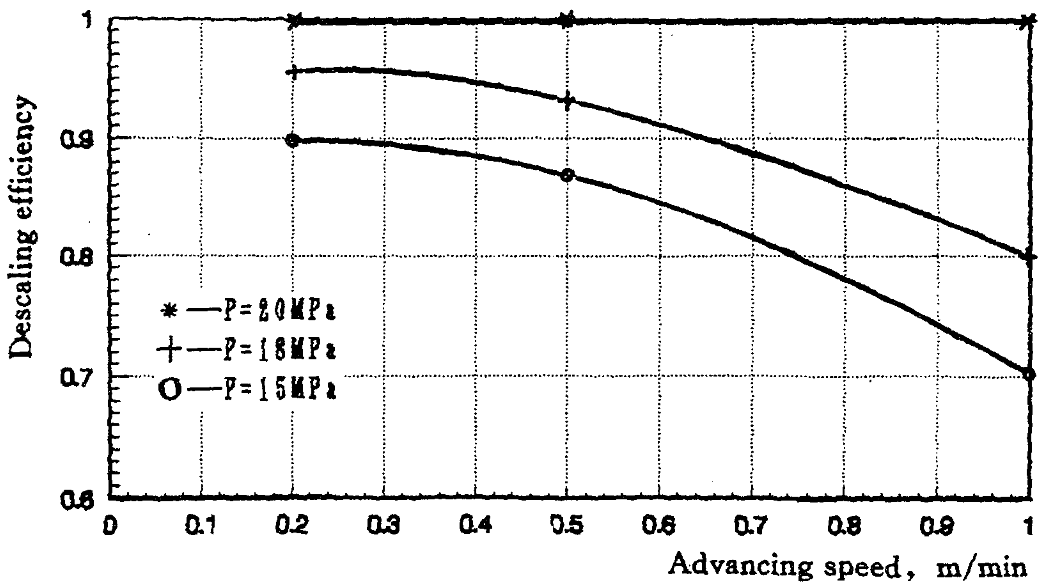
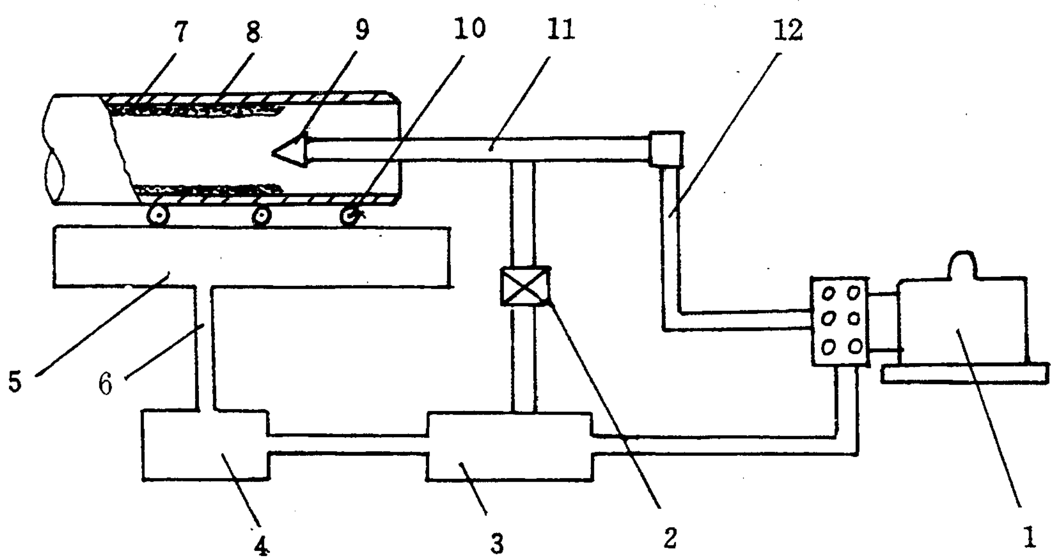


Fig.4 The Relation Between Descaling Efficiency and Advancing Speed



(1) High pressure pump; (2) Pressure regulator; (3) Water supply tank; (4) Water clarifying pool; (5) Settling pool; (6) Water circulating line; (7) Scale deposit; (8) Tubing; (9) Nozzle head; (10) Conveying belt; (11) Conductor tube; (12) Flexible hose.

Fig.5 Schematic of the Stationary Descaling System

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Paper 45

UHP WATERJETTTING GAINS ACCEPTANCE

FOR SURFACE PREPARATION

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ABSTRACT

This paper will discuss all elements that have moved Ultra High-Pressure (UHP) waterjetting into position as an accepted, and sometimes preferred, method for surface preparation; including: Improvements in technologies and equipment — development of new waterblast coating systems by major coating manufacturers, and advantages of the process — better coating adhesion / lower level of residual chlorides and sulfates.

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1. INTRODUCTION

Proper surface preparation is the most critical element to the success of any coating project. An improperly prepared surface may lead to coating failure due to corrosion or loss of adhesion. As an alternative to abrasive blasting — a technology entrenched in the surface preparation industry for nearly 100 years — ultrahigh-pressure (UHP) waterjetting has recently evolved as a viable tool for commercial applications.

Surface preparation with UHP waterjets involves water pressurized to ultrahigh-levels (> 35,000 psi) to remove a paint or other surface coatings in preparation for applying a new coating. A combination of technological advancements and external factors such as increasingly stringent environmental regulations have driven acceptance as a method of surface preparation.

Abrasive blasting has dominated the surface preparation industry for most of this century, primarily due to economic and performance benefits. High productivity rates, particularly for large area surfaces, reinforced abrasive blasting's popularity with contractors. Industry wide acceptance of a surface prepared by grit blast and familiarity with the process were also factors.

External factors such as environmental and occupational regulations have prompted the surface preparation industry to seek alternatives. Airborne dust generated by grit blast has caused government agencies to scrutinize its impact on the environment. Health problems caused by exposure to toxic airborne dust have also raised concerns.

Grit blasting normally takes place in an open air environment. Air quality regulations constantly change and are growing more restrictive. To satisfy new regulations, grit blast users must build elaborate and costly containment systems to prevent dust from contaminating surrounding areas. Containment devices add to the cost and complexity of a project. Users spend approximately one-third of their time assembling and disassembling containment systems and shoveling abrasive from tarps. Operators must wear respiratory equipment for protection against airborne dust. This article will discuss the advantages of UHP waterjetting for today's surface preparation applications.

1.1 Recent Evolution

In the past two to three years there has been a rapid growth in the acceptance of UHP waterjetting for surface preparation. Until this time period waterjetting was used only on very unique or very challenging applications. Today it is used widespread on many kinds of surface preparation projects such as coating removal on bridges, storage tanks, ships, and large complex shaped steel structures. There have been many recent advancements that have lead to this widespread acceptance.

1.2 Increased Productivity

Productivity levels of older hand held UHP lances were once one quarter to one third that of hand held abrasive nozzles which limited commercial viability. UHP waterjetting coating removal rates generally fell into the 20-30 ft^2/hr per hand held UHP tool, as compared to productivity ranges of 90-120 ft^2/hr per nozzle for abrasive blasting.

Reasons for the lower productivity were numerous. Operating pressures in the 30,000 - 35,000 psi range limited productivity rates. Slow nozzle rotation speeds further slowed removal rates. Technology has rapidly advanced between 1992 and 1996 to meet the production rates demanded by the surface preparation industries. Pressure ranges have increased to 40,000 psi. Higher nozzle rotation speeds in the 3000-3500 rpm range augmented advancements in operating pressures. Advancements in nozzle technology also improved productivity. Higher pressures and nozzle advancements have pushed productivity to rates comparable to hand held abrasive blasting. Typical removal rates are 80-100 ft^2/hr for UHP versus 90-120 ft^2/hr for abrasive blast on similar materials.

1.3 Lower Capital and Operating Costs of Equipment

Surface preparation equipment in the field is subjected to harsh conditions such as those found in shipyards and infrastructure rehabilitation work on bridges and storage tanks. UHP equipment previously experienced difficulties withstanding the demands of such environments. Attempts to convert hydraulic intensifier pumps from factory to field applications failed due to unpredictable conditions. Intensifiers were unreliable and complex, requiring well trained technicians to maintain the equipment.

Technical advancements in the past few years have significantly improved reliability. The evolution of positive displacement (plunger) pumps has been the single most significant development. Positive displacement pumps performing in the 10,000 to 20,000 psi range have been in the field for a number of years. They are much easier to maintain and do not need the clean operating conditions intensifiers require. Ease of maintenance makes positive displacement pumps a popular choice for work in harsh industrial environments. Users don't need to hire or train specialists to operate and maintain the equipment.

Positive displacement pumps capable of 40,000 psi are now operating in the field. To date, more than 200 such pumps are in use. Operation of UHP systems now differs little from low pressure waterblasting, a staple for decades in industries such as automotive and marine. Operators familiar with waterblasters can now operate UHP systems.

1.4 Acceptance of Light Flash Rust

A waterjetted surface will show signs of light flash rusting shortly after preparation. There has been hesitance from owners and coating manufacturers to apply coatings over a flash rusted surface. It is the coating manufacturer who takes final responsibility or warranty for the long term performance of the coating. Recognizing the benefits of UHP waterjetting, most major coating manufacturers have developed surface tolerant coatings that can be applied directly over a waterjetted surface. At a recent Marine Log seminar Dr. John Kelly of International Coatings stated "There are two kinds of rust. General atmospheric rusting or rusting from immersed conditions which is contaminated with chemicals from the environment to which the metal has been exposed such as chlorides or sulfates. In contrast, flash rust formed after preparing waterjetted surfaces using potable water consists of pure iron oxide, which is a constituent of most coatings. At low to medium levels, flash rusting is suitable for overcoating with many coating systems, since it is tightly adherent and won't react with the metal substrate or the coating applied over it." (1). There is now an industry wide acceptance of a light tightly adhered flash rust.

1.5 Improved Coating Performance on Waterjetted Surface

An abrasive-prepared surface is impacted with many small, discreet abrasive particles that tend to flatten out the sharp peaks created from original profile. On a microscopic level, abrasive particles will actually fold over and trap contaminants such as chlorides and sulfates, affecting the quality of the finished product.

Detecting cracks and imperfections are also very difficult due to the flattening phenomena. Flattening hides cracks and complicates visual inspections. The importance of a proper visual inspection for cracks increases in magnitude when preparing sensitive pieces of equipment such as steel pressure vessels or natural gas transmission pipelines for recoating. Furthermore, abrasive blasting fails to remove all corrosive materials from the substrate. Chloride levels as low as $10\mu g/cm^2$ and sulfate levels higher than $20\mu g/cm^2$ present on a grit blasted surface can cause blistering of coating films after a few weeks of exposure to condensing humidity (2). Numerous tests conducted have shown that soluble salts still remain at these levels on steel surfaces after abrasive blasting.

UHP removes soluble salts with ease. One major coating manufacturer states, "Wet blasting, particularly ultra high pressure hydroblasting, is a very effective method for removing soluble salts from substrates. Salt removal is perhaps the greatest advantage hydroblasting has over dry abrasive blasting." The company found that if potable water is used for hydroblasting, surface salt levels below the level specified by the joint SSPC and NACE of $7\mu g/cm^2$ are achievable on old rusted and pitted steel (3). SSPC and NACE have published this level in their joint standard "Surface Preparation and Cleaning of Steel and other Hard materials by High and Ultra High Pressure Waterjetting Prior to Recoating".

Recognizing this superior surface coating manufacturers now accept and sometimes prefer a waterjetted surface. Since coating manufacturers ultimately assume final liability of the coating, it is critical they guarantee coatings for UHP-prepared surfaces. International Coatings, Courtsland, England, has stepped forward to publish interim specifications. Visual specifications provided by International Coatings are now published in the field handbook. Most other major coating manufacturers have also accepted International Coatings' specifications as the standard.

Extensive testing has quantified the differences in residual contaminants on UHP prepared surfaces. All studies to date show conclusively that a much lower level of contaminants remain with waterjet prepared surfaces than grit blasted surfaces. Some of the most extensive analysis was presented at the 1992 NACE Annual Conference and Corrosion Show.

2. UHP WATERJETTING APPLICATIONS

2.1 Drydocks and Shipyards

Environmental attributes of UHP have broadened markets for the equipment. Shipyards, with their proximity to environmentally sensitive areas, comprise the largest market for UHP surface preparation equipment. As opposed to grit blasting there is no risk of abrasive contamination to neighboring residential or industrial areas. Also, there is no risk of abrasive contamination to surrounding areas of a ship repair project. This allows for other repair processes to be conducted simultaneously. For example, repainting or equipment repair work can go on just adjacent to waterjetting area. This significantly reduces the time in dry dock contributing to cost savings to both the vessel owner and the shipyard.

In addition there are several other cost savings benefits to the shipyard owner and vessel owner. There is no cost of grit to collect and dispose of; the water can be simply filtered and disposed of down sewer system while the paint chips are disposed of as a separate waste. Waterjetting eliminates the need for complex and costly containment systems. Waterjetting can be used adjacent to sensitive deck equipment such as winches, electric motors, and cranes without the need for masking or tarping and without the risk of abrasive contamination of these sensitive pieces of equipment, again reducing the cost and time of the project.

2.2 Lead Based Paint Removal

The second largest application of UHP Waterjetting is removal of lead based paint form steel structures. UHP surface preparation generates no airborne dust, eliminating the necessity to construct costly containment systems. It provides improved health hygiene for operators, operators can wear lightweight face masks in place of cumbersome respiratory equipment. A recent NIOSH report states "Ultrahigh pressure waterjetting suppresses the lead based dust by agglomerating the dust into the water droplets. The water may be disposed of through a public sewage system after it has been cleaned and treated." (4)

Waterjetting eliminates the disposal of lead-tainted abrasive. Abrasive blasters use 4 to 10 lbs. of abrasive per square foot. On the other hand waterjetting uses approximately two to three gallons per square foot treated. This small amount is easily collected and treated; the water can be simply filtered and disposed of down a treated sewer while the lead based paint particles are separated and disposed of as hazardous waste.

3. LIMITATIONS OF WATERJETTING

Waterjetting has become an accepted and many times preferred method for surface preparation. However, there are still some limitations of the process that limit some specific projects. Among these projects and applications would be:

- **Projects Requiring a Profile of the Steel**

Waterjetting alone will not profile the steel structure like grit blasting; that is why it is not typically used when removing paint from non profiled steel such as on many pre-1975 constructed bridges. However in some instances such as with lead based paint the paint is removed with waterjetting and grit is used as a secondary process to profile the steel. This eliminates the disposal of lead based paint contaminated grit. The lead based paint chips are filtered out of the runoff water during waterjetting and disposed of separately from the water as hazardous waste.

- **New Construction**

Waterjetting is typically not used in new steel construction due to the need for surface profiling prior to coating which is not achievable with waterjetting; it is typically done in production plants with large recycling shot blasters.

- **Areas where there are no Environmental Regulations**

There are still some areas where open air abrasive blasting is still viable; these projects are drastically reducing. On these projects it is sometimes more cost effective to do abrasive blasting especially if collection and disposal of grit are not issues.

4. CONCLUSION

Many times UHP waterjetting is viewed as a higher cost alternative to traditional removal methods. However, when all the benefits of UHP waterjetting are understood and recognized it provides in many cases a lower overall cost to both the owner and surface preparation contractor. As environmental pressures continue to become more stringent this process will become even more economically viable.

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Paper 46

CLEANING PROCESS EQUIPMENT WITH AUTOMATED HIGH PRESSURE WATER

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ABSTRACT

Automated water jet cleaning systems have been recently installed to clean process equipment in the Petrochemical industry to help minimize personnel exposure to the high pressure and the uncomfortable environment of humid heat. This paper covers a hydraulically powered Chlorine Cell Cleaning System and a pneumatically powered Rubber Dewatering Cleaning System using high pressure water to solve cleaning problems. These systems use 10,000 psi and 20,000 psi pump units, powered nozzle movements and control hardware to remove unwanted materials from process equipment.

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1. INTRODUCTION

Automated systems using high pressure water have been developed within the last thirty years. Machol (1994) discussed the use of 400 psi at 10 gpm in 1947 to clean a cooling tower. The high pressure hand gun, for example, seems to have been developed in the 1950's and has been re-designed and improved ever since. In the 1960's, some steel mills were using a pump and spray nozzles to scale billets and slabs of red hot steel. This fixed water jetting process was probably used for many years and has been automated for descaling forgings using up to 10,000 psi in present applications. For the last ten years, the Ultra-High pressure industry has taken the reverse direction of development, starting with highly sophisticated automation to developing hand held guns with rotating nozzles. The lower pressure water blasting has often lead to mechanical devices that can improve safety, speed the cleaning process and allow the use of more horsepower in the cleaning process.

Heavy industry tends to have specific applications that must be done on a regular basis and lend themselves to the development of automated high pressure water jetting systems. Conn (1986) discusses automated water jetting systems to remove explosive from munitions while capturing the water and debris. In industrial applications, the systems can be permanently installed and may include an electric driven pumping unit, powered movement of the cleaning nozzles and even the manipulation of the item being cleaned. In the case of a large but portable item to be cleaned, a cabinet or special room can be designed so the work moves through the cleaning chamber. Good examples are found in the automotive industry where Auto Bodies, Paint Carriers and Conveyors are cleaned in automated booths. Gracey (1995) describes a hydraulically powered, automated system using a pulsed nozzle to remove rocket propellant.

One example of a hand held process that developed into an automated method of cleaning can be found in the petrochemical industry. In the 1970's, chemical plants and their contractors were using hand held guns to clean chorine cells. In the 1980's, there were portable air powered fixturing devices available to rotate the nozzle while moving it vertically and horizontally. With the installation of an electric powered pump unit, this fixed system became a remote operator controlled cleaning station. In addition to the nozzle movements, the rotating lance could move into and out-of the chlorine cell being cleaned thus allowing an X,Y,Z coverage.

2. CHLORINE CELL CLEANER

By the 1990's chemical plants were more familiar with the benefits of automating some of their cleaning jobs, so a customer requested a system to clean their large chlorine cells that are used in making the gas from salt brine. The customer had been using a water blaster and hand held gun that was capable of 10,000 psi at 10 gpm to remove the asbestos coating from the cell anodes and now wanted a system that would clean the cells while rotating them for access to all sides. Ideas were discussed and evaluated to improve their present situation. The completed design included:

- A cleaning glance that moves in, out and rotates the high pressure nozzle
- An indexer that moves the lance up, down and from left to right
- A work table that supports and rotates the chlorine cell for cleaning
- A control console to operate all the automated functions
- A 300 horsepower electric driven high pressure pump for 10,000 psi operation
- A hydraulic power unit to operate the system movements

Illustration I shows the device, called the indexer, to move the nozzle for cleaning the chlorine cell. The complete system includes a containment room for the cleaning process, a control room for the operator and a pump room for the high pressure pump. Illustration II shows the 300 horsepower, electrically driven high pressure pump that can deliver 10,000 psi at 42 gpm. The increased horsepower capability of the automated system tends to improve the cleaning effectiveness and the personnel are exposed to less danger in the remote control room.

There are so many excellent examples of automated systems including PLC controlled process cleaning equipment, semi-automatic accessories and robotic applications. The hand held water blasting lends itself to the development of mechanical devices, then motorized movements and finally complete computer controlled movements of the high pressure water jet for cleaning, cutting and surface preparation.

3. WATER EXPELLER CLEANING SYSTEM

Another customer wanted to automate a process to clean their rubber dewatering equipment. A piece of equipment they called a " Continuous Expeller" squeezes the water from the rubber being made by this plant facility. The main problem is that the rubber extrudes out of the narrow openings in the expeller during the dewatering process and requires a regular cleaning that was being done by manually operated water blast equipment and hand guns. The job was not pleasant because of the heat and humidity in the expeller room. The customer requested a system with the following features:

- Be able to run continuously in a dirty, hot and humid atmosphere
- Have about ½ hour cleaning cycle
- Include an electric driven pump unit with minimum flow
- Be removable for servicing the expellers

The first phase of the proposal was a design concept for the cleaning mechanism, a recommended pump size and a budge price for the system to clean four of these expellers. Illustration III shows the concept of the proposed equipment. The mechanism was to be pneumatically powered and fit inside of each expeller cabinet. There were four extruders and each side needed cleaning , so eight cleaning devices were proposed to automatically move from side to side, while moving vertically to cover the entire side of the expeller. The air logic would allow for continual operation of any of the selected pairs of the cleaning mechanisms. By running only two of the mechanisms at a time, minimum water and minimum horsepower could be used. The high pressure pump that was first recommended, included a 150 H.P. electric motor for 10,000 psi at

20 gpm. Later tests and prototype hardware proved that 20,000 psi at less than 10 gpm could do the job.

After reviewing the design concept, the customer decided that a PLC (programmable logic controller) would be desirable to control the functions of the system. Illustration IV shows the concept of the system incorporating the PLC, automated valves and air logic. A proposed operating procedure included a selection for both manual and automatic operation, as indicated in the following list:

1. Supply electrical power to the system (pump & PLC), following the company's procedures.
2. Select "Manual" or "Automatic" operation of the system.
3. On "Manual", the following equipment could be started or stopped:
   a. Water supply valve to high pressure pump
   b. Cleaning device (one of four)
   c. High pressure pump motor (on or off)
   d. High pressure (on or off)
4. On "Automatic", the following sequence would take place when the "Start Cycle" button was pushed:
   a. The water supply valve to the high pressure pump opens
   b. Cleaning device to operate would receive water from the high pressure pump
   c. Cleaning device to operate would receive air for powered movement
   d. High pressure pump motor would start
   e. After timed delay, high pressure pump would pressure-up
   f. System would run for a pre-set time period, then pressure down, switch to the next cleaning device and repeat until all four devices have run
   g. When cycle is completed, the system depressurizes, the device movement is stopped, the high pressure pump motor is stopped and the water is turned off. The system would be in "stand-by" until electrical power is locked-out.

The final design changed when the customer agreed to remove the expeller cabinets to allow better access. Illustration V shows an idea of the mechanism that was tested on the job site and developed into the completed system.

4. CONCLUSIONS

Automated systems have developed into highly sophisticated designs, in some cases. It takes more engineering time, production time and field work to complete a system than a simple water blaster, but our industry needs these automated systems to do some of the work that puts people in danger or makes working conditions uncomfortable. The water jet industry should use all of the new technology that becomes available to build better automated systems.

5. ACKNOWLEDGMENTS

Many new ideas are just improvements on old ideas and the author wants to thanks those people who share their ideas to help the water jetting industry. The author also wants to thank Mr. Brian McMillion for the illustrations used in this paper.

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Illustration I — Indexer

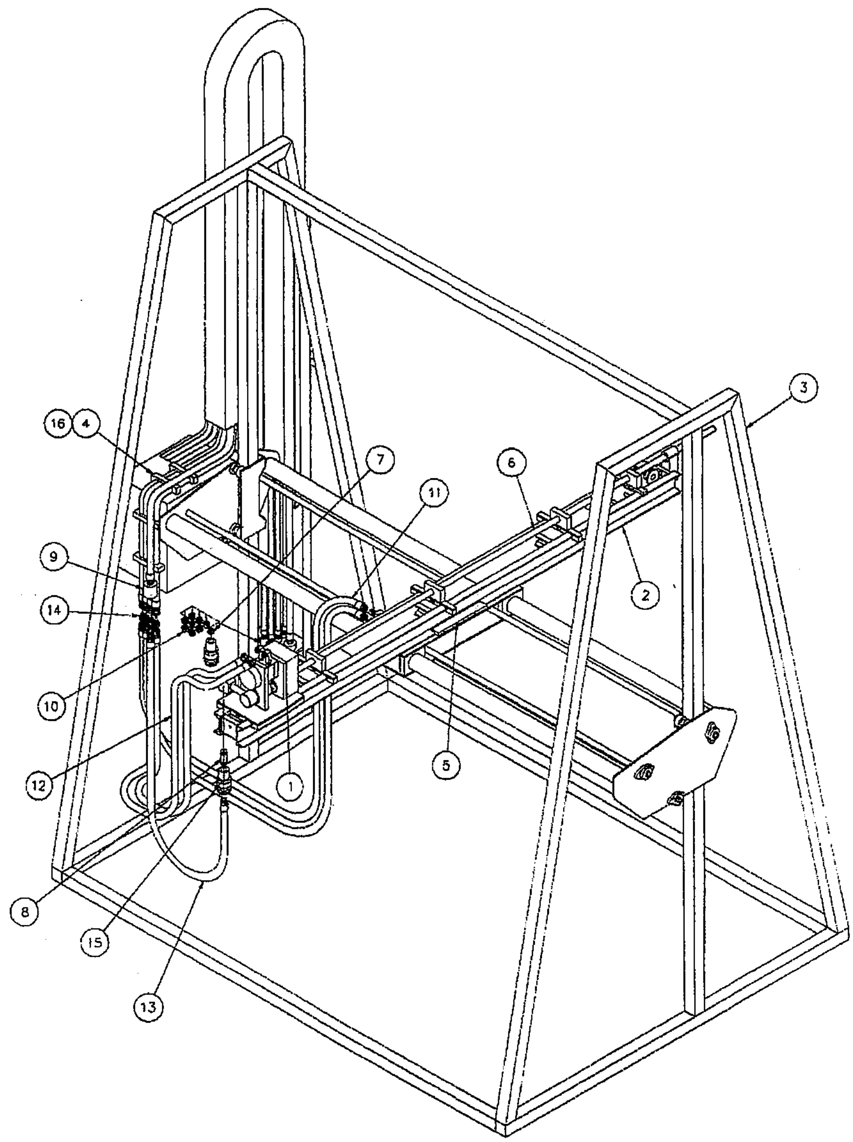


Illustration II – High Pressure Pump

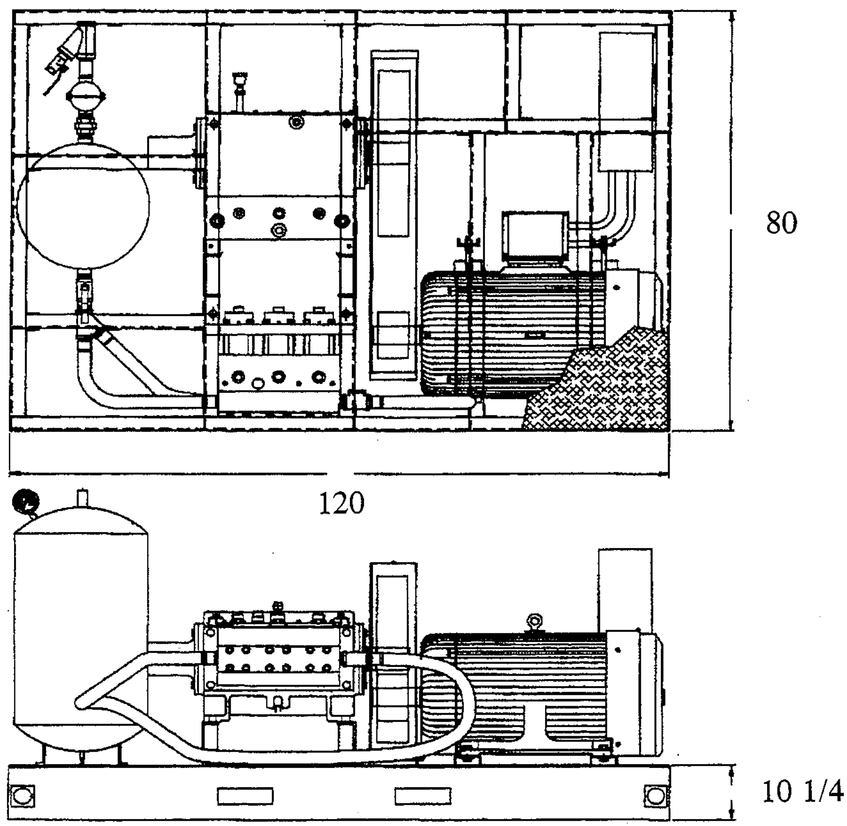


Illustration III — Automated Cleaning Mechanism

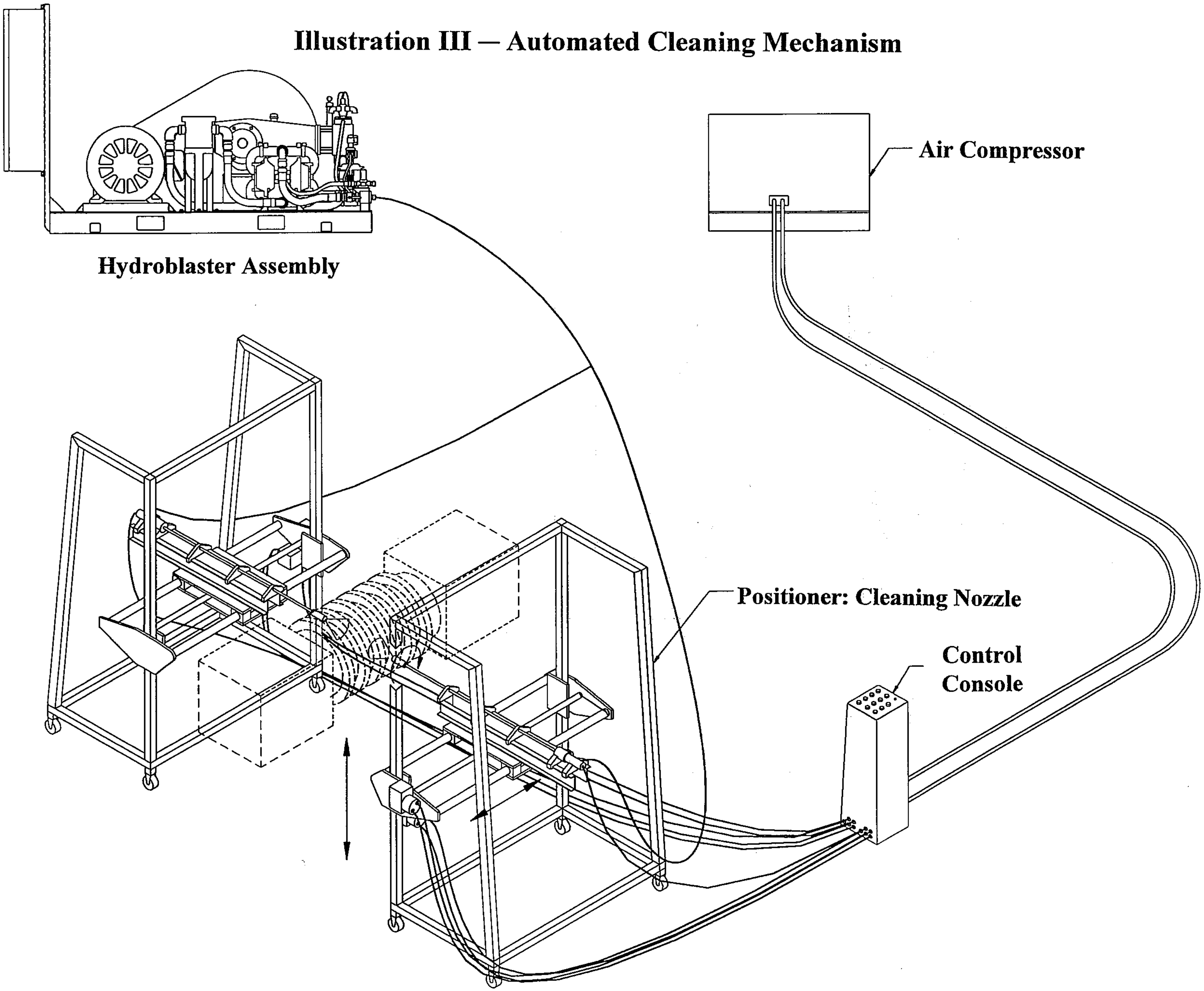


Illustration IV — Conceptual Cleaning System With PLC Controller

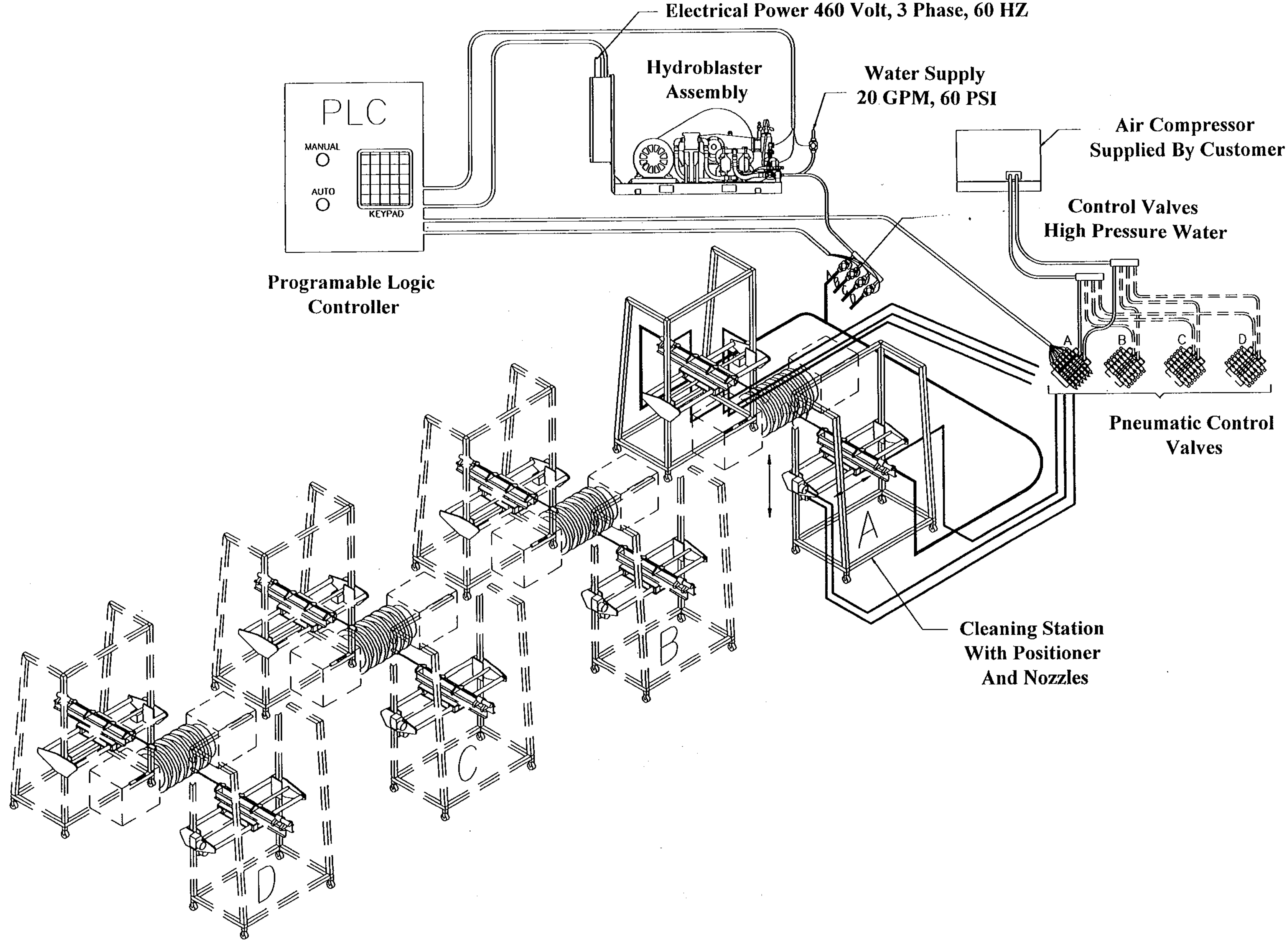
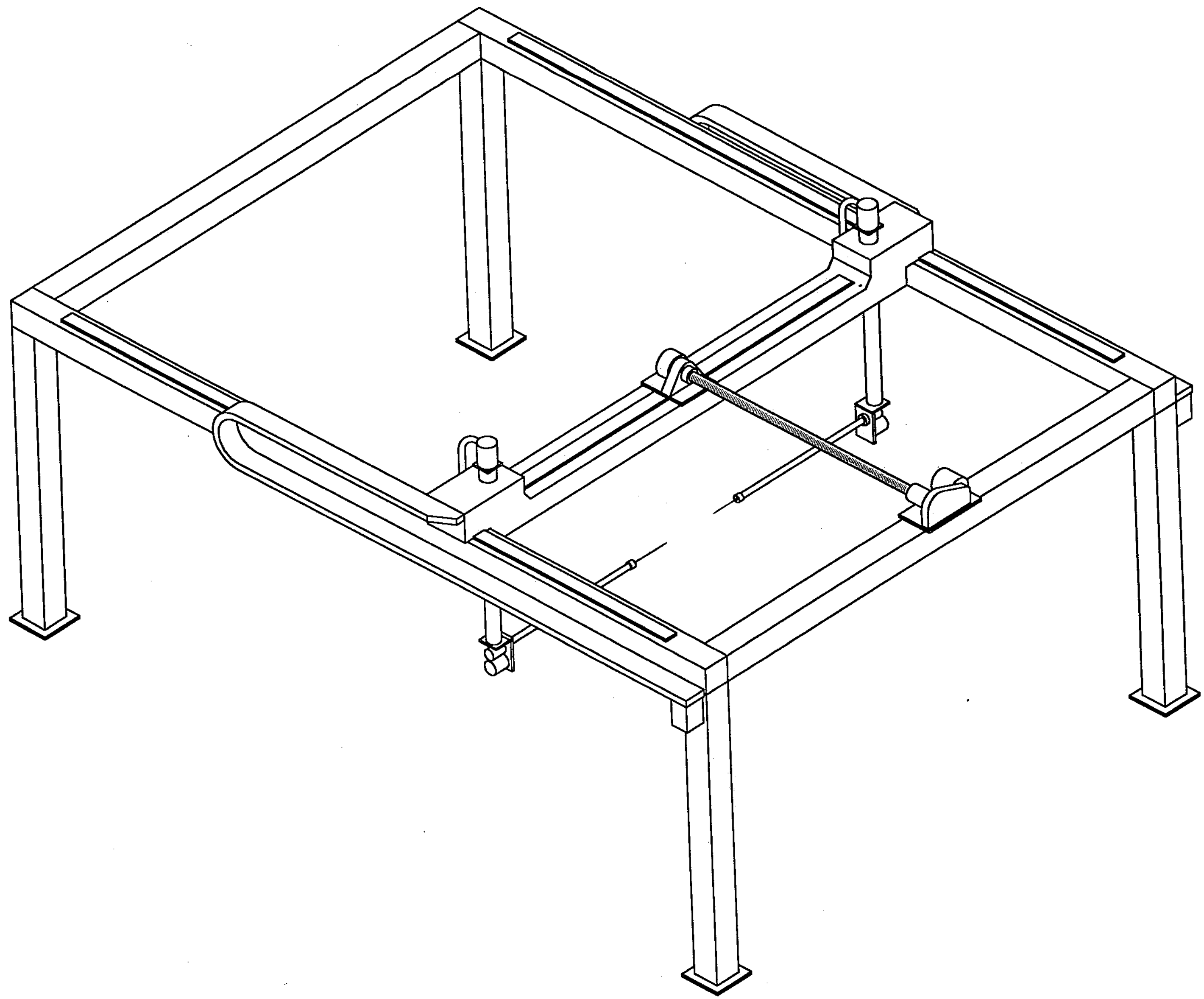


Illustration V — Motion Mechanism



9th American Waterjet Conference
August 23-26, 1997: Dearborn, Michigan

Paper 47

USE OF ULTRA-HIGH-PRESSURE WATERJETTING FOR ROCKET MOTOR REFURBISHMENT

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9th American Waterjet Conference
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Paper 48

DEVELOPMENT OF A ROBOTIC SYSTEM FOR CLEANING OF CHEMICAL REACTORS

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ABSTRACT

The design of a cleaning system for decontamination of chemical reactors is discussed. Special attention is paid to the selection of the devices for water compression and design of a robotic arm for guiding a water nozzle within the reactor. The tests of laboratory and industrial scale prototype demonstrated both feasibility and effectiveness of the use of developed system for application in chemical and pharmaceutical industries. The expected rate of cleaning by the use of the system in question is 7 m^2/hr at the water consumption of 3.2 litter/m^2

Organized and Sponsored by the Waterjet Technology Association.

1. INTRODUCTION

Low cost and comparative simplicity of the use of cleaning substances assured their almost universal application for surface preparations. A growing branch of chemical industry manufacturing solvents, cleansers, detergents, soaps etc., etc., has emerged. The use of cleansers, which provide inexpensive and reliable soil removal has been adopted by the industry as a main surface decontamination technology. The principal shortcoming of this technology is, however, the environmental effect. A cleaning medium is expected to be dumped after a single use. The tightening environmental regulations and public awareness make existing approach unacceptable in some cases and nonaffordable in others. Another deficiency of the use of cleansers is insufficient quality of the decontamination of complex surfaces. It is difficult if not impossible to assure adequate cleanser delivery at blind holes, cavities and other problem areas.

The current practice of decontamination of pharmaceutical reactors demonstrates the shortcomings of the cleansers based technology. A conventional cleaning of a pharmaceutical reactor involves the following:

-rinse a vessel with minimum amount of the solvent of the last use.
-aqueous cleaning by two to three vessel volumes
-reflux vessel with methanol or acetone (25% of the vessel volume)
-boiling solvent for about 30 minutes
-condensing the vapor
-cooling the solvent to the room temperature
-discarding the solvent as a waste
-rinsing the vessel by a solution (5% of the solvent) for a test
-if the contaminant content in the solvent exceeding the reactor exceeds a permissible level the cleaning is repeated.

The solvent based cleaning technologies results in the use of a high volume of various hazardous chemicals and water (from 600 to 900 gallons of water for 300-gallon vessel); high energy consumption for heating and mixing of the solvents; loss of reactor productivity because of the duration of cleaning, excessive emission of liquid and gaseous pollutants. The solvent-based cleaning technology is extremely time consuming. It often takes 2-3 days to clean a vessel using solvents. This incurs not only a substantial loss in productivity but also a cost of purchase and maintaining of additional vessels. A number of cleanings at a middle size specialty chemicals company ranges between 10,000 and 20,000 per year. Thus amount of aqueous wastes for such a company ranges between 7,500,000 and 15,000,000 gallon per year. Total down time due to cleaning operations is 40,000 -60,000 days of vessels operations. Thus cleaning of chemical equipment is becoming one of the major contributors to the cost of chemical products.

Increasing cost and environmental regulations resulted in emerging new cleaning technologies. EPA (EPA,1994) suggests to use carbon dioxide snow and ultrasonic cavitation as alternatives to the use of solvents. Although these processes can replace solvents in a number of case, the cost and complexity of the cleaning limit their application. The only universal, practical and environmentally benign tool which can replace solvents is the high speed waterjet.

The principal advantage of the waterjet cleaning is practical elimination of the use of solvents and potential for complete recycling of offproducts. In the most cases the offstream generated in the course of waterjet cleaning constitutes a mechanical mixture of water and debris. These debris can be readily removed and water recycling is feasible. Moreover, the debris recovered from the off stream generated during water cleaning are not contaminated by solvents or other foreign substances and can be at least partially reused. At the same time the deposit removed by the solvent is not only difficult to separate but also impossible to reuse.

The deposit removal by an impinging waterjet is the most traditional cleaning technology. Waterjets have been customarily used for various cleaning applications such as street and car washing, removal of paint, rust, scale etc. Commercial waterjet cleaning equipment including the equipment for tanks cleaning is manufactured by several companies. Moreover, there is a number of contractors routinely providing waterjet cleaning services. However, the high rate of water consumption, insufficient quality of cleaning and cost of equipment and its operation limit the use of water based deposit removal. Because of this at the present , the use of solvents for cleaning applications is more practical than the use of waterjets.

Despite centuries of practical use the fundamental studies of waterjet cleaning were initiated at the late 1970's. Important aspects of the mid-pressure (2,000 - 10,000 psi) waterjet cleaning of chemical reactors and petrochemical equipment were investigated by Barorick I. D. (1978). Schikorr et al. (1982) defined the concept of cleaning process and list possible waterjets cleaning applications in many fields. Summers (1982), Louis and Schikorr (1982), Louis et al. (1984) discussed various aspects of waterjet based deposit removal. Removal of hard-to-separate deposits from surfaces by waterjets of very high pressure was developed by Singh, et al. (1992) and Watson (1993). Improvement of cleaning technology was suggested by Saunders et al. (1986), and Conn. (1992). Remisz. (1993) evaluated and discussed a problem of how to process the wastage after waterjet cleaning. Conn. (1992) examined the economic aspects of waterjet cleaning using rust removal from ship hull as a case study.

Recently NJIT's Waterjet Laboratory (Geskin, 1993, Geskin et al., 1996,1996a, 1997,1997a, Meng, 1996, Meng et al, 1995, Meng 1996, 1996a) investigated deposit removal process using high-pressure waterjets. These results have demonstrated that waterjet cleaning is an effective method for removing various contaminants and can be used for decontamination of complex convex and concave surfaces, for example lining of vessels, tanks etc. The desired effect is achieved by the direct impingement of the sites to be decontaminated by the water stream. The momentum of the stream should exceed the critical level, which assures soil removal, but is below than the level which might cause substrate damage. If these conditions (direct impact and the value of the water momentum) are met, the decontamination is attained due to mechanical interaction between the jet and lining. The decontamination is carried out in such a manner that a high productivity (m2 of decontaminated surface/hour) is attained at low water consumption (litters/m2 of decontaminated area). The developed technology enables us to the replace volatile solvents for cleaning batch processing equipment and storage tanks with high-pressure, low-volume, directed waterjets. One can expect that high pressure aqueous jets not only will replace hazardous chemicals, but will also substantially improve the economics of cleaning (Meng, 1996, Meng et. al. 1996). If, for example, the current procedure requires 2-3 days to clean a chemical reactor, waterjet cleaning can be accomplished in several hours.

2. DESIGN OF THE CLEANING SYSTEM

As it was shown by Meng et. al (1996) the following conditions are to be met in order to assure jet based precision surface cleaning:

- the surface which is expected to be decontaminated is subjected to the direct impact of the jet.
- the momentum delivered to the impact zone must exceed the minimal critical level, that is the level which assures contaminant removal to a desired degree
- the momentum delivered to the impact zone must be below than the momentum which might cause a modification of the reactor lining.

In order to assure process competitiveness the rate of decontamination must be sufficiently high and the water consumption must be sufficiently low. As it was shown in our previous study (Meng et. al, 1996, Meng, 1996) at the water pressure of 340 MPa, traverse rate of 100 m/min, stand off distance of 5-10 cm and impact angle of 90 degree the rate of the surface decontamination might reach 100 m2/hr at the water consumption of 1 litter/m2.

The principal feature of the developed technology is the direct impact of the high speed jet at all contaminated sites of the reactor. The direct impact is attained by the continuous jet positioning within the reactor. The high pressure water is supplied inside the reactor via available opening, which is usually a hatch of 11 cm diameter with a fixed angle with the reactor axis. This hatch is also used for the insertion of a robotic arm for the nozzle guiding inside the reactor.

The nozzle must be guided in such a manner that while all contaminated areas are subjected to the direct jet impact, the moving parts do not approach to the lining, impeller, baffles and other parts of the reactor. It is necessary that such problem areas as the surfaces of the impeller and baffles, lining beneath the impeller and behind the baffle, the washer between the reactor cover and main reactor body etc. are subjected to the direct jet impact . The desired conditions of the nozzle motion can be met by the selection of the kinematics of the robotic arm and the use of flexible hoses for water supply. In order to minimize the loading of the end point of the robotic arm the jet must be generated by a low weight nozzle head.

The complete surface coverage and non-collision with reactor parts are the dominant constraints imposed on the design of the robotic arm guiding the nozzle. Due to the specific conditions of pharmaceutical reactors no lubricants except for water or air can be used to assure high speed motion of the nozzle. The use of water lubricants dramatically increases water consumption, while the use of air bearing is too complicated for the system operating inside a reactor. Thus, the robotic arm will operate without lubrication. It is anticipated that the system could be used for a multiplicity of reaction vessels types and for various contaminants. Thus, the nozzle trajectory must be readily readjustable. The necessity to generate a complex trajectory within a complex enclosure makes it difficult if not impossible the use of various swivels, pressure rotary joints etc. The nozzle must be connected to the water source located outside the reactor by a flexible hose. However, the use of a flexible hose for water supply imposes the limitation on the water pressure.

The limitations above were taken into account in the course of the design of the system in question. The available flexible hose limited the water pressure by 90 MPa. Because of this additional experiments were carried out to demonstrate the feasibility of complete decontamination of the reactor lining (Pfaulderglass) at this pressure. The glass samples were submerged into molten polyethylene. Water pressure of 90 MPa and less was used to remove a polyethylene layer. The experiments showed the feasibility to decontaminate glass surface at thepressure of 80-90 MPa. Then it was necessary to select a portable inexpensive source of compressed water. A pneumatically driven pump (Maximator pump) was selected for this purpose. At the air pressure of 100 psi the pump generated 1 litter of water per minute at the pressure of 90 MPa.

The next step in the system development was the design of the robotic arm. The selection of the arm kinematics and motion planning will be carried out by the solution of the variational problem determining the position, velocity and acceleration of the robot end point. The duration of the cleaning will constitute the criterion optimality of the problem. The problem constraints will include minimal distance from the reactor lining and the reactor parts (impeller, baffle); standoff distance, attack angle and the traverse rate at each individual point of the nozzle trajectory. The trajectory must assure the complete coverage of thereactor lining. The solution of this problem is currently sought. At this stage of the project computer modeling of the nozzle motion was used to select both robotic arm design and the trajectory of the nozzle. A computer graphics package enabled us to visualize nozzle motion as well as coverage of the lining. The intersection between the beam emitted from nozzle and reactor surface determined the area covered by the impinging jet. The modeling enabled us to evaluate the selected arm kinematics. Particularly, the feasibility of the complete coverage of the reactor lining and noncollision conditions were demonstrated.

3. TESTING OF THE LABORATORY SCALE PROTOTYPE

A laboratory scale prototype was constructed and tested in order to demonstrate the feasibility of the reactor decontamination using the water nozzle guided by the constructed robotic arm. A general view of a laboratory scale cleaning system is shown on the Figure 1. The robotic arm (Fig. 2) consisted of two links. The link 1 had one rotational (rotation around axis Z) and one translational (translation along axis Z) automatical degrees of freedom. The link was supported by a spherical bearing which provided manual two rotational degrees of freedom. The link 2 having 1 automated rotational (rotation around axis X) degree of freedom was connected to the en point of the link 1.

A flexible high pressure hose terminating in the sapphire nozzle was used for water supply. The hose was connected to the exit of the Maximator and terminated at the water nozzle. The nozzle trajectory was generated automatically while the initial position of the nozzle and adjustment of the links were established manually. Special attachments might be used to clean difficult to reach areas, such as lower surface of the impeller, baffle, lining behind the baffle etc.

The system was tested at the laboratory reactor of the Waterjet Technology Laboratory. The tests included paint removal from the reactor lining. The test demonstrated that the developed system is able to remove deposit from more than 95% of the reactor surface. In order to secure complete coverage of the reactor lining special attachments must be used or the kinematic of the robotic arm should be improved. The latter approach was selected in the design of the industrial scale system.

4. INDUSTRIAL SCALE SYSTEM

A system for cleaning of Pfaulder Glassteel 50 gallon reactor model ES-50-25 was designed and constructed. The reactor constitutes a cylinder lined with the Phaulder glass. The height of the reactor and its diameter are 75 cm. A three rudder impeller is installed at the axis of the tank. Reactor is also equipped by a baffle. The only entrance to the tank is an 11 cm diameter opening at the top of the tank lid, offset 10 cm from the lid surface and at a 20 degree angle with the horizon.

The schematic of the system is shown in Fig. 3. The high pressure water is generated at by a pneumatically driven pump and via a flexible hose is supplied to the nozzle. The Maximator pump generates 0.5 litter/min of water at the pressure ranging from 10 to 400 MPa. Air is supplied at the pressure of 0.7 MPa at the rate of 10-100 cfm depending on the required pressure and flowrate of the compressed water.

The nozzle is driven by a robotic arm shown in Figs 4-8. The arm consists of 4 automatically driven links. The sliding link 2 (Fig. 4) , driven by the nut and screw transmission moves along the axis Z and supports the link 4 rotating around axis Z. The rotational link 5 (rotation around axis X) is connected to the end point of the link 4 and the rotational link 6 (rotation around the axis X) is connected to the end of the link 5. The nozzle is connected to the end of the link 6. Each automatically controlled link is driven by AC motor. The order and the duration of the motors operation is determined by a program developed offline and downloaded to the controller memory (Fig 5). The motion of the nozzle is determined by the length of links and the order and duration of the motor operations. The lengths of the links were selected in the course of computer simulation of the nozzle motion. The duration and the order of the operations of the motors, which in this case constitute control variables, were selected in the course of the of the visual observation of the nozzle motion within the laboratory reactor.

The total weight of the robotic arm does not exceed 10 kg. The weight of the water sources is below than 30 kg. The system is fed by city water (up to 1/2 GPM), compressed air (90 -110 psia) and 110 V alternate current. Feasibility of the arm installation at the reactor opening constitutes a significant technical problem. The area around the opening is occupied by piping, motors and other facilities and the space available for the system installation is rather limited . The facilities located outside of reactor occupies the cylindrical envelope of 0.1 m diameter and 0.4 m heights.

5. LABORATORY TESTING

The testing was carried out at a modified Pfaulder Glassteel 50 gallon reactor model ES-50-25. The arm was installed at the reactor opening and Maximator pump was fed from the air supply line (Figs 6-8). The operational conditions were as following: the water pressure 70 -80 Mpa, the nozzle diameter - 150 micron, water flow rate - 0.4 l/min. Estimated values of traverse rate and stand off distance..

Prior to testing the robotic arm was run during 12 hours without water supply. The system operation was stable, no excessive vibration or other mechanical problems were detected. The motion of the endpoint was smooth and controllable. After the installation of the robotic arm in the reactor several motion control strategies were tested, the cleaning pattern was selected and a program of the control of the arm operation was established and downloaded to the controller..

In the course of the experiments the interior of the reactor was painted by Super Animal and the moving stream was used to remove the paint. The visual observation of the lining showed that the_at the areas subjected to the direct jet impact_the paint was removed completely. The trajectory of the jet motion did not effect surface decontamination. No surface damage was detected. The cleaning water exited the reactor via the bottom opening. The water was clean and contained particulate of the removed paint. The particulate were removable and the water stream was recyclable.

6. ECONOMY OF WATERJET CLEANING

We assume that the cleaning is carried out by the nozzle rotating around the axis Z. Then the rate of cleaning is determined by the equation $A = 120\pi Rnh$ [m2/hour], where R=the distance between the axis Z and the surface, m; n= the number of revolutions around the axis Z , rpm; h= the width of the strip generated by the moving nozzle. During the test n was equal to 60 rpm. We assume that h was equal to the diameter of the nozzle that is 0.0001778 m (0.007") and R = a+b, where a is the distance between the nozzle edge and the axis Z and b is the standoff distance. In our case a=0.127 m (5") and b= 0.254m (10"). At this conditions the rate of the paint removal was 120x3.14x0.381x60x0.0001778=1.53 m2/hr. The estimated exposed surface area of the reactor lining is 4 m2. The duration of the cleaning of the reactor in question is 2.6 hr. The duration of the system installation and the change of the arm position is approximately 3 hours. Thus total duration of the paint removal from the reactor surface does not exceed 6 hours.

However, the removal of actual deposit from the lining of a reactor can be carried out at the rate exceeding that of the paint removal in 5-10 times. At this stage we can assume that the rate of reactor cleaning is 7-8 m2/hr at the water consumption of 3.2 hr/m2. The increase of the cleaning rate is attained by the increase of the traverse rate attained by the superposition of arm rotation around the axis Z and nozzle swing around the axis X. The real increase of the productivity will be attained by the use of the advanced NJIT's nozzle which generate an effective cleaning strip 5-10 times wider than that generated during this experiment.

7. CONCLUSION

The feasibility of cleaning of reactor and other tanks using water stream was demonstrated. The selected robot architecture enables to reach various problem areas of reactor. However , the practical system must be suitable for cleaning a wide variety of reactors. In order to accomplish this goal the length of the links must be variable and a practical routine for motion planning must be developed.

8. ACKNOWLEDGMENT. The work was supported by the grants of the NSF-Industry Emission Reduction Research Center, Newark, NJ and New Jersey Commission on Science and Technology. The assistance of Dr. S. Kiang and Ms. D. Chen (Britol-Myers-Squibb) and Drs. D. Watts and K. Moritz (Emmision-Reduction Research Center) in the conducting of this work is appreciated. is appreciated.

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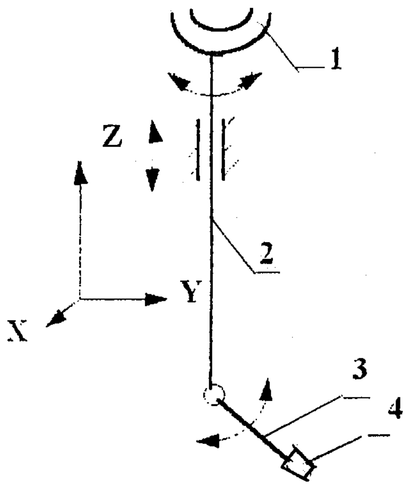
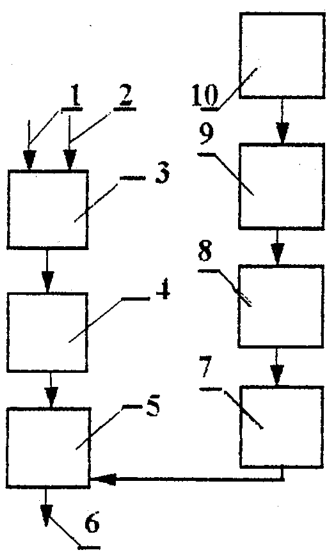
Figure 1. Laboratory Scale Prototype of the Cleaning System



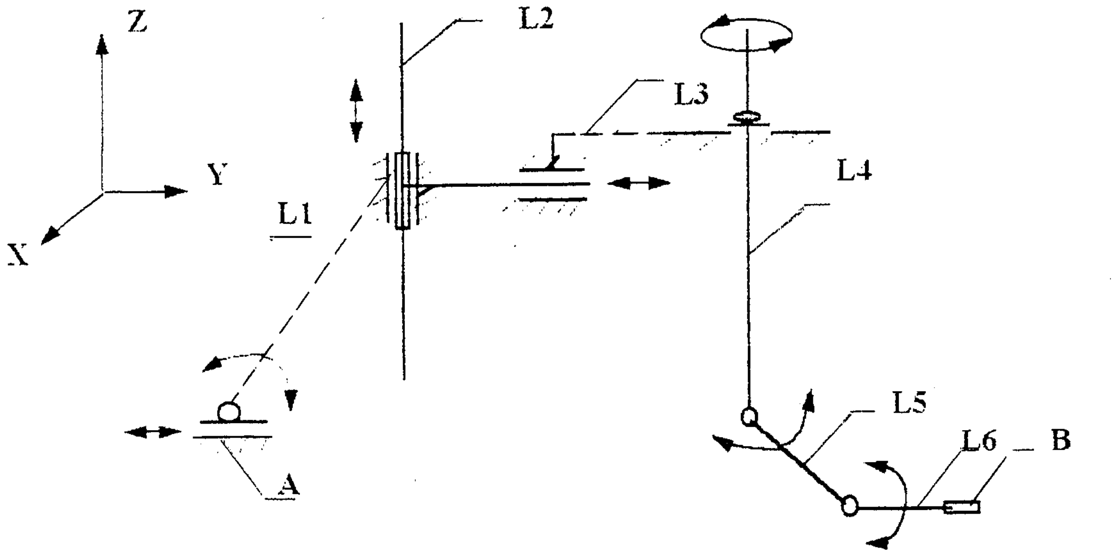
1 -spherical bearing
2 - sliding link
3 - rotational link
4 - nozzle head

FIG.2 KINEMATICS OF THE ROBOTIC ARM OF THE LABORATORY SCALE SET UP.



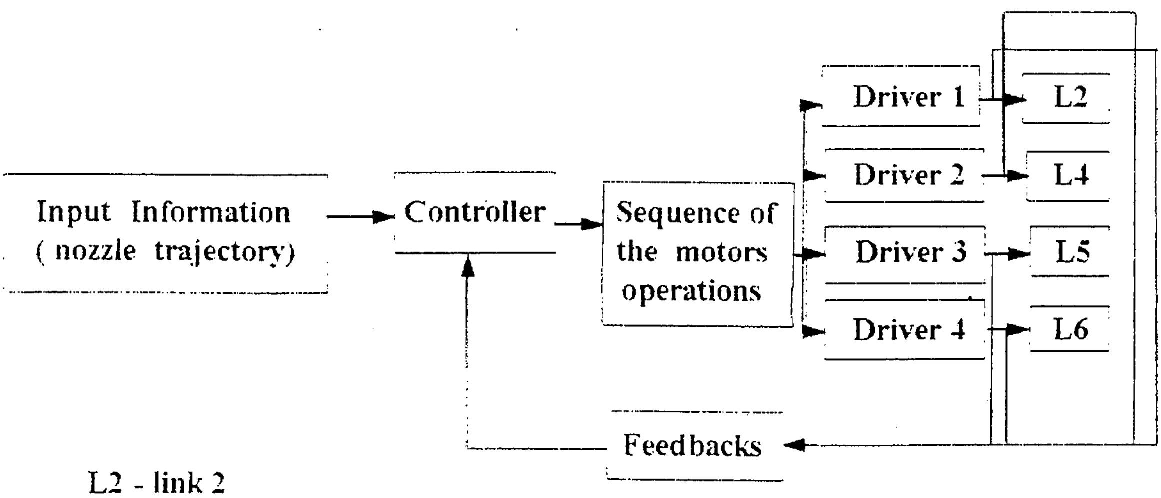
1 - air
2 - city water
3 - pneumatic pump
4 - water supply line
5 - nozzle head
6 - waterjet
7 - robotics arm
8 - controller
9 - memory
10 - task

FIG.3 SCHEMATIC OF THE CLEANING SYSTEM.



A - base
B - nozzle head
L1 - rotational link
L2 - sliding link
L3 - sliding link
L4 - rotational link
L5 - swing joint arm
L6 - the lowest part of arm
—— - automatic links
– – · - manual links

FIG.4 KINEMATICS OF THE ROBOTIC ARM.



L2 - link 2
L4 - link 4
L5 - link 5
L6 - link 6

FIG.5 SCHEMATIC OF THE INFORMATION FLOWS IN THE CLEANING SYSTEM.

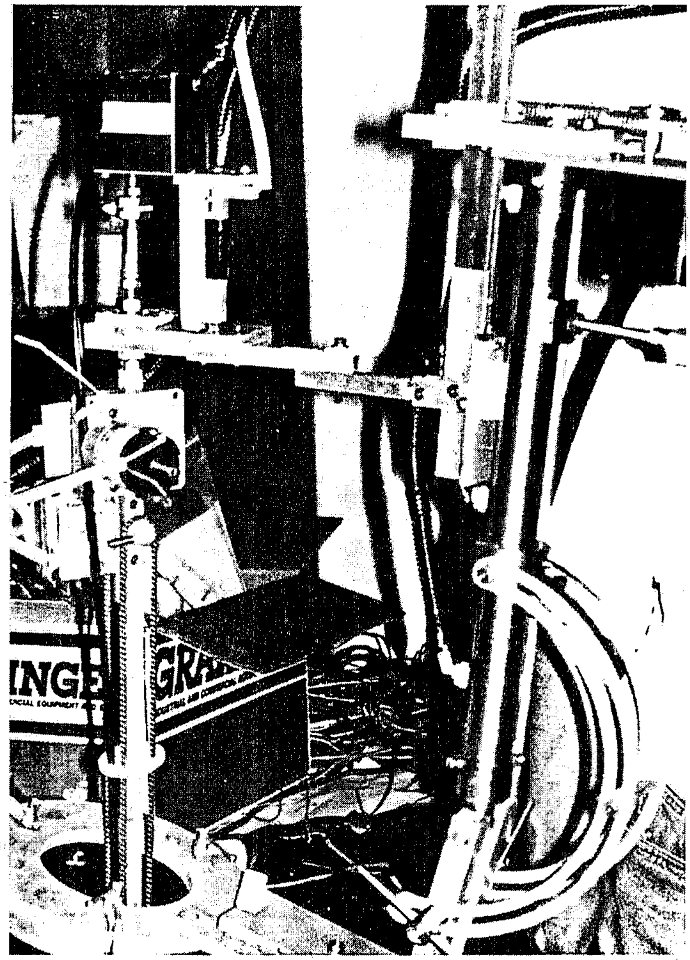


Figure 6. Upper Part of the System Located above Reactor

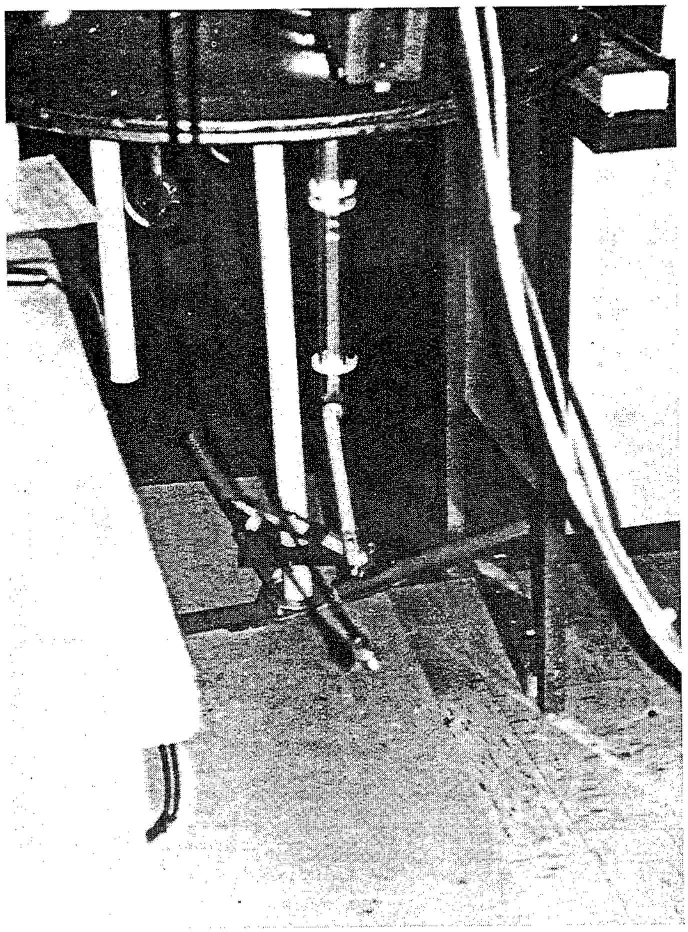


Figure 7. Bottom part of the Robotic Arm Located within the Reactor

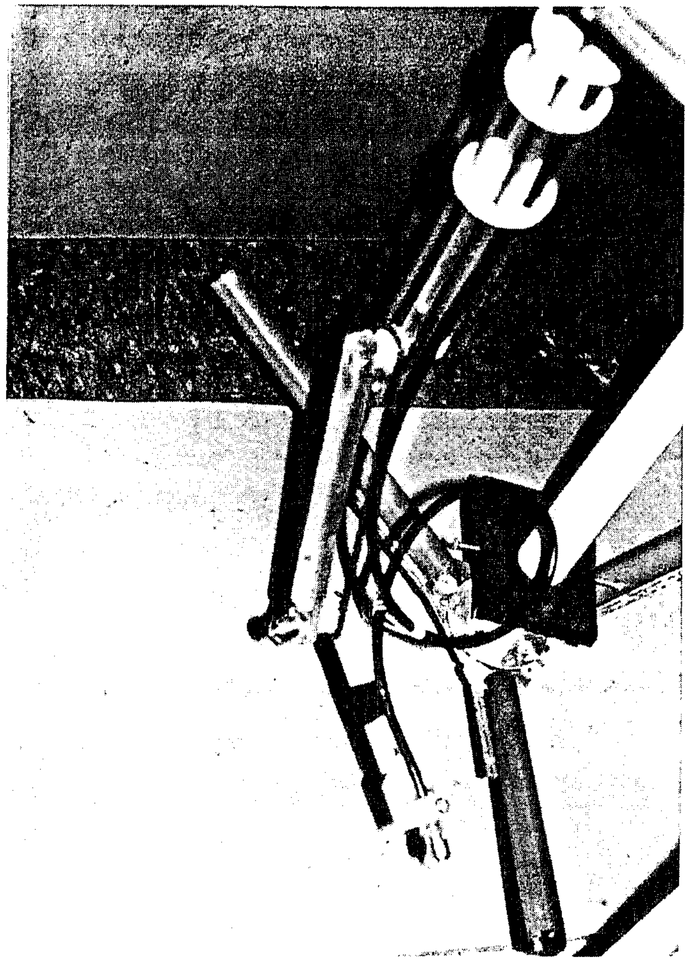


Figure 8. Links 5 and 6 Located in the Vicinity of the Impeller

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Paper 49

HIGH VELOCITY WATER-JET TECHNIQUES ASSIST IN SEISMIC REPAIR AND RE-HABILITATION OF CONCRETE STRUCTURES

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ABSTRACT

As a result of recent earthquake activity in Los Angeles, California and Kobe, Japan, engineers and researchers worldwide are developing strengthening and/or repair strategies. For the most part, these strategies include non-destructive horizontal and vertical concrete removal. The result exposes embedded steel, cleans and clearances existing reinforcing and readies the removal zones for further repair. Additionally, high velocity water-jets selectively excavate concrete, greatly reducing overbreak and unnecessary removal, which is traditionally a problem with conventional methods of demolition. Most seismic upgrade programs require additional masses of new concrete to be added around existing columns, foundations, walls, beams etc. Therefore, high quality surface preparation (including a measurable anchor profile) and the removal of any and all existing smooth form lines, is quickly becoming the "Standard" for consulting engineers and specification writers. Feature projects including slides:

a) Concrete drinking water reservoir upgrade
b) Bridge column and pier strengthening
c) Structural retrofit for existing parking structure

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1. INTRODUCTION

Currently, interest in seismic resistant design and/or repair strengthening of existing concrete structures is increasing as owners and regulators realize the economic need to safely extend the service life of an aging infrastructure. Major rehabilitation of bridges and buildings located in regions of high seismic risk have begun in North America - particularly on the west coast. Durable repairs to 20 - 40 year old concrete are a difficult task; when combined with the complexity and uncertainty of loading during an earthquake, new challenges are presented to engineers. For the most part, analyzing and correcting early oversights - as they pertain to seismic zone movement - is now routine and predictable. Thorough assessment of a particular structure prior to a proposed project, forms the **CONDITION SURVEY** (Figure A). Incorporating deficiencies and/or problems found by the **CONDITION SURVEY,** together with any upgrade, further compounds the repair/strengthening strategy. Many engineers now concede that in actual fact - repair, restoration and/or earthquake strengthening are all interrelated parts affecting the overall performance of a given structure often in distress. Over the past few years, high velocity directional waterjets have emerged as the tool of choice for concrete surface preparation, concrete removal and cleaning of corroded reinforcing steel. Progressive consulting firms are now employing the same jetting equipment to help prepare the **CONDITION SURVEY,** which is creating new opportunities for these nondestructive applications.

2. CONDITION SURVEY

The purpose of the survey is to systematically collect sufficient detailed data to establish a reasonable evaluation of overall condition. As structures differ, so may the requirements of each survey; but in general the aims of the investigation are:

- to assess the safety and serviceability of the structure
- to study the history, design, construction details and various loading of the structures over time
- to inspect all individual components (foundation, columns, beams, decks and slabs) for concrete type, aggregate size and characteristics, placement techniques etc.
- to determine, type, size, layout and state of the reinforcing steel and embedded metals. Corrosion of the reinforcing steel is regarded as among the most serious elements of the deterioration process.

NOTE:

Corrosion of embedded metals in concrete structures is an electrochemical process, involving an anode where electrochemical oxidation takes place and rust forms, a cathode where electrochemical reduction occurs, an electrical conductor (the embedded metal), and an electrolyte (the concrete). Bare reinforcement in concrete is usually protected by the thin oxide film remaining after manufacturing and by the passivating effect of the highly alkaline concrete. However, the presence of free chlorides at the embedded steel, in sufficient concentration, breaks down this protection, allowing corrosion to commence. The corrosion byproducts occupy a volume at least 2.5 times that of the parent metal. This causes high bursting stresses (up to 35 MPa or more) and subsequent cracking and delamination of the concrete. (See Figures B and C) This remains the principal phenomena associated with evaluating concrete cracking and repair deterioration.

A variety of chemical & physical mechanisms contribute problems as shown below.

2.1 Chemical Mechanisms

A. Acid Attack:	Acid Base Reaction
B. Sulfate Attack:	Calcium Hydroxide & Calcium Sulfate --> Calcium Sulfate Calcium Sulfate + Tri-Calcium Aluminate -->Tricalcium Sulfo-aluminate
C. Alkaline Reactions:	Solubilize Calcium Hydroxide especially when solutions are hot! Solubilize/Crystallize in pores like Sodium Sulfite
D. Alkali-Silica Reactions (ASR):	Is complex. Involves reactions of OH(-) ions in alkaline cement paste with siliceous aggregates. Expansive degradation.
E. Carbonation:	Natural process in concrete; CO_2 from air-forms dilute carbonic acid, reducing pH of cement paste.
F. Chloride Induced Rebar Corrosion:	Cl(-) destroys passive protection and promotes rebar corrosion.
G. Oils & Fats:	With Glycerides --> Fatty Acids React with Alkalis in cement paste - saponify.
H. Gases:	CO_2, SO_2, SO_3, etc. Oxidize to form acids - cause acid attack.
I. Microbiological Attack:	SOB/SRB Form acids-acid attack.
J. Seawater:	Crystallization in pores results in scaling/spalling chloride ion induced corrosion of reinforcement.

K. Sugars:	React with Calcium Hydroxide, form saccharates - Loss of strength plus acid attack.

2.2 Physical Mechanisms

A. Abrasion/Wear:	Physical damage from friction.
B. Cavitation:	Oxygen implosion and erosion.
C. Corrosion of Reinforcing Steel:	Cracking/spalling from expansion of corrosion products.
D. Freeze-Thaw Damage:	Expansive pressure causes physical failure.
E. Design or Construction Practice Related:	Self-explanatory
F. Thermal Stress:	Strength loss due to pore water loss - spacial, cracking due to movement vs. restraint
G. Shrinkage/Settlement:	Causes cracking of various types

There are two separate and distinct durability aspects that must be addressed in most concrete structures. They are:

1) corrosion of reinforcement and embedded hardware due to absorption of chloride ions by the concrete; and

2) leakage of water through joints, or voids and through the inevitable cracks that form, in all concrete. Leakage through joints and cracks is deleterious two respects:

   a) The chloride-laden water runs along the slab soffit and vertical surfaces such as beams, columns, corbels, ledges, and walls, and is absorbed into the concrete, causing corrosion of reinforcement and subsequent concrete delamination.

   b) The water dissolves lime from the concrete which damages other contact areas and destroys cementious finishes. This occurs even where the water is not chloride contaminated.

3. TESTING AND ANALYZING METHODS

Selection of the appropriate tests, the extent or number of test points adopted is usually a compromise between reliability, time, cost and magnitude of the repair/strengthening scheme. Frequently, test results from unaffected areas are necessary to serve as a datum for comparison, especially when nondestructive test methods are employed. The following test examples demonstrate these methods.

3.1 Test

Carbonation and/or chloride content.

3.1.1 Destructive Method

(impact, vibratory & drilling tools)

- drill holes and collect removed material; concrete (2"-4")(50 mm-100 mm) core samples are extracted c/w reinforcing steel
- sent to lab where samples are mechanically pulverized to be analyzed for chloride and/or other contaminations
- (2"-4")(50 mm-100 mm) core hole voids are patched usually with no preparation of remaining concrete or steel

3.1.2 Nondestructive Method

(low volume, high velocity waterjet tools)

- remove concrete <u>only</u> leaving all reinforcing steel intact and corrosion free
- collected aggregate, cement, sand, water and corrosion byproduct are sent to lab to be analyzed without further pulverization
- the pH reading of the collected water can then be compared to pH of the actual concrete surface substrate (in-the-field)
- the remaining void is prepared during the removal process and is therefore readied for a durable patch repair

3.2 Test

Cross sectional measurement of embedded reinforcing bars.

3.2.1 Destructive Method

(impact, vibratory & chipping tools)

- excavate and/or (2"-4")(50 mm-100 mm) core concrete to extract samples c/w reinforcing steel and send to lab

- (2"-4")(50 mm-100 mm) cores are broken open and remaining reinforcing is measured
- (2"-4")(50 mm-100 mm) core hole voids are patched usually with no preparation of remaining concrete or steel

3.2.2 Nondestructive Method

(low volume, high velocity waterjet tools)

- remove concrete only leaving all reinforcing steel intact and corrosion free
- corroded reinforcing steel is cleaned, measured and observed in the field for diameter loss and corrosion activity
- the remaining void is prepared during the removal process and is therefore readied for a durable patch repair

3.3 Test

Evaluation of the concrete strength of a whole or apart of a structural surface.

3.3.1 Destructive Method

(impact tools, scabbling, planing and chipping tools generally followed by grit blasting)

- the above described methods can clean, prepare and remove concrete; - introduce unnecessary stresses to complete structure
- crack & loosen aggregate creating microfractures
- loosens and de-bonds reinforcements
- damage remains on surface substrate to be tested

3.3.2 Nondestructive Method

(low volume, high velocity waterjet tools)

- by varying pressure and regulating dwell time of these directional streams, different depths (ie. 1/16"(1 mm),1/8"(3 mm),1/4"(7 mm), 3/8"(9 mm),1/2"(13 mm), etc.) of uniform surface preparation can be achieved
- allows for a true evaluation of the concrete surface strength over a range of removal depths
- as high-velocity streams follow the path of least resistance, weak/or problem areas are highlighted by deeper exposures
- the remaining surface is contamination free ready for PH testing etc.

3.4 Test

Determining the amount of concrete cover above & below embedded reinforcing (columns, beams, foundations).

3.4.1 Destructive Method

(impact tools and/or small coring tools)

- chipping removes the concrete cover to expose random bars
- the amount of concrete cover is measured and averaged
- reinforcing bars are loosen by removal
- remaining concrete aggregate is fractured by removal
- contaminates remain on surface of both concrete and steel

3.4.2 Nondestructive Method

(low volume, high velocity waterjet tools)

- probe surface to expose reinforcing
- clean and clearance embedded reinforcing for measurements
- prepare remaining substrate during removal for immediate repair

3.5 Test

Estimating the amount and extent of damage to a suspended slab or traffic deck.

3.5.1 Destructive Method

(impact tools, chipping tools and (2"-4")(50 mm-100 mm) core samples)

- lay out a test grid over entire deck
- take a number of (2"-4") (50 mm-100 mm) cores and send to lab for analyzing
- patch (2"-4") (50 mm-100 mm) core/void

3.5.2 Nondestructive Method

(low volume, high velocity waterjets)

- lay out test grid over entire deck
- remove & de-contaminate concrete selectively to represent a good cross section of all regions of the structure
- removal usually extends to the underside of the second bar in the top mat of reinforcing (typically 2"-4"(50 mm-100 mm) deep)
- edges of removal zones are straight with exposed rock evident
- reinforcing steel layout is exposed, cleaned and clearance readied for further in-place inspection, (example - bar loss diameter recorded and corrosion pit depth measurement noted)
- after tests, removal zones are filled with repair concrete (some engineers use different types of repair material to evaluate their in-service performance)

- strain, corrosion, cathodic and other probes can be cast into the removal zone to further monitor loads, movement and/or corrosion activity

3.6 Test

Other test methods may include the following.

- potential mapping with half-call potentiometer, or similar instruments
- concrete petrographic (concrete matrix)
- impact hammer (schmidt test)
- ultra sonic test
- crack measurements (width and depth)
- echo-test
- x-ray test

Once the inspection, testing, and analyzing is completed and the repair/strengthening formulated the project can begin.

4. THE SEISMIC REPAIR/STRENGTHENING

Most repair/strengthening strategies require that an additional amount of concrete and reinforcing steel be cast and/or affixed to the original structure. In other cases, various amounts of concrete are removed before placing new material. It is well-known fact in the construction industry that pneumatic, impact and/or vibratory tools (designed for pure demolition work) severely damage remaining substrates and contribute to structural degradation. The following are areas of nondestructive repair where controlled high velocity waterjetting techniques are employed.

4.1 Surface Cleaning Of Aged Concrete

Clean surface concrete removing loose scale, dirt, organic growths, moss and other lightly adhered materials. Existing concrete finish remains unaltered after cleaning.

(pressures to 5000 psi).

4.2 Surface Preparation Of Aged Concrete

The objective of surface preparation is to produce a sound concrete surface. The degree and quality of the prepared concrete surface is usually determined by a particular application. Inherent variations in the surface conditions as seen in walls, columns and beams versus finishes found on decks, slabs and floors, should be considered when specifying techniques. For example, walls, columns and piers are more likely than decks, slabs and floors, to contain voids, form pastes, fins, release agents, curing compounds and mixture inconsistencies. Contamination usually affects surface finishes, but can penetrate through cracks and voids into the concrete matrix. Chemical attack and/or contamination is generally a reaction between the cement and the contaminate. The cement is the binder in the concrete makeup and by the very nature of the way concrete is placed, compacted and finished, different thickness of cement paste form the finished texture. The intent of a properly prepared surface is to alter the original finish by removing the layer of thin cement paste, which affects the adhesion and/or the bond mechanism. Once the layer of hardened cement is removed, the bond mechanisms are improved in several ways:

- rough exposed and cleaned aggregate increase the mechanical interlock between substrates and replacement material
- opens the cement pore structure in the substrate which increases absorption at the contact point (between old & new)
- increases the bond line profile
- removes residual salts at interface

Surface profile increases the contact surface area, which is a critical requirement for durable repairs. It is estimated as an average measurement between peaks and valleys on the remaining concrete surface and quantified in mm(mils).

Three examples:

- 0-3 mm - light sand exposure, removes all contaminants, surface paste lightly exposing aggregate
- 3-7 mm - exposes sand and cleans aggregate, removes all contaminants and hardened surface finish paste medium course
- 7-15 mm- heavy exposure, exposes reinforcing steel close to surface, deepen weak crack areas, all original for or trowelled finishes very coarse and aggressive

(pressures 15,000 to 36,000 psi)

4.3 Removal Of Aged Concrete

Concrete removal with waterjetting equipment (HYDRO DEMOLITION) consists of a pumping system supplying pressurized water to a remote applicator and is gaining acceptance; however, some concerns remain:

- large water consumption systems (30 to 70 gpm) pose supply, containment and environmental questions
- inconsistency in uniform removal is caused by a varied waterjet delivery; some systems move a fixed jet back and fourth others use a notched-jet motion, still others use rotation
- cleaning, clearancing, exposing embedded metals and reinforcing steel is achievable with some systems
- straight exposed aggregate edges as per neat line removal or deeper zone at perimeter face of repair is achievable with some systems
- variable depth controlled removal (1"(25 mm),2"(50 mm),3"(75 mm), 4"(100 mm),6"(150 mm), etc.) is available with some systems
- overhead, vertical and horizontal robot/applicators are available in <u>one machine</u> on some systems

- angled, indexing, programmable robot/applicators are available on some systems
- hand held lance work is generally not considered hydro demolition
- general production rates and costs are unpredictable industry wide, as pump pressures, flow rates, applicators, robots and/or positioning devices differ

(pressures 20,000 to 40,000 psi)

5. CONCLUSIONS

In summary waterjetting methods and techniques are offering new and practical solutions for difficult surface preparation and concrete removal projects. Engineers, consultants and owners are becoming familiar with the advantages of nondestructive selective removal testing as applied to seismic repair/strengthening projects.

To increase the use of waterjetting equipment in these fields several aspects need to improve:

1) better waterjet tools, robots, applicators and devices are required.

2) collection, containment and environmental concerns must be addressed separately for each project.

3) contractor's performance on these specialized projects may require additional skills and a better understanding of why/how repairs are to be done.

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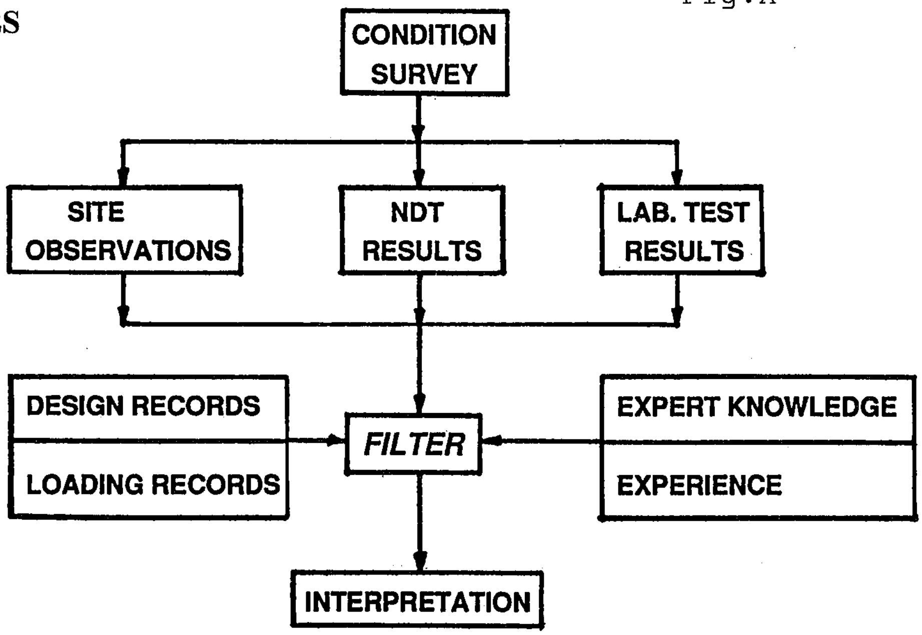
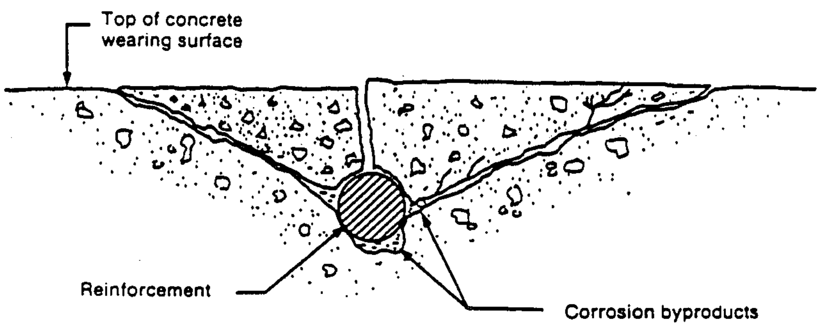
Purposed NACE /SSPC Joint Standard "Surface Preparation Of Concrete"

7. FIGURES

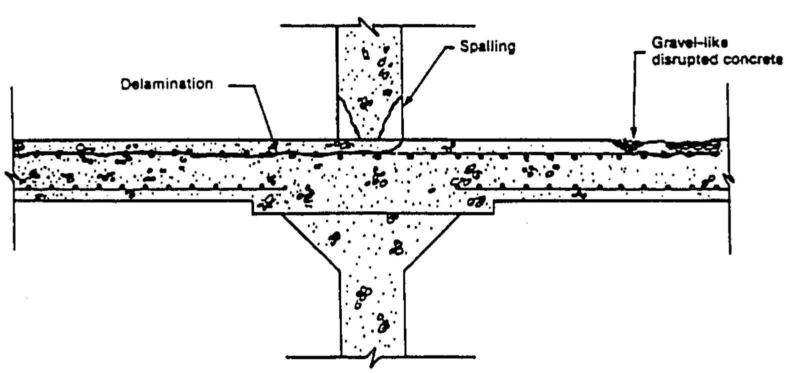
Fig.A





Shallow V-Shaped Fracture Surface at Corroded Reinforcement

Fig.B



Delamination at Corroded Reinforcement

Fig. C

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Paper 50

ABRASIVE WATER SUSPENSION JETS FOR NUCLEAR DECOMMISSIONING – FINAL INVESTIGATIONS FOR THE FIRST APPLICATION

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ABSTRACT

The abrasive water jet cutting technology has been successfully introduced into many applications, such as cutting off- and onshore and in industrial manufacturing, cleaning, decoating and others. Although the characteristic advantages of the technology are well known and clearly defined, there have only been a few applications in the field of nuclear decommissioning. Between 1981 and 1986 the abrasive water injection jet (AWIJ) has been used to cut the biological shield of a nuclear power plant in Japan (Nakamura et al., 1989).

Due to the increasing research activities and the recent technical developments, the abrasive water suspension jet (AWSJ) became an alternative cutting technique for decommissioning purposes. A 200 MPa-prototype system has been built up at the Institute of Material Science to reach a drastical reduction of the required water and abrasive flow rate. For the same hydraulic power input and the same abrasive flow rate the AWSJ cuts at least twice as deep as an AWIJ. And because the AWSJ carries no air into the cutting process, the risk of aerosols is very small.

In 1997 the first inset of the AWSJ-technology in an activated environment will take place in Germany at the VAK power plant in Kahl, Germany. Some final investigations for this application need to be carried out, concerning the optimal cutting parameters, the nozzle lifetime and the process control.

Due to the activated environment the cutting process has to be carried out remote operated. This makes the usage of under water cameras absolutely necessary. This requires a sufficient quality of the water, so that the cloudiness, caused by finest abrasive particles, has to be minimized. Therefore different abrasive particles have been investigated related to their clouding behavior.

This paper will describe the environment inside the nuclear power plant VAK and the target component and will summarize the final investigations.

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1. INTRODUCTION

In the past eight years the research work at the Institute of Material Science (IW), University of Hannover, Germany has focused on the further development of abrasive water suspension jets (AWSJ). In 1993 the first laboratory AWSJ-system with a maximum working pressure of 200 MPa has been built up. Since then the influence of all important parameters has been investigated intensively (Brandt et al. 1994). In 1996 a 400 MPa-AWSJ-system has been designed and installed. First cutting tests have been carried out successfully, so that further investigation of process parameters will be started in the near future.

Due to the pressure increase the flow rates of water and abrasive have been reduced drastically. Compared to an abrasive water injection (entrainment) jet (AWIJ) of the same hydraulic power and with an identical abrasive mass flow rate the suspension jet is able to cut twice as deep or two times faster. In addition the AWSJ consists only of two phases, water and abrasive.

The advantages of the abrasive water jet cutting technique combined with the reached developments and the additional advantages of the AWSJ gave the German nuclear power plant VAK close to Frankfurt the idea, to qualify this technique as a alternative decommissioning technique in their facility.

In the frame of a research project # 02 S 7686 sponsored by the Federal Ministry of Education, Science, Research and Technology, Germany (BMBF) the first world wide inset of the AWSJ for nuclear decommissioning will take place.

2. TARGET COMPONENT

The target component for the first cutting inset is called lower core shroud, and carried the lower grid plate, which held the fuel elements in position. Figure 1 shows a sketch of the nuclear power plant VAK. Most of the shown reactor components have already been taken out, only the core shroud and the lower core shroud are still in position. In the moment the core shroud is decomposed by a disk milling cutter.

Figure 2 shows the dimensions of the lower core shroud and two possible cutting strategies. The material thickness is 50 mm in the top and bottom section and 110 mm in the middle. To fit the core shroud into the final storage container, it has to be decomposed into two circular parts and each of those into 16 segments.

The first strategy in Figure 2 is the simplier one, but depends on the space between the lower core shroud and the pressure vessel wall. This space is approximately 250 mm, which should be enough to fit in a handling device and the AWSJ-nozzle. Although the cutting tests showed, that both strategies are possible and the first strategy is considerable faster, a final decision has not been made yet.

3. CUTTING EQUIPMENT

For the "hot" cutting work the company ALBA Industries GmbH, Germany has been taken into the project. The first task of ALBA was to develop a AWSJ-system with a working pressure above 70 MPa, to reduce the amount of water and abrasive and to increase the cutting performance. A maximum working pressure of around 150 MPa was planned.

In only four month a 140 MPa-AWSJ-system (20.000 psi) has been developed and built up. The system is a two vessel machine, following the bypass principle. For further information about different principles of suspension jet generation see Brandt et al. (1994). The two vessels are not for continuous cutting operation, but a redundancy for the case of a failure on one of the circuits. This allows the user to continue the cutting operation in about ten minutes. The pressure is provided by a Hammelmann plunger pump. A picture of the whole cutting equipment will be given in the oral presentation.

The data of the system are:

- pressure p = 140 MPa
- water flow rate $\dot{Q}_w$ = 8 - 20 l/min
- abrasive flow rate $\dot{m}_a$ = 0.8 - 2 kg/min

4. RESULTS OF FINAL INVESTIGATIONS

Due to the nuclear environment all decommissioning cutting techniques have to have the ability to be operated remote controlled. In case of the cutting process with an AWSJ this depends mainly on the handling system, since only a high pressure hose and the nozzle holder need to be manipulated. The pump and the jet generation unit can be positioned out side the control area.

To supervise the cutting process itself, in most of the cases video cameras are used. From this point of view the AWSJ seems to have a big disadvantage, since, due to the disintegration of the abrasive particles, the reactor water will get cloudy very fast, which will affect the camera controlled manipulation of the jet drastically. The first target of this research project was therefore to find an abrasive material which reduces the clouding of the water.

4.1 Investigations of different abrasive materials referring of their clouding behavior

4.1.1 Setup for the clouding tests

Five abrasive materials with different properties but similar particle size distributions have been used for cutting tests and the investigation of their clouding behavior. Table 1 shows the characteristics of the used abrasives.

With every abrasive material a cutting trial on stainless steel has been carried out and the exiting jet has been caught. From the caught abrasive material a representative sample has been taken the clouding experiments. For the determination of the clouding behavior two different test methods have been developed, adapted to the standard DIN EN 27027.

For the first method, called static clouding measurement, 50 g of the sample was mixed into one liter of water and the suspension (loading ratio 5%) was stirred for one minute in a stirring machine. After two minutes all larger particles, which are not responsible for the water cloudiness, have settled. The water above this settled particles was filled into a glass cylinder, with a test symbol (letter highness 5mm, line thickness 1mm) and a 75 W light source beyond its ground. Following the water level was slowly reduced till the test symbol was visible. The remaining water level was used to characterize the static clouding behavior. The higher the remaining water level is the better is the visibility in such a suspension.

For the second method, called dynamic clouding measurement, the same suspension is stirred for one minute, but the symbol is positioned behind the glass and the light source in front of it. The time until the symbol is visible has been determined.

Figure 3 shows a photograph of the clouding test equipment. On the left side you see the static clouding measurement equipment with the glass cylinder, the setup for the dynamic clouding measurement in the middle and the stirring machine on the right side.

The disintegration behavior of Barton Garnet has been investigated intensively by Guo et al. (1994). The clouding investigation have been started with Barton Garnet and it was found, that the very small particles in the range of 0 to 20 μm are mainly causing the cloudiness. Figure 4 shows the effect of the particle size on the drop velocities for steel and abrasive particles. It is obvious, that smaller particles settle very slow. This effect corresponds with the dynamic clouding measurements with different particle ranges of Barton Garnet. As Figure 5 shows, the main cloudiness is caused by the particle range of 0 to 20 μm.

In general an abrasive material which causes less clouding, should either have a higher solid density (Hematite), a different disintegration behavior than Garnet, a higher toughness, a higher hardness (zirconium corundum, silicon carbide) or is a softer material (Olivine).

It was the target of these investigations to find an abrasive, which disintegrates less into the particle range of 0 to 20 μm and has a similar or even better cutting performance than Barton Garnet. For the evaluation of the cutting performance kerfing tests were carried out on stainless steel. Due to the fact, that the abrasive is stored in the pressure vessel filled with water, the usage of Fe_2O_3 (Hematite) was not possible, because it corroded very fast and a feeding out of the storage vessel was not possible. However, cutting tests with the entrainment jet (AWIJ) show, that the cutting performance of Hematite is only 10 to 20 % smaller than Barton Garnet.

During the cutting test with silicon carbide a dramatic nozzle wear was detected, so that also this abrasive material was excludes from further investigations. The results of the kerfing tests are summarized in Figure 6. It is obvious that the depth of kerf is similar and in the range of measurement accuracy for all four abrasive materials. The working pressure for these tests was put to 75 MPa to allow an easier catching of the jet to determine the abrasive mass flow rate and the particle size distribution.

Figure 7 shows the static and dynamic cloudiness of the three remaining abrasives after cutting 50 mm of stainless steel. At this point of investigation zirconium corundum excels by a large static cloudiness, which means, that the visual range is larger than for Garnet and Olivine, and a low dynamic cloudiness. This means, that the particles settle faster. Following these results zirconium corundum seemed to be the most useful investigated abrasive material for a video controlled inset of the AWSJ in nuclear environment.

To take also the influence of the working pressure into consideration, cutting tests were carried out at 150 MPa. The abrasive material was Barton Garnet HP80, which is the standard abrasive at the IW. Also at these test the exiting jet was caught and the static and dynamic cloudiness was determined. Figure 8 shows the results. It is interesting to see, that, although the amount of particles in the range from 0 to 20 μm is larger at 150 MPa, both clouding values are better than at 75 MPa. The only explanation for this effect is, that the particle size distribution inside the sieve range 0 - 20 μm is different. In other words, at 150 MPa the particle size distribution in the class 0 - 20 μm moves to larger particle sizes. This effect could not be proved by the analyzing systems available at the IW.

During similar cutting tests with zirconium corundum P80 a drastical increase of nozzle wear has been detected. While at 75 MPa the diameter increase was determined to 1,1 μm/min it increases to 15 μm/min. For Barton Garnet HP80 it increases only from 0,1 to 0,6 μm/min. This increase is based on the fact, that the wear is proportional to the square of the particle velocity. An explanation for the big difference of the increase factors might be the abrasive hardness (see Table 1).

Due to the nuclear environment the change of the suspension nozzle is relatively difficult. Therefore the nozzle lifetime should exceed the total cutting time, so that the nozzle, if no nozzle blockage or break occurs, will not have to be changed. Due to these results Barton Garnet HP80 will be used for this cutting job. Although it causes a higher cloudiness the aspect of a longer nozzle lifetime has a higher priority. Right now some investigations concerning the cleaning and filtering of the reactor water are carried out at the IW. Depending on the results the installation of an additional filtering device into the pressure vessel of VAK might be necessary.

4.2 Optimization of cutting parameters

The main influencing cutting parameter, the working pressure, has been set to 140 MPa. To reach a high cutting performance an increase of nozzle diameter is very effective. However, the maximum usable nozzle diameter is limited by the maximum flow rate of the pump. This maximum flow rate was set to 20 l/min, so the maximum nozzle diameter is around 0.95 mm.

To ensure a nozzle lifetime, which exceeds the total cutting time of 7 to 11 hours, depending on the cutting strategy, the start-off diameter of the nozzle has to be 0.6 mm for the usage with Barton Garnet HP80. So the resulting start-off parameter are a pressure of 140 MPa and a nozzle diameter of 0.6 mm, which means a water flow rate of around 8 l/min. This corresponds to a hydraulic jet power of 18.4 kW. At a nozzle diameter of 0.95 mm these values will change to a water flow rate of 19,7 l/min and a hydraulic jet power of 46 kW.

As it is shown in Figure 9 the increase in nozzle diameter results in an increase in cutting performance. Please note that these results are taken from another research project, so that the pressure, abrasive size and the target material are different. However, an increase of the nozzle diameter from 0.6 to 0.7 causes in this case a 10% deeper kerf. For a constant material thickness that means, that the traverse speed can be slightly increased with increasing nozzle wear.

So the only jet parameter, which can be varied, is the abrasive mass flow rate. In general the abrasive mass flow rate should be kept as low as possible to minimize the amount of secondary waste. As Figure 10 shows the effect of abrasive mass flow rate on the depth of kerf and the specific cutting performance, which evaluates the utilization of the used amount of abrasive, is opposite. It was found out, that the cutting process becomes stable above an abrasive flow rate of 1 kg/min. Different cutting tests were carried out on a model of the target component (see Figure 11).

With the second cutting strategy the best cutting result was achieved at 1 kg/min. Compared to the cutting speed at this flow rate the cutting speed for 1,5 kg/min has to be increase about 33%. Due to this effect the abrasive usage is at 1,5 kg/min about 4 kg/m higher than for 1 kg/min. For the second cutting strategy an abrasive flow rate of 1,5 kg/min generated optimal cutting results.

For both cutting strategies the impact angle α, which is the angle between the jet axis and the sample surface in cutting direction, has to be different from 90°. For the second strategy it has to be 45° to be able to cut into the corner and cut the L-shape part of the target component totally through. For the second strategy an impact angle of 15° was chosen, to ensure a total cut through also at the end of the component. The result of this cutting setup is shown in Figure 11, left side.

Hashish (1989) investigated the effect of the impact angle on the depth of kerf for the entrainment system. He found that the depth of kerf is deeper for an impact angle beyond 90° and less deep for angles over 90°. This effect has found to be different for kerfing with the AWSJ. Figure 12 shows the results of these cutting tests. In this case a positive angle means, that the jet axis is inclined towards the sample, a negative angle means a inclination away from the sample.

Due to the kerfing tests the results for negative angles are influenced by a secondary damage (wash out) caused by the draining jet. This effect will not occur for cutting through a sample. In this case a negative angle of attack will require a slower traverse speed to cut through the same material thickness than with a positive angle. For the test cuts in Figure 11 on the right side a the traverse speed was set to 30 mm /min to ensure a total cut through, since the jet starts cutting pulling, then pushing, pulling again and finally finishes the cut pushing.

5. DETERMINATION OF NOZZLE LIFETIME

For the calculation of the nozzle life time wear tests have been carried out with two different nozzles. A 0.7 mm nozzle has been loaded for one hour under constant conditions. For a 0.6 mm nozzle the wear has been recorded during the cutting test, where the abrasive mass flow rate was change in the range of 1 to 1.5 kg/min. Figure 13 shows the results of these wear test. The change in water flow rate was chosen for the evaluation, since an on-line measurement of the nozzle diameter was not possible. A linear regression has been fit to both nozzle diameters. It was shown, that the nozzle wear is generally identical. The different inclination factor for the 0.6 mm nozzle might be caused by the varying abrasive flow rate. From these results the following lifetime calculation can be made:

starting nozzle diameter / flow rate	0.6 mm / 8 l/min
maximum nozzle diameter /flow rate	0.95 mm / 20 l/min
flow increase per min	0.015 l
life time	≈ 13 h

The total cutting time for strategy #1 was calculated to 11 hours, while only 7 hours are required for the cutting following strategy #2. As mentioned above, the final decision concerning the cutting strategy has not been made yet. But whatever the decision might be, the nozzle life time exceeds the total cutting time in both cases.

6. CONCLUSIONS

The clouding behavior of an AWSJ can be reduced generally by using zirconium corundum as abrasive material. But due to the larger hardness of this material the nozzle wear increases drastically. With the Boride ROCTEC 100 nozzles available today an inset with zirconium corundum seems not to be useful. With Barton Garnet the nozzle life time has been determined to around 13 hours, depending on pressure and abrasive mass flow rate.

To minimize the clouding caused by abrasive particles sized 0 - 20 μm, additional cleaning and filtering devices have to be used to allow a camera controlled operation and supervision of the cutting process.

By changing the impact angle an AWSJ cuts deeper, no matter if the jet is rotated towards the sample or away from it.

7. ACKNOWLEDGEMENTS

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The industry partners for the research program are the VAK GmbH, Germany, Alba Industries GmbH, Germany and Paul Hammelmann Maschinenbau GmbH.

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9. NOMENCLATURE

α	impact angle	
d_{Sd}	suspension nozzle diameter	mm
d_P	particle size	μm
d_{Pm}	average particle size	μm
$d\dot{Q}_w$	change of flow rate	l/min
k_m	average depth of kerf; $k_m=(k_{min}+k_{max}/2)$	mm
k_{max}	maximum depth of kerf	mm
k_{min}	minimum depth of kerf	mm
$\dot{m}_A$	abrasive flow rate	kg/min
P'_S	specific cutting performance	mm^2/kg
p	pressure	MPa
$\dot{Q}_w$	water flow rate	l/min
T_{Dyn}	dynamic cloudiness	min
T_{Stat}	static cloudiness	mm
t_E	loading time	min
s	standoff distance	mm
v	traverse rate	mm/min
v_A	drop velocity	cm/s

10. FIGURES, TABLES AND ILLUSTRATIONS

Table 1: Characteristica of investigated abrasive materials

	Barton Garnet HP 80	**Hämatit (Fe_2O_3) FG 007**	**Zirconium corundum P 80**	**Silicon carbide F 70**	**Olivin ASOASF 90**
material	mineral	ferromagnetic	mineral	mineral	mineral
color	red/brown	grey	black	green	light green
solid density [g/cm^3]	3,84	7,14	4,16	2,90	3,33
powder density [g/cm^3]	2,2	3,2	2,1	1,7	2,0
hardness [Mohs]	≈ 8	-	≈ 9	9,7	6,5 - 7
average particle size d_{Pm} [µm]	264,2	228,1	202,5	220,7	265,4

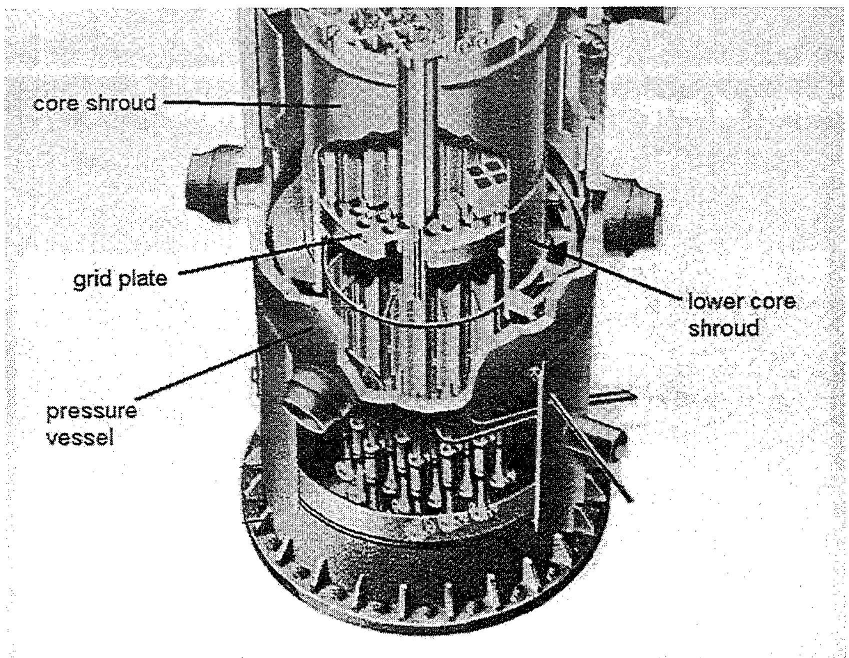

Figure 1: position of the target component (lower core shroud) in VAK

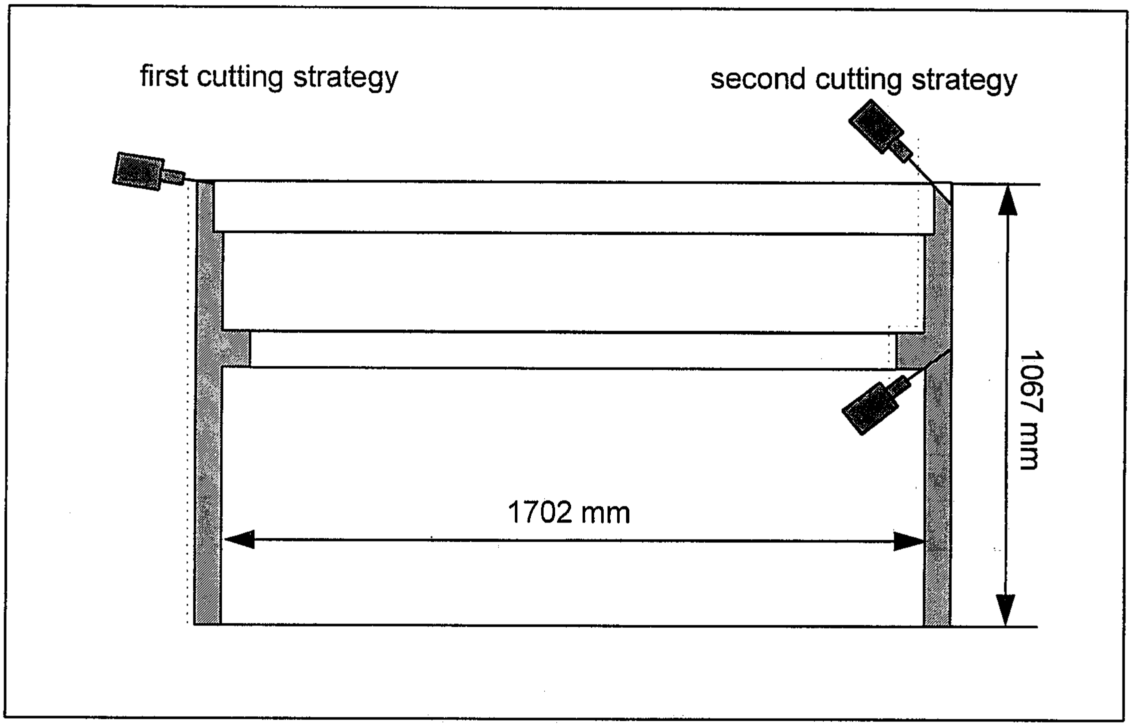

Figure 2: dimensions of target component and cutting strategies

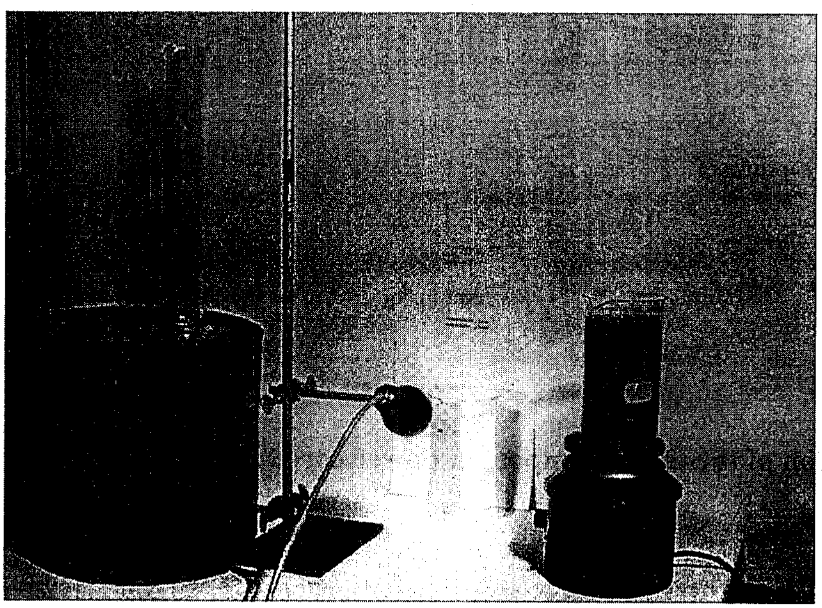

Figure 3: Setup for the static and dynamic clouding measurements

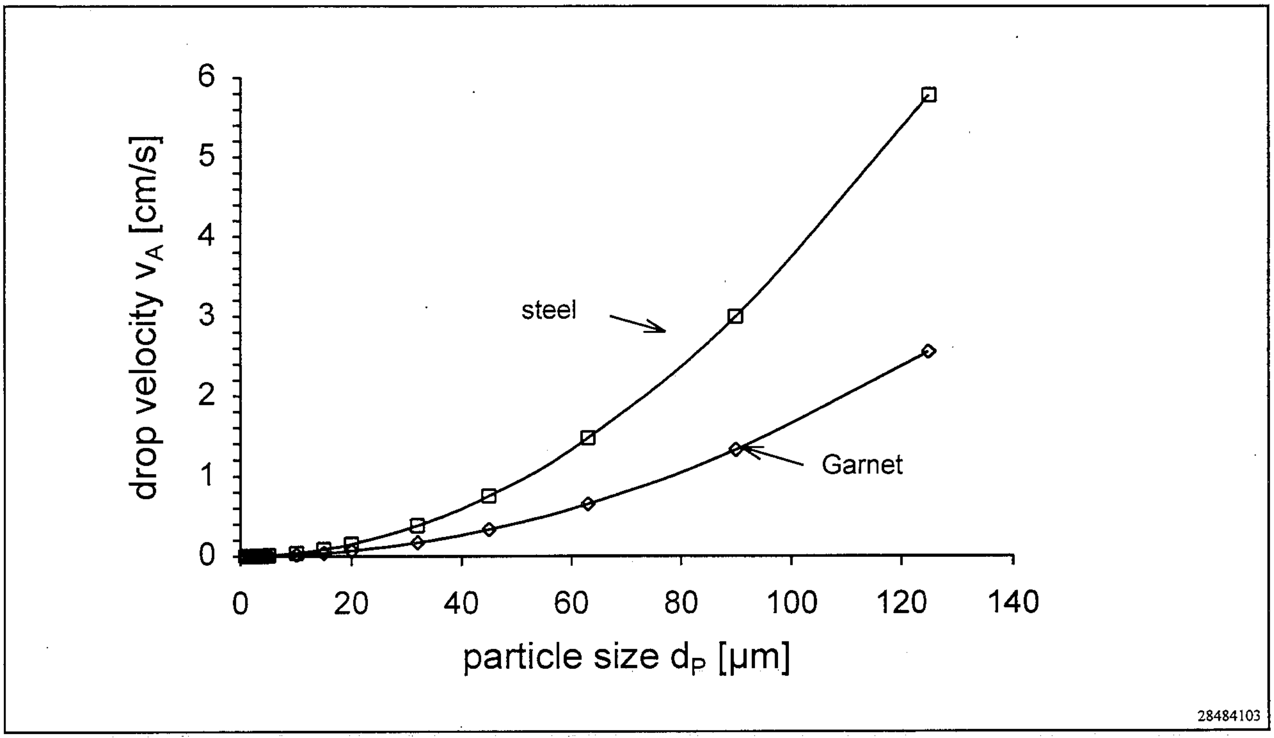

Figure 4: Effect of particle size on drop velocity for steel and Garnet

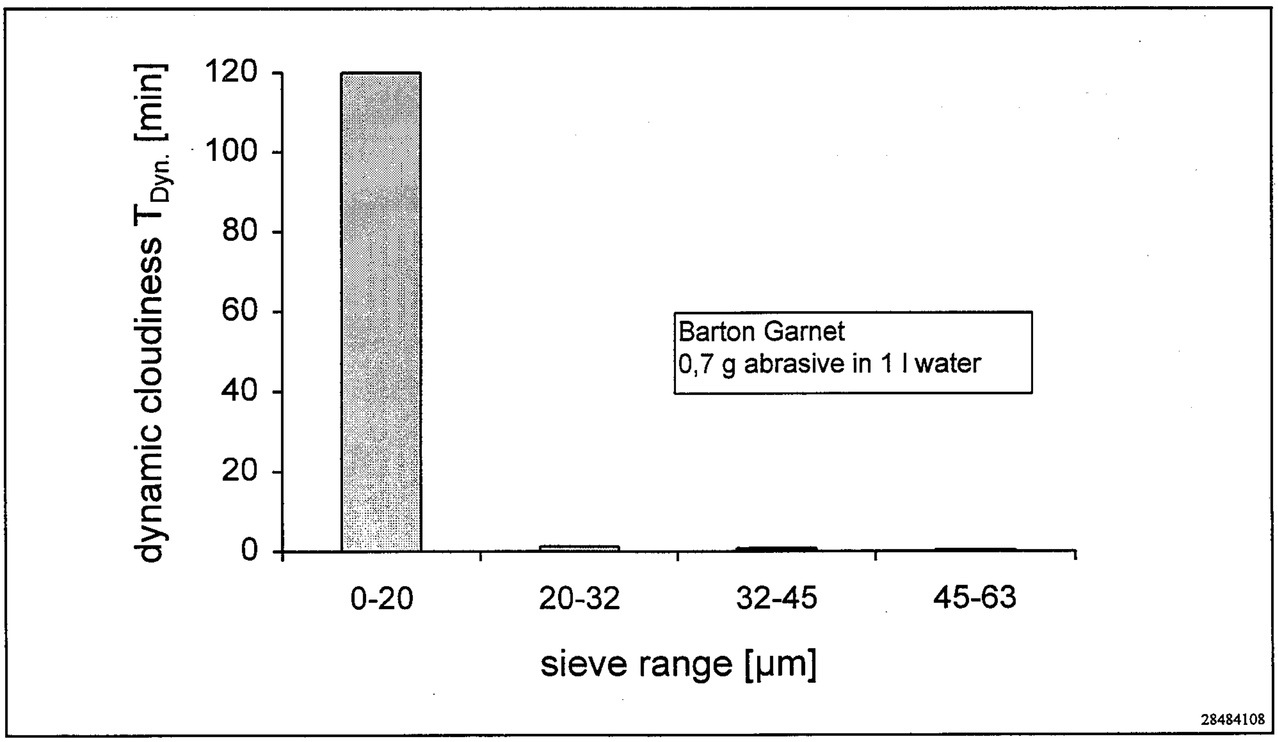

Figure 5: Influence of particle range on dynamic cloudiness for Barton Garnet

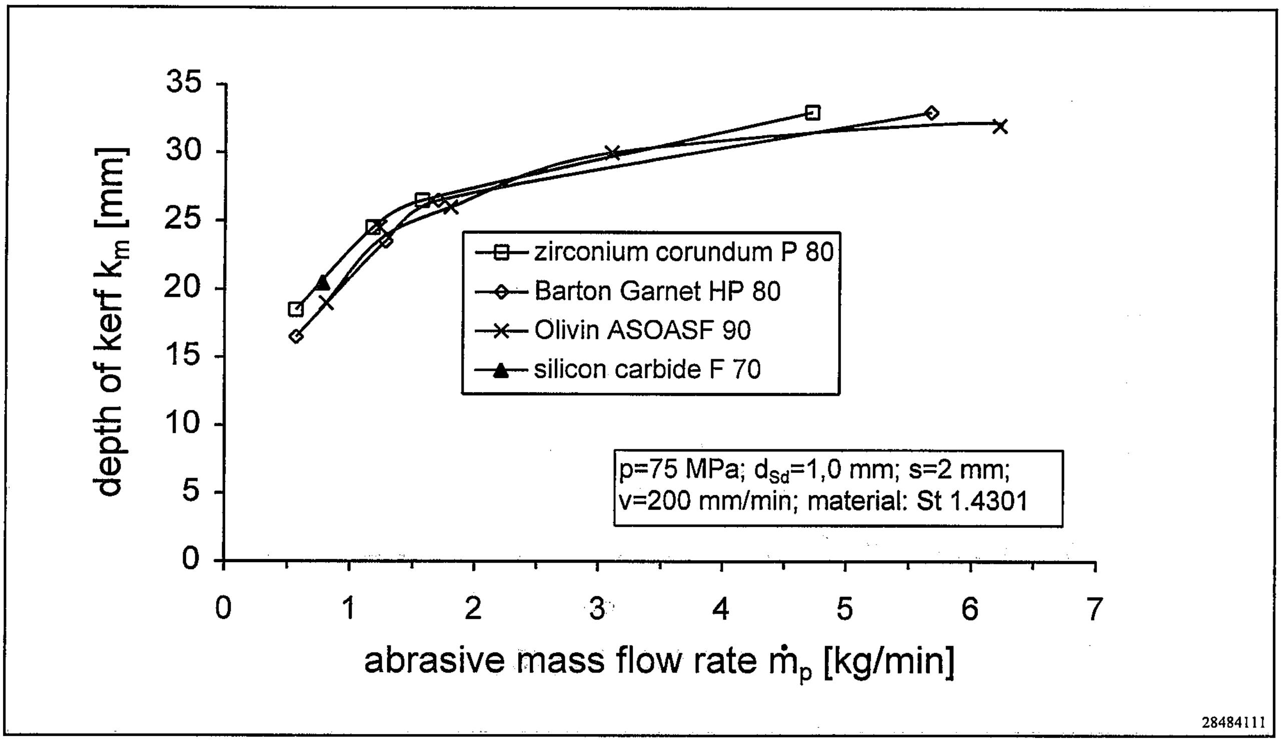

Figure 6: Effect of abrasive mass flow rate on depth of kerf for different abrasive materials

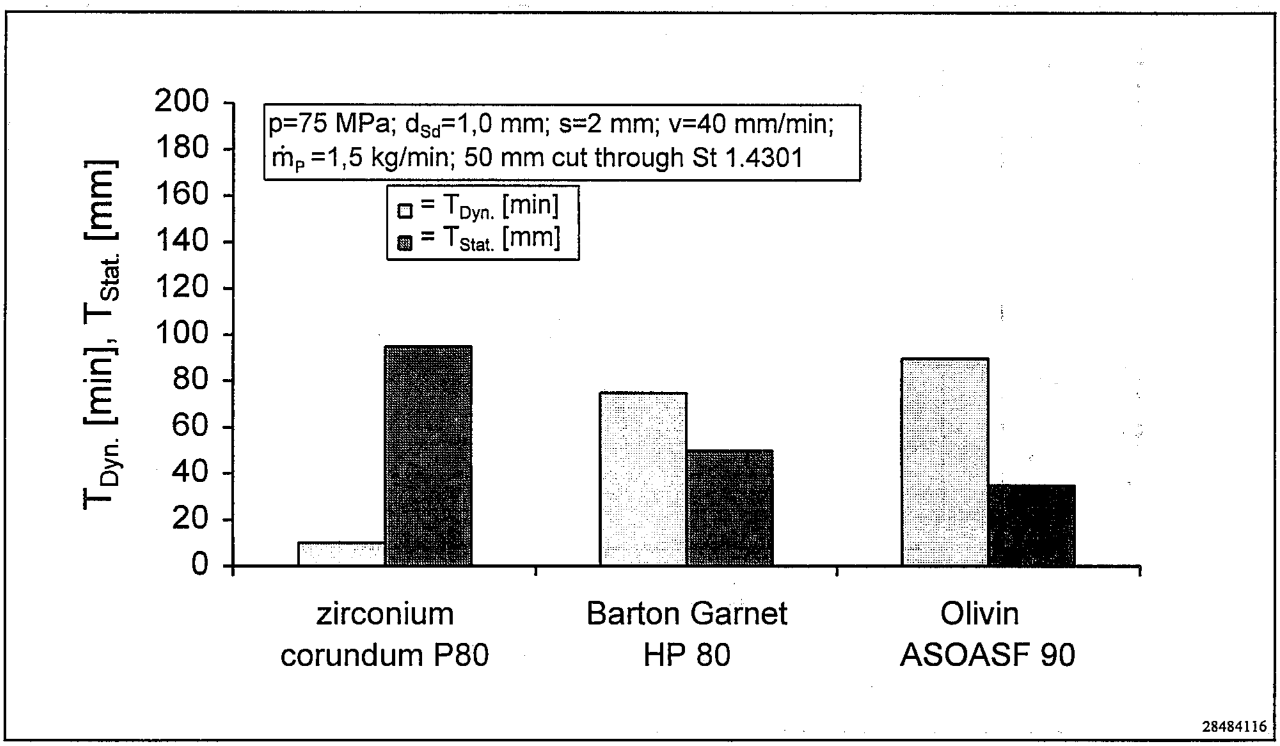

Figure 7: static and dynamic cloudiness of the remaining abrasivve materials

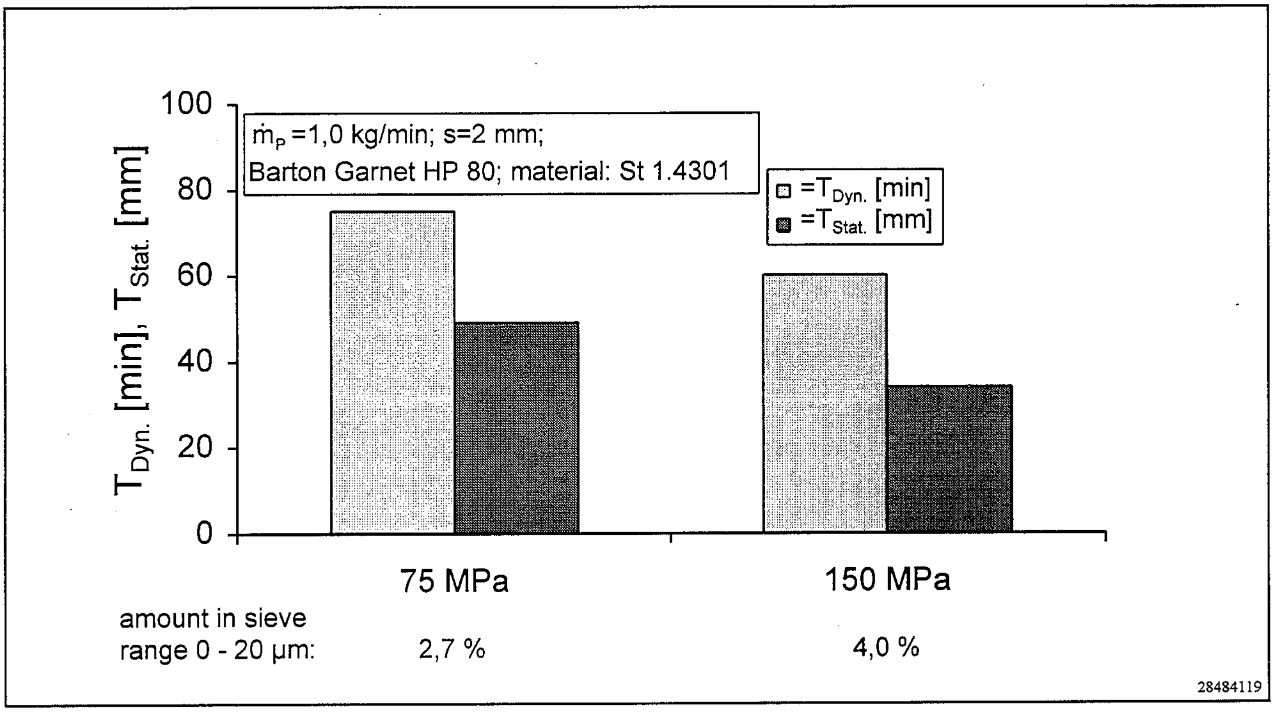

Figure 8: Influence of working pressure on the cloudiness for Barton Garnet HP80

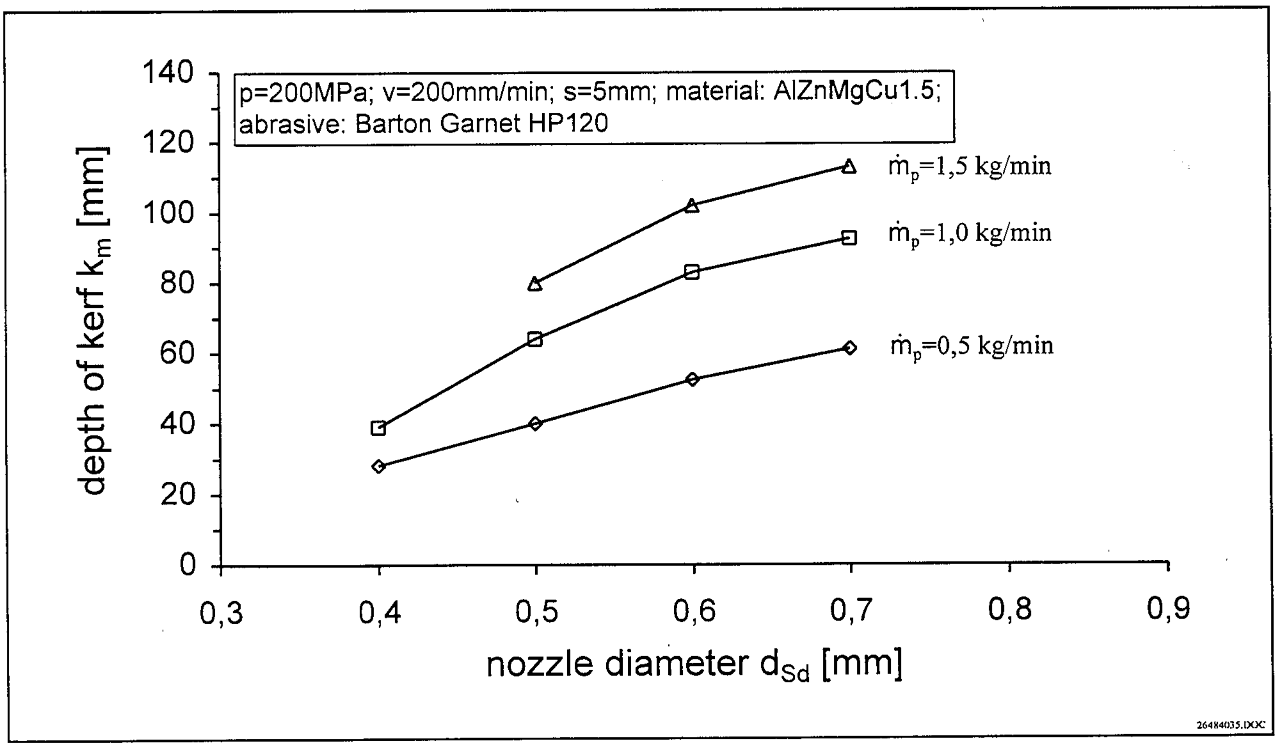

Figure 9: Effekt of nozzle diameter on depth of kerf for different abrasive flow rates

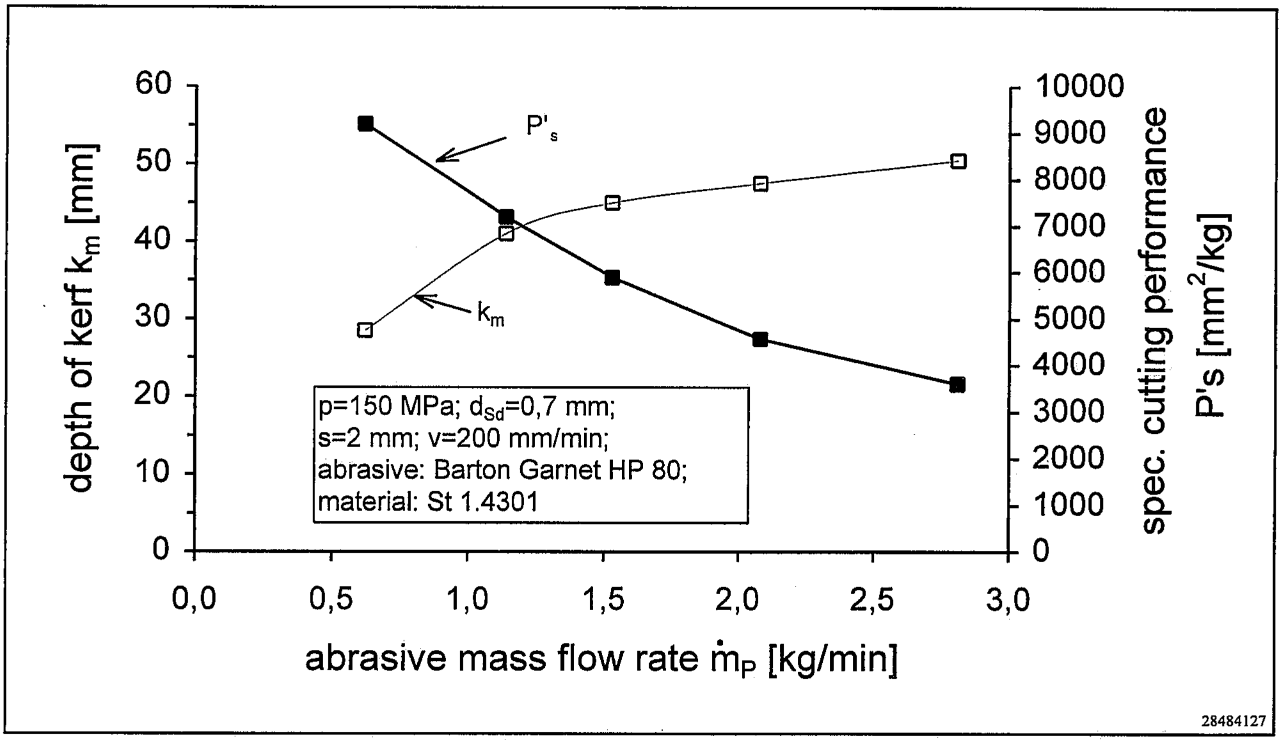

Figure 10: Effect of abrasive mass flow rate on depth of kerf and specific cutting performance related to the used amount of abrasive

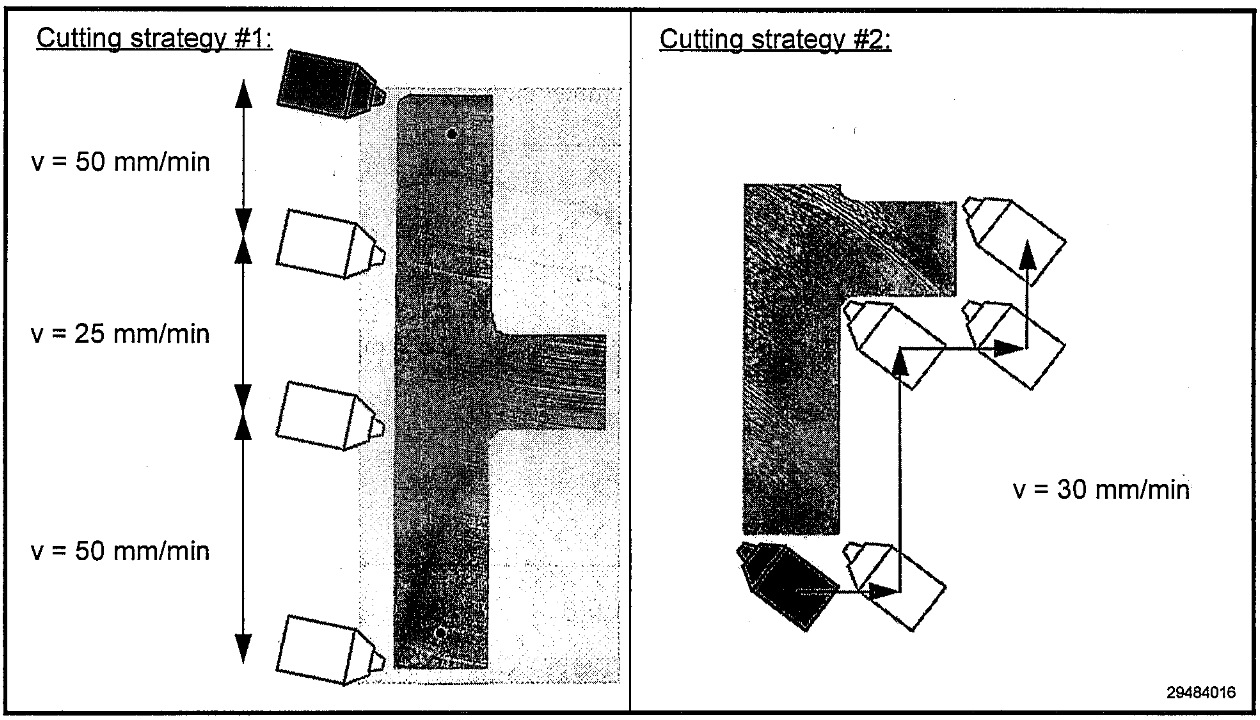

Figure 11: Cutting results on the model of the target component: left: cutting strategy #1; right: cutting strategy #2 (see Figure 2 for details)

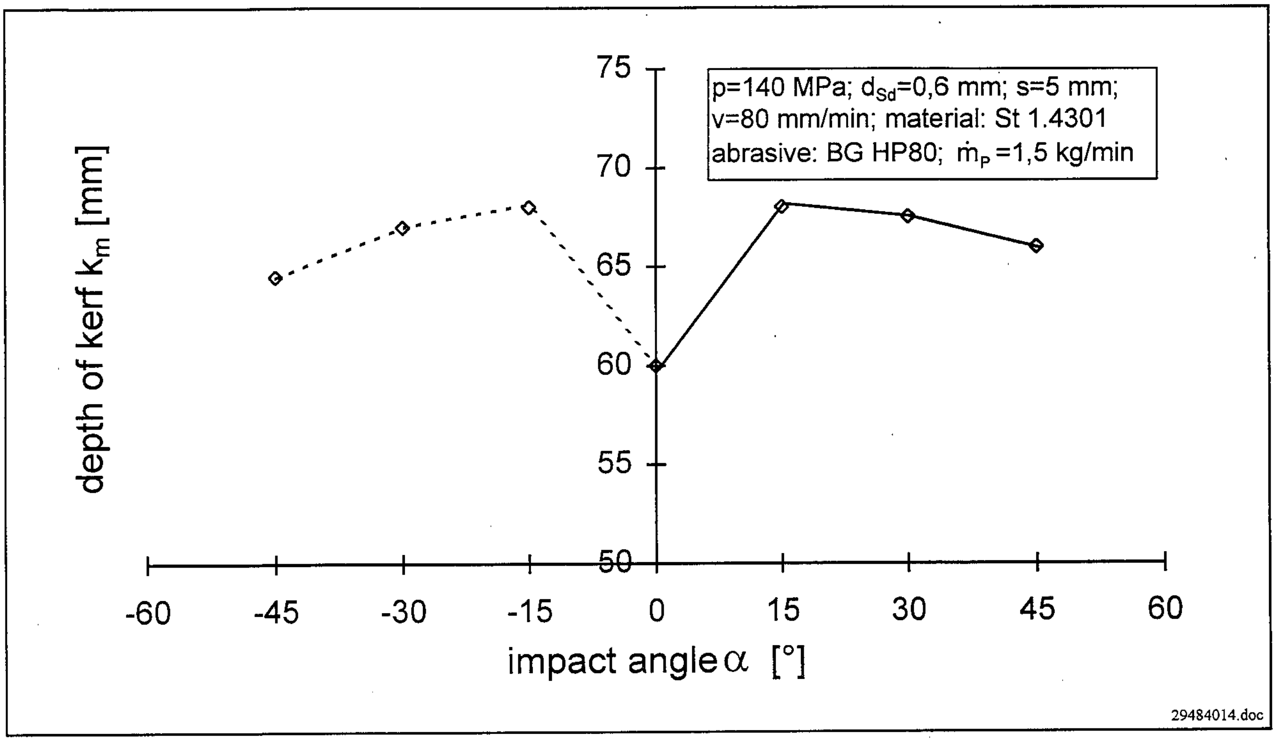

Figure 12: Effect of impact angle α on depth of kerf

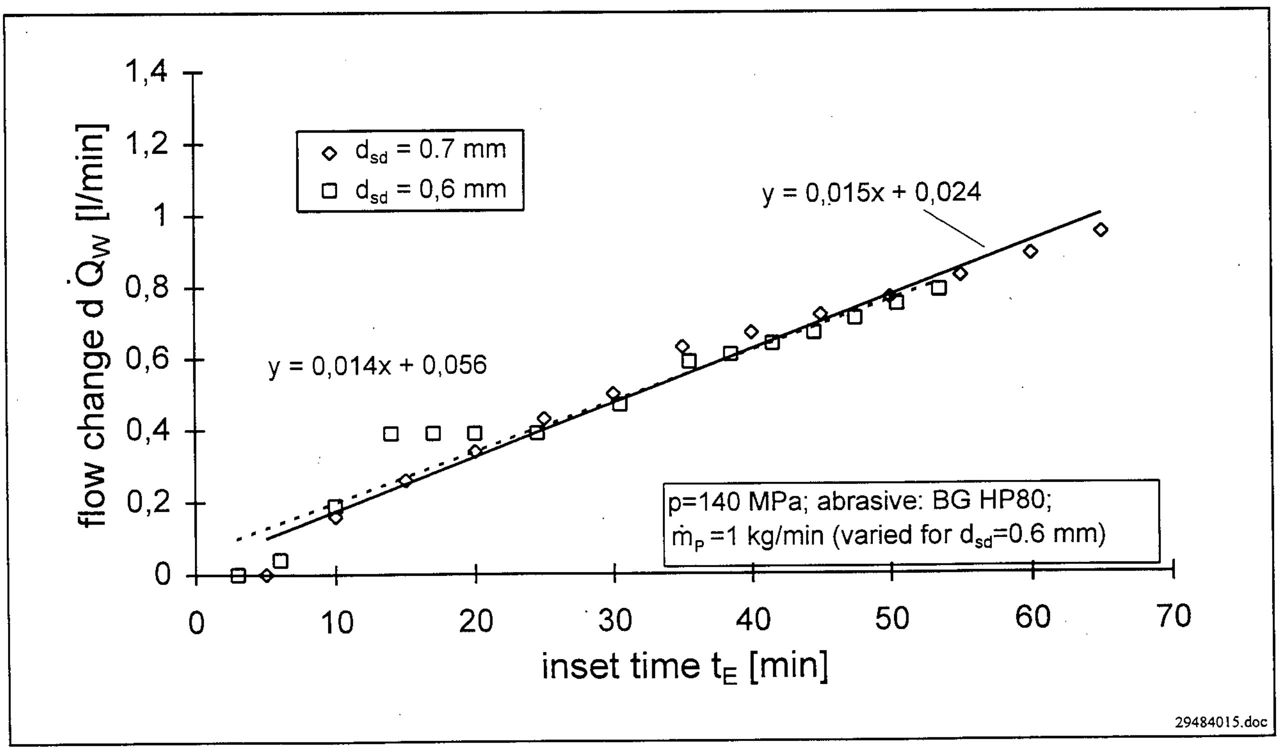

Figure 13: Nozzle wear for two nozzle used with Barton Garnet HP80

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Paper 51

PRACTICAL PROBLEMS IN THE DEMILITARIZATION OF MUNITIONS

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ABSTRACT

The University of Missouri-Rolla, in collaboration with Wilkes University, has installed a facility for the automated removal of plastic explosive from 5-inch rounds in Crane, Indiana. Although the work has previously been described through the development of the concept, there were considerable problems in bringing the final operation of the system up to the design condition.

These problems ranged from the need to install a chiller to reduce the temperature of the recirculated water, to the need to more accurately align the shells to ensure that both coring and reaming operations could be achieved in a single pass. The problems and their solutions are discussed, together with modifications to the system to increase the range of materials which can be removed, and to establish the safe operational limits for using the system for shells of varying size and explosive content.

Organized and Sponsored by the Waterjet Technology Association.

1. INTRODUCTION

Thousands of tons of explosive laden materials, many considerably older than their designed safe storage life, are warehoused at military bases around the country and throughout the world. Many of these obsolescent munitions pose a considerable storage cost in both dollars and good will from surrounding communities. Many also pose a risk to those communities and the environment.

2. BACKGROUND

Disposal of surplus munitions has historically been a relatively simple process with three alternate methods; burning, blowing, or burying. None of these methods is a long term acceptable solution in today's ecologically aware environment, and the University of Missouri, among others, pioneered the use of high pressure waterjets as a viable alternative. Research from 1982 through the present developed a method of using water as a safe, economical and environmentally benign method of demilitarizing conventional munitions. The development of the automated system located at the Naval Surface Warfare Center in Crane, Indiana began in 1995 as a straight forward marriage of proven equipment and techniques that appeared to easily validate the confidence placed in their ability to eliminate the munitions disposal problem.

3. SYSTEM CONCEPT AND DESIGN

The washout system was specifically designed to remotely demilitarize one particular size and shape of projectile that was loaded with a single explosive. These rounds are the 5" mark 54 shells and are loaded with PBXN-106, a relatively soft, insensitive explosive. These casings carried the added benefit of being needed for refilling immediately upon completion of their being cleaned, so the recycling would be immediate and make the washout even more cost effective. The remote operation and need for precisely positioning the shells called for the entire operation to be under control by PLC's, or Programmable Logic Controllers.

4. SHELL HANDLING

The shells are stored (and delivered to the washout facility) palletized in a vertical orientation with the open fuse well, the access for the washout, pointing up. From lessons learned in the past, the shells needed to be presented for washout with the opening oriented down to allow gravity to assist in the removal of freed explosives. Economics dictated that multiple shells must be in the loop for washout at all of the four stations as well as queued awaiting an opening. It was determined that a minimum of 12 positions were to be filled at all times and therefore 12 carriages were needed and built that would lift the vertical shells and rotate them to a declining orientation for insertion into the automated power and free overhead conveyor that delivers the rounds to the washout stations. Following washout the procedure is reversed and the shells are returned to the vertical orientation, palletized and conveyed out of the bay for short-term storage.

5. WASHOUT STATIONS

A two phase washout system was instituted as the most rapid way of cleaning the shells and two independent lines were installed to allow for the completion of a shell each minute of operation. The first phase of the operation is to drill out a two inch core through the length of the shell and the second is to ream out the remainder of the explosive. A combination of vacuum and gravity move the explosive and cutting water away from each station. Both operations rely on a rotating multi-orifice nozzles mounted on a lance that advances into the shell as material is removed.

6. WATER CIRCUIT

In order to minimize any waste streams generated, the water for the washout was designed into a closed loop system. 3000 gallons of tap water were stored in tanks on site, and fed through a surcharge pump to the high pressure pumps where 50 gallons per minute of 5000 psi water is supplied to the washout stations and a jet pump. The jet pump moves the post-wash water and explosives away from the washout operation and into a separation system to put the solids into drums for shipping and the water through a series of increasingly fine filters for return to the storage area.

7. SYSTEMIC CONCERNS

At the time installation was completed and the first shells were introduced, it became obvious that consistency of fabrication in the carriage portion of the shell handling system had not been up to standard, although all carriages appeared alike. This variation in construction allowed the shells to move into unacceptable positions, either too high, too low, or at an imprecise angle relative to the washout stations. The unacceptability of this fact became evident in the first test runs as the washout station lances advanced into shell casing walls and pushed themselves out of alignment, spraying the entire work bay with water. Weeks of modifications ensued until it was determined that alignment was sufficient for live round tests.

During live round tests it was determined that the angle of presentation was still not consistent enough from carriage to carriage as two continually came through the washout process with material left in the shell, which necessitated repeating the entire washout process and dropping production to an unacceptable level. Again, these two carriages were taken out of service and modified until they were able to repeat their tasks successfully.

Limited full scale production runs followed and appeared to be successful until it was noted that steam was appearing at various points in the water recirculation system and the shells were too hot to comfortably touch after washout. Additionally, small leaks began to appear in joints throughout the filtration area. Analysis of the water in the storage tanks suddenly showed an unacceptably high level of explosive contamination and a temperature of over 120 degrees Fahrenheit. Two obvious problems were that of heat buildup and filtration failure. These two problems were at least partially related as it was discovered that the explosive, which had been promoted as non water soluble, was in fact dissolving to an extent in the water as the temperature raised and moving through the filters as a liquid only to precipitate out as the temperature dropped. The higher the water temperature climbed, the higher the level of contamination in the water, and the more explosive that was loading the activated charcoal, the final filtration step.

A two pronged approach was adopted to solve the water problem. The first step was to introduce a heat exchanger into the system that would cool the water down and maintain a temperature level consistent with the overall system requirements. To reduce costs a heat exchanger which utilized ambient water was introduced that could drop the process water 10 degrees at 50 gallons per minute. This was about one tenth the price of a comparable chiller.

The second approach was to change the filtration method. Rather than rely on a series of increasingly fine barrier filters, a settling tank and clarifier tank were incorporated along with coagulant and flocculant polymer injection. A polymer is injected that causes some coagulation of the solids and as the flow of slurry stills in the settling tank, the explosive solids, which have a specific gravity of 1.6, settle to the bottom of the cone bottom tank. A valve can then be opened as necessary (about once an hour) and the explosive will gravity feed into a shipping drum. The flocculant is then injected and mixed with the slurry adding an anionic charge to any remaining fine particulates in the water. This change in charge coalesces any remaining particulate and the clarifying plates allow sufficient time for those fines to clump and fall out of suspension. This filtration approach along with temperature control and a final polishing with activated charcoal minimizes contamination of the water and eliminates the problems associated with disposal of filter media.

A concern that is now in the forefront is that there are a finite number of 5" mark 54 projectile in inventory and a much larger number of 5" mark 38 rounds. While the mark 38 rounds are the same diameter, for the purpose of automated washout that is the only similarity. These new rounds are considerably shorter and are filled with a wholly different explosive, one that is at the same time more sensitive and more resistant to washout. While the original system was designed with only one shell type in mind, there was a considerable investment of time and money in its development and modifications. With the tremendous number of conventional munitions to be disposed of, the decision was made to modify as necessary to accommodate the new shell geometry. The modifications need to be made to the handling system, so a carriage can pick up a shell and position it properly for rapid washout, and to the high pressure pump which may require more aggressive pressures for complete cleaning. Concurrently, a safety review of physical distances from personnel to washout area must be done.

8. CONCLUSIONS

In installing a sophisticated system, especially one in which remote operation is needed, it is necessary to demand precision in all components. The physical act of washing the explosive from munitions is a proven technology and, as such, presented virtually no problems. Materials handling, positioning and water treatment continue to be concerns, but as more and more facilities are forced by environmental law to stop the use of open burning and detonation, the use of remote waterjet washout systems promises to be an increasing part of the de-mil arsenal.

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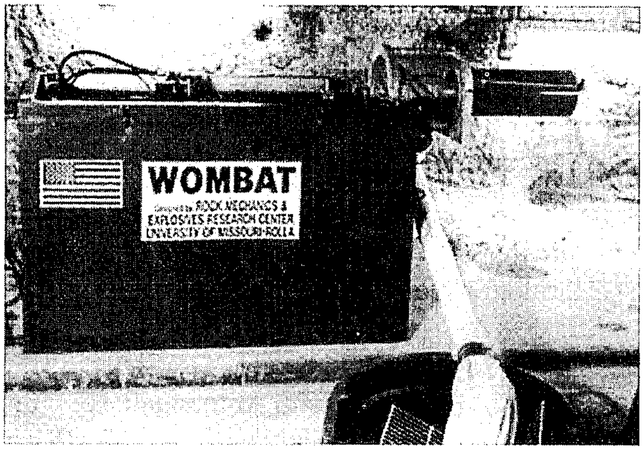

Figure 1. The W.O.M.B.A.T. - UMR's First Waterjet De-militarization System.

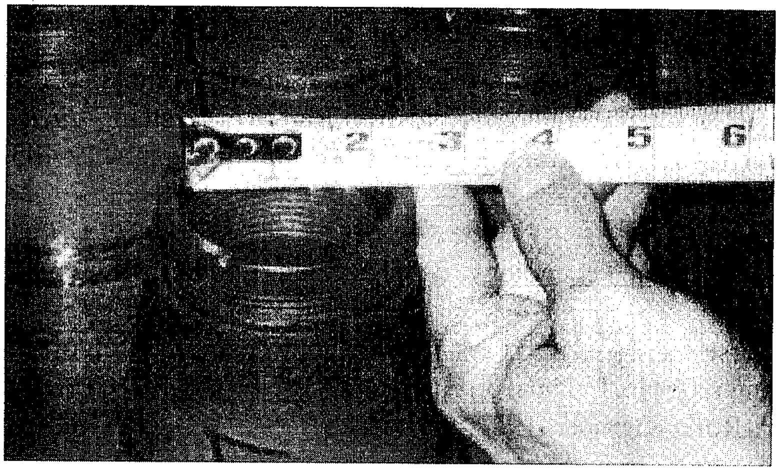

Figure 2. The 5" Mark 54 Shell.

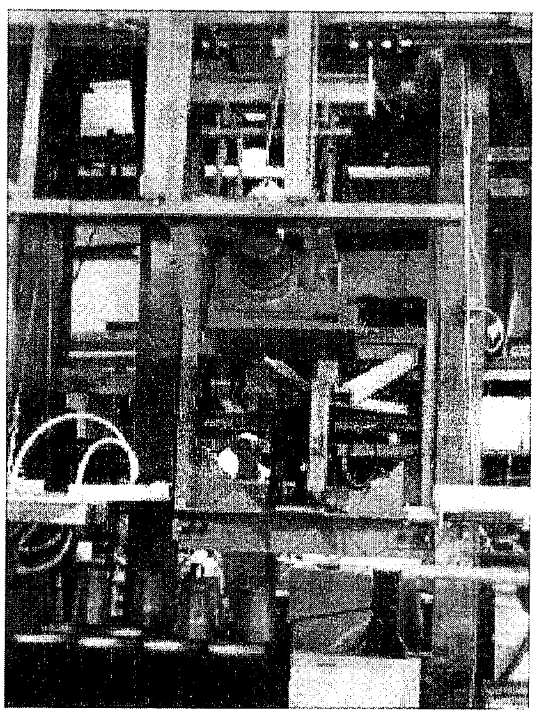

Figure 3. Upright Shells Entering Washout Facility.

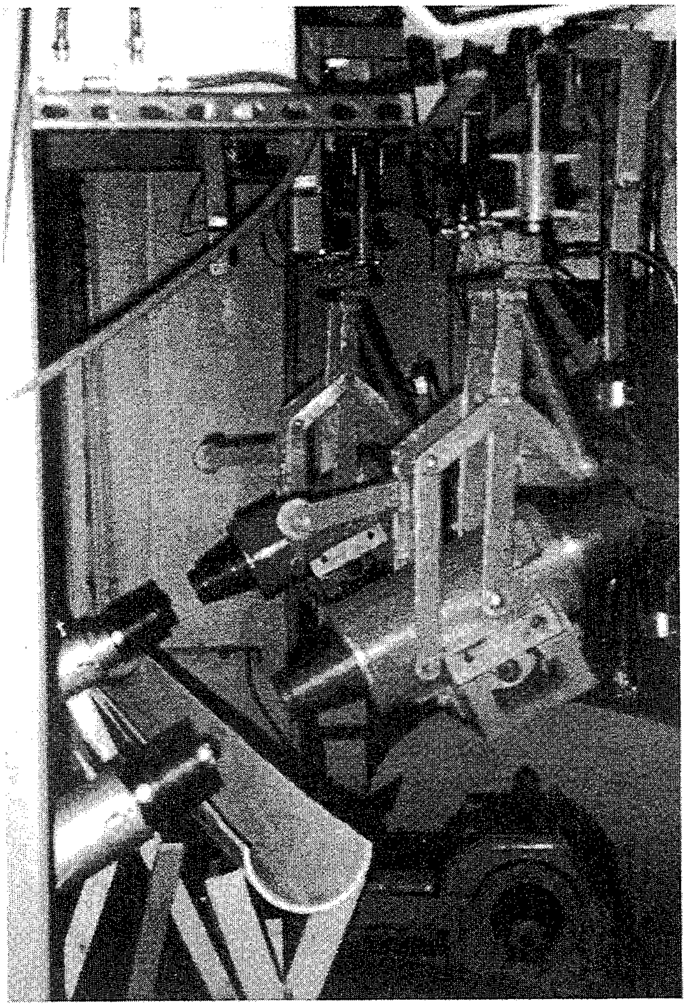

Figure 4. Shells Rotated into Proper Orientatiion.

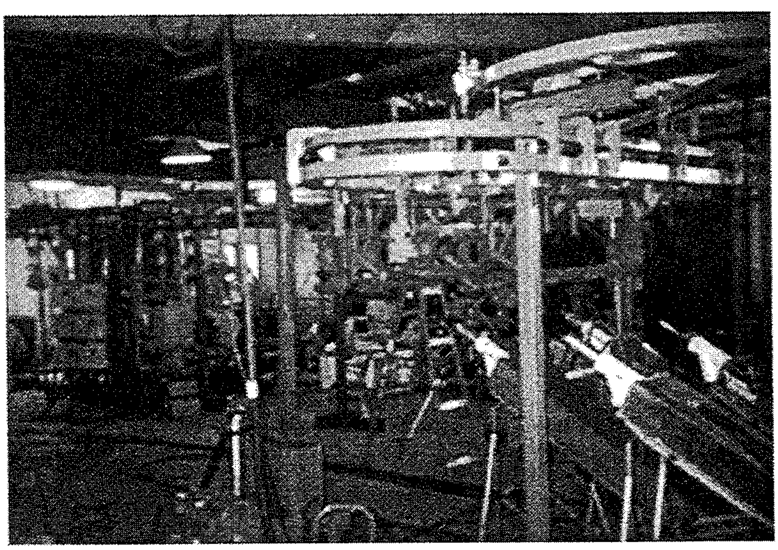

Figure 5. Dual Washout Lines with Two Phase Washout.

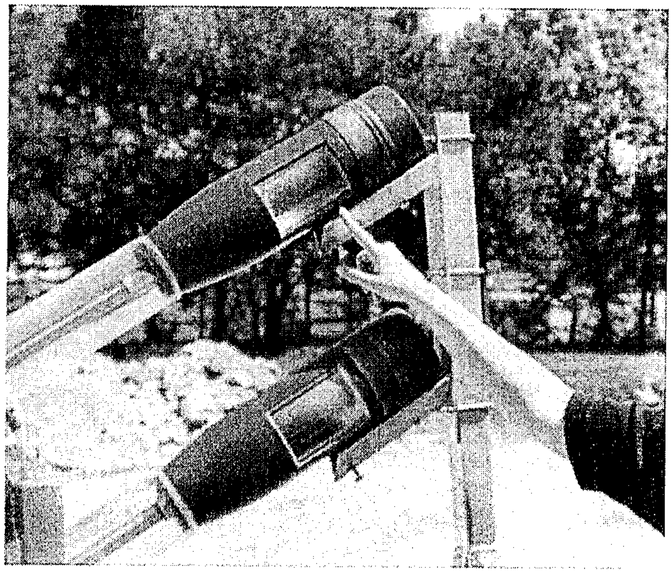

Figure 6. The Two Phases, Coring (above) and Reaming.

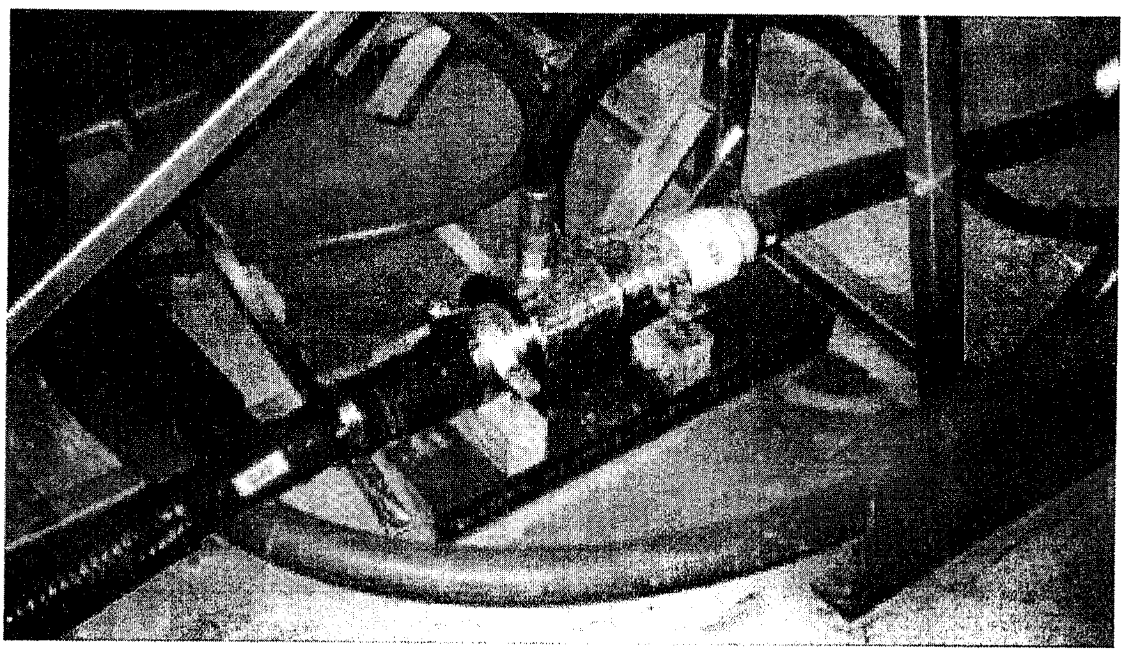

Figure 7. Jet Pump Used for Removal of Washed Out Explosive Slurry.

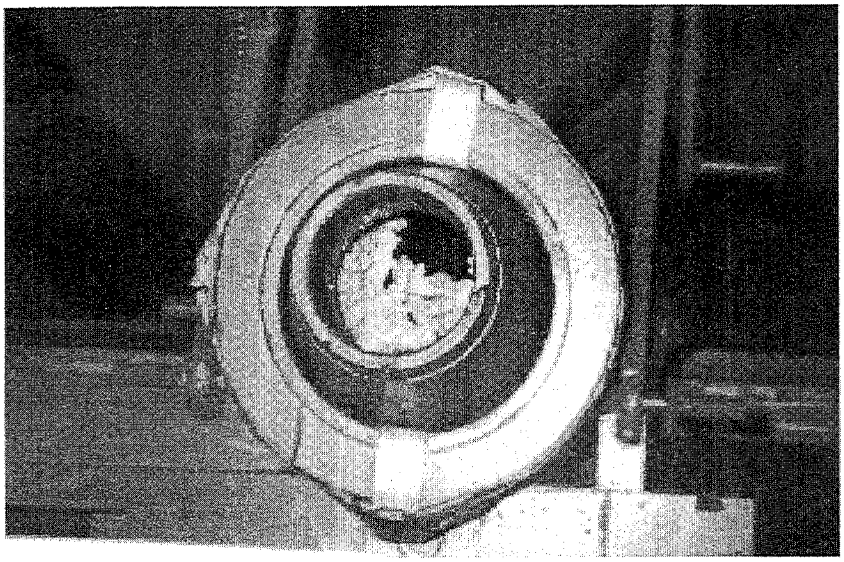

Figure 8. Misallignment Result.

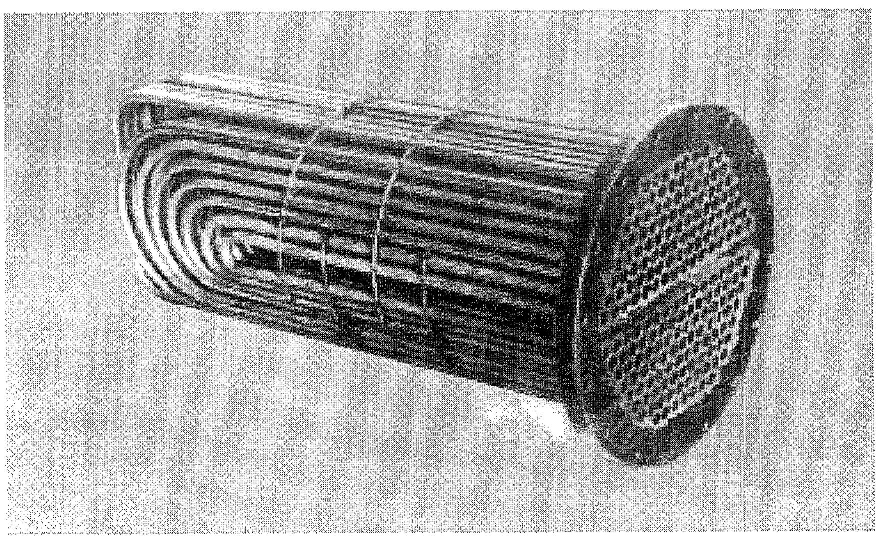

Figure 9. Heat Exchanger.

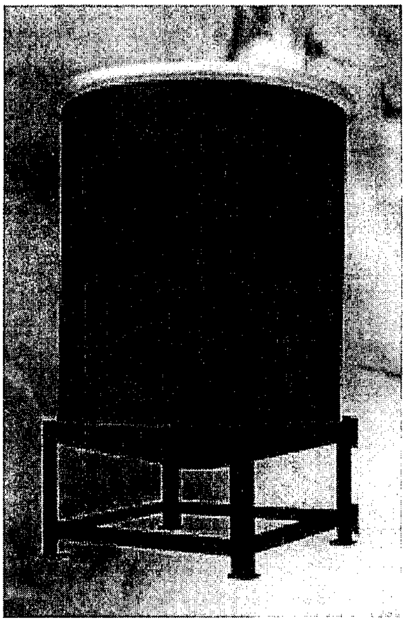

Figure 10. Settling Tank.

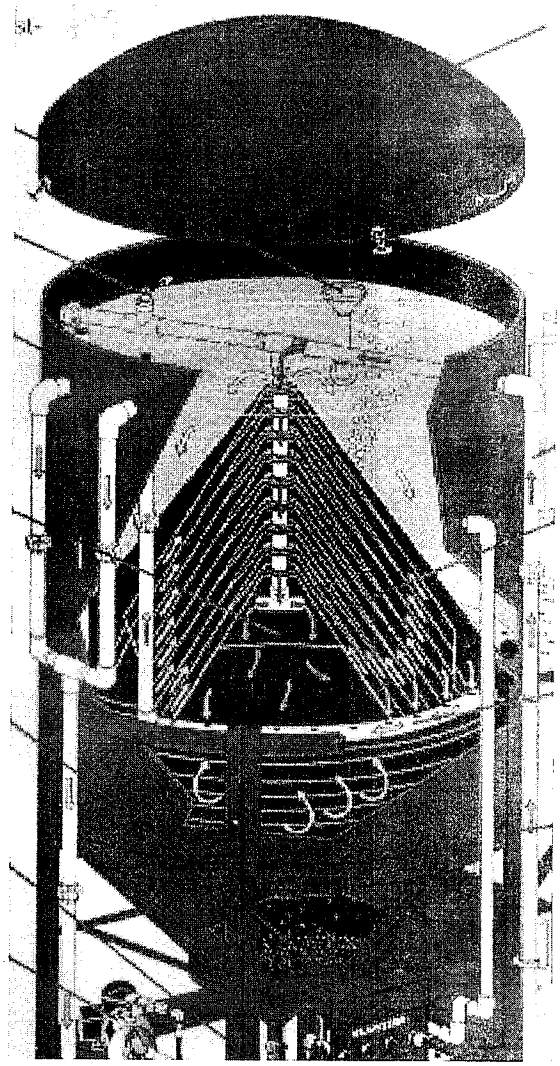

Figure 11. Clarifier.

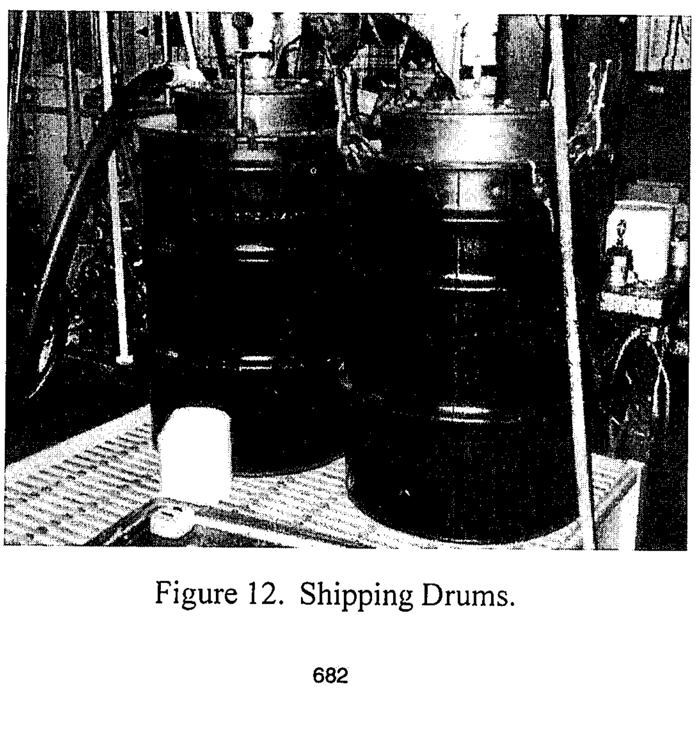

Figure 12. Shipping Drums.

9th American Waterjet Conference
August 23-26, 1997: Dearborn, Michigan

Paper 52

DESIGNING A WASTE RETRIEVAL SYSTEM FOR RADIO-ACTIVE WASTE RECOVERY

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ABSTRACT

Previous papers have discussed the basic development of a system for the removal of waste from underground storage tanks, using high pressure waterjets to cut the waste into small fragments, from which point they are aspirated into a tube and, powered by a jet pump, then hoisted to the surface.

Details are provided of the testing of a design required for the Idaho National Engineering Laboratory. Concurrently a discussion is held on the development of the high pressure jet pump system used to remove material from the tanks. In this discussion some of the parameters to be considered in the construction of such pumps, which are becoming increasingly available commercially, is provided.

Organized and Sponsored by the Waterjet Technology Association.

1. INTRODUCTION

For the past fifty years the United States has stored the waste products from nuclear research in underground storage tanks located near the National Laboratories at which the work was being undertaken. The tanks have typically been on the order of 75 ft. in diameter, and buried so that the floor may lie up to 60 ft. below the surface. Access to the tanks has been achieved through small manhole sized openings and risers which stretch from the tank to the surface (Figure 1).

It is now timely to remove the waste from these tanks, to process it and to decommission the tanks, once cleaned. The nature of the waste material, and the location, make it a difficult material to extract by conventional means. The University of Missouri-Rolla has become a member of a development team headed by staff from Pacific Northwest National Laboratory (PNNL), and including industrial representatives as well as government and academic personnel. This group has developed several approaches to the problem, one of which utilizes high pressure waterjets to dislodge the waste, and then a high pressure jet pump to aspirate the resulting slurry into a delivery line, from which it can be pumped to the surface, for subsequent processing. The difficulties associated with the waste removal have varied with the site at which the work must be carried out. Earlier papers have discussed the development of the technology at Hanford, WA and at Oak Ridge, TN, so those systems will be only briefly described in order to provide a background to the current work, which relates to the particular problems to be found at the Idaho National Engineering Laboratory.

2. PNNL SYSTEM

The waste held in the tanks at the PNNL site in Hanford, comes from a variety of sources, and range in strength from that of peanut butter to a relatively weak sandstone. Target production from the excavators to be used at this site was about 4 cu ft/min of waste which must be reduced in size to roughly pea gravel for conveyance out of the tank. The equipment developed has been described in detail earlier, Summers et al., (1993) and will only be summarized at this point.

The need for a low reaction cutting tool which could be manipulated by a robotic arm some 75 ft in length, meant that only limited force could be applied to achieve the necessary mining rate. Waterjets provide such a tool, and a set of four cutting nozzles were incorporated into two rotating cutting heads, which were themselves rotated, as the assembly traversed over the surface of the waste. The jets were designed to operate at a pressure of 10,000 psi following a series of experiments which validated that the required depth of cut could be achieved with jets at such pressure. Each jet would cut into the waste to a designed depth of an inch, so that, in total a depth of four inches would be carved from the waste surface, over a width of cut of 12 in while the assembly moved over the surface at a speed of 12 ft/min to give the target production rate. The water used to liberate the particles of waste also provided a lubricant and transport medium to carry the waste into the suction pipe, through which it would be carried to the surface (Figure 2).

All three systems were designed to use a high pressure waterjet pump as the power source for the conveyance line, and since this is common to all systems the experimentation to develop this will be described at the end of the paper. In order to minimize the amount of water that would be left in the tank, a mining strategy was also evolved in which the jets cut an oval path of gradually increasing size, revising the center, which would be cut deeper, at regular intervals. In this way the debris not immediately collected would flow down to the central collection trough, and the head would aspirate it out of the tank on its next visit.

3. OAK RIDGE SYSTEM

The access passages to the tanks in Hanford allowed the deployment of a large robotic arm, which, as a result, had considerable strength. The second site to be addressed was at the facilities at the Oak Ridge National Laboratory (ORNL) TN, where the tanks were smaller. In addition the tank walls in this site had been constructed from gunite, a sprayed on concrete with much lower strength than the steel.

The smaller tanks also had a smaller entrance diameter, so that the overall size of the arm which could be used during the removal process had also to be reduced. The smaller arm had a lower strength, and thus the overall size of the end effector which could be fielded at the Oak Ridge site was reduced to a maximum dimension of 16 inches, with an overall weight restriction of 70 lb. The design requirements were met and have been described in an earlier paper, Summers et al. (1995), and the changes required to meet the target will be only briefly summarized at this time.

Because there is less waste to handle at the ORNL site, volume removal rates are less critical, and a smaller unit was acceptable. Rather than dealing with a solid product, however, the waste at this site is more commonly a finer grained particulate bed with a high fluid content. At the time that the end effector would start to work it is likely that it will most closely resemble a thick mud in consistency, and that within the mud will be lumps of harder material which will need to be fragmented. As with the PNNL system this unit will feed to a suction line which will carry the waste up and out of the tank, through a jet pump.

The soupier nature of the waste created immediate problems in the control of the flow of waste from the impact point. A considerable part of the effort in this phase of the effort was directed at the waste stream control, and ensuring that the material was all collected by the suction tube. The solution (Figure 3) required that three jets be rotated around the suction tube, inclined to direct the waste stream into the center of the unit. In order to protect the rapidly spinning arm from contact with the wall an outer shroud was then included as a cover.

The combined system proved to be more sensitive to operational parameters than had originally been expected. At rotation speeds above 150 rpm the waste coming into contact with the outer wall of the suction tube is thrown out under centrifugal force, beyond the original diameter of the cleaning jets. Thus, that portion of the waste thrown behind the unit would require an additional pass of the system for collection. This could be overcome by increasing the operational radius of the jets, and where the jet path on the surface was increased to six inches, this lay beyond the range over which the debris was being scattered. An alternative solution, which also worked, was to incline the cutting head so that it was tilted back from the direction of advance by five degrees. This opened the access for waste being mined, while reducing the amount of suction applied behind the unit, where there was little need for it. A combination of the three approaches, helped resolve the problem of removing the waste.

One additional problem had to be resolved, and prior to actual testing in the waste tanks themselves, only a potential solution could be proposed. The problem arose since part of the inner lining of the concrete tanks had fallen into the tank over the course of the years of operation. This material should be removed during the cleaning process, which requires that the pieces of concrete be fragmented. However, the material is close in strength to the concrete of the floor, and this should not be damaged during that fragmentation. The process proposed to solve the problem is to size the nozzle diameter so that the jet loses its structure and the majority of its cutting power at the lower edge of the shroud. It has been known for decades that the decline in jet power can be quite sudden at the end of the coherent length, and by choosing the nozzle diameter appropriately this distance can then be set to occur just above the surface of the concrete floor.

At present, the system has moved from university concept, through commercial fabrication at Waterjet Technology Inc. and has been put through cold testing in a simulated tank, prior to being fielded in the hot tanks at ORNL.

4. INEL SYSTEM

The third site to be addressed is at the Idaho National Engineering Laboratory (INEL) where the tanks are made of steel. However, in this case, the access channel is just over ten inches in diameter, and thus the robot arm must, correspondingly, also be smaller. The limit currently stands at a 10 inch diameter end effector which can only weigh less than 25 lb. The unit fielded for ORNL weighed 35 lb, and thus the initial challenge has been to simplify the design to accommodate this dietary requirement.

The configuration of the tanks at Idaho is also somewhat different from that of the other two sites. Not only is the access passage smaller, but the tank is lined with steel cooling tubes, each some two inches in diameter, and all held at a distance of some four inches above the walls by an underlying structure of support beams.

The problems to address involve not only developing the design to remove the waste, but also to clean the infrastructure of the pipes and beams, both top and bottom, over the geometry of the tank.

A review of the geometry (Figure 4) suggested that it would be less likely that the large particle problems encountered at the earlier sites would be present. Thus, the central rotating suction tube was not included, and a simpler shroud design developed in which two passageways would feed the fluid up from the cutting head.

Tests indicated that the debris in the tank could be used to scour the undersides of the pipes if sufficient turbulence could be generated by the streams of fluid from the cutting nozzles of the end effector. A test stand was built to include full scale pipe simulation, with underlying support, and with the coating simulated using a commercial patching compound. A series of tests have been carried out varying the nature of the simulated material used for the waste (from clay, through limestone particles with the earliest proof of concept testing being done using fine sand). The jets were inclined at varying angles to the horizontal during the tests, which were carried out with the head moving at different heights above the floor of the cell. By adjusting the height of the debris in the tank and the overlying height of the water over the simulant, it has been possible to identify the conditions required for the debris to effectively scour the pipes and provide the necessary cleaning of the sub-structure to reach the levels required.

As currently anticipated, the procedure to be followed in cleaning the tank, will begin with a pass of the cleaning head over the surface of the pipes removing the material on the top of the pipes. A second pass would then be made with the head traveling down between the pipes, and lowered so that the jets were below the pipe level. In this run the jets would be on for cleaning but the jet pump would not be activated. Finally, when the coatings on the surface had been dislodged a third pass would be made using the suction from the jet pump to remove the material. Cleaning jets would be operated at lower pressures to flush the remaining material from the surfaces as the head progressed.

A prototype head has been developed for this program (Figure 5) and is currently undergoing evaluation at PNNL. It is interesting to note that as the designs have progressed for the different sites, the waste to be removed has become softer and easier to dislodge, so that while the system designed for PNNL was to operate at 10,000 psi, that for ORNL was designed for 7,000 psi and the unit to be fielded at INEL should not need to operate at pressures above 3,000 psi although for both the latter installations the system is sized to operate at higher pressures if required.

5. JET PUMP EVALUATIONS

Throughout the development of the end effectors for the different sites, the method proposed for removal of the material from the tanks has remained the same. In the earliest evaluations it was thought that the material could either be removed using an air evacuation system, or by use of a jet pump design. Based upon the original acquisition of an Aqua-Dyne unit, it was shown that the use of a high pressure jet pump would be effective in removing the material from the tanks. The use of a jet pump has several advantages over the alternative, in that it provides a very small power unit, which can be placed in the tank, and provide a positive push to remove the material up the height of the pipe, rather than relying on suction from the top to provide the power.

Tests at UMR, originally by Mann et al. (1993), developed the design from the original unit and modifications to the design, including an enlargement of the feed and exit pipe sizes, and a lengthening of the internal throat section (Figure 6) led to the design of a unit which was capable of pumping a three phase flow (solid particles: water: and air) at a rate of over 100 gpm up some 60 ft. in a simulated layout of the configuration for the ORNL layout (Figure 7).

In evaluating the performance of the pump, it was found critical that the jets converge inside the throat section of the unit, and that the machining tolerances be held to a high level to ensure that the jets converged at the same point, and with the same power. Because the jet pump design is very similar to that of some of the systems used to entrain abrasive into high pressure waterjets to develop streams capable of "cutting everything", there was some concern with the life of the pump being used. Early tests with metal throats for the pump indicated that the lifetime which could be anticipated was considerably below that which would be needed in a radioactive tool. This is because of the relatively high costs in both time and personnel which would be required to change out any failed component, even if this were, under normal circumstances, a very simple operation.

An inner liner was developed for the jet pump, in which the throat of the pump was covered with a length of ceramic tubing. This proved to give the increase in lifetime expected. The decision to make this change was based upon the reduced erosion which has been reported to occur where abrasive waterjets were directed at brittle target materials, as opposed to ductile material such as metal. This increased resistance is particularly evident at shallow angles of impact, such as those found in the throat of the pump.

A full set of parameterization tests for the jet pump design is currently under way at UMR, with a more comprehensive set of instrumentation, to more effectively define the roles of jet pressure, nozzle diameter, convergence angle, and throat length on the overall performance of the pump in conveying fluid of varying composition.

6. CONCLUSIONS

The work carried on for these three sites has shown that the combination of high pressure waterjet nozzles to dislodge waste, and a jet pump to then aspirate and convey the resulting debris from a tank, can be an effective tool for the removal of high level radioactive waste from environments where other alternative methods are constrained.

Tools have been developed to meet increasingly restrictive operating conditions and the capability of waterjet systems to meet those requirements have been met. In the process an improved jet pump has been designed, which has been shown capable of meeting the demands for material handling that are required in the proposed hot tank environment. Modifications to existing commercial hardware have been made and have been found to resolve some of the concerns for their use in final application.

7. ACKNOWLEDGMENTS

This work could not have been carried out without the continued support of the staff of the Rock Mechanics and Explosives Research Center at UMR, and the students at both graduate and undergraduate level who have carried out much of the design and testing described above. The program has been funded through PNNL by the U.S. Department of Energy, and it is a pleasure to recognize this support and the considerable amount of advice which has been freely provided by those involved in the Tank Focus Area group and particularly those in the Retrieval Process Development and Enhancements project.

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Galecki, G., Summers, D.A., Sprung, J., and Yount, J., "Development of a Waste Excavation End Effector," *Proceedings of the 12th International Conference on Jet Cutting Technology*, Rouen, France, pp. 637 - 648, October, 1994.

Mann, M.D., and Iyoho, A.W., "A High Pressure Waterjet Pumping System," *5th Conference on Ground Control for Midwest U.S. Coal Mines*, Collinsville, IL, pp. 325 - 335, 1994 .

Summers, D.A., Galecki, G., Rinker, M., Christienson, C., and Randolph, J., "The Use of Low Reaction Dislodging Tools for Waste Retrieval from Underground Storage Tanks," *Proceedings of the 8th American Water Jet Conference*, Houston, Texas, pp. 629 - 640, August, 1995.

Table 1 — Data Sheet For Use With Gypsum

Test #	Parameters	Date	Time	Rating	Comments
1-A	.021,5000,60,0	3/7 1997	2:50		Pipes set for 30 min. Top: 70%, Inside: 100%, Outside: 5%, Bottom: 5%
1-B	.021,5000,60,5	3/7 1997	3:25		Pipes set for 40 min. Top: 95%, Inside: 100%, Outside: 80%, Bottom: 30%
1-C	.021,5000,100,0	3/7 1997	3:35		Pipes set for 35 min. Top: 98%, Inside: 80-90%, Outside:70%, Bottom: 15-20%. One of the vacuum tubes came off during the test. It was near the end, so the test was valid.
1-D	.021,5000,100,5	3/10 1997	3:20		Pipes set for 45 min. Top: 100%, Inside: 100%, Outside: 90%, Bottom: 80%
1-E	.021,5000,100,10	3/11 1997	3:50		Pipes set for 40 min. Top: 90%, Inside: 40%, Outside: 90%, Bottom: 10%
1-F	.021,7000,100,0	3/7 1997	3:50		Pipes set for 30 min. Top: 100%, Inside: 100%, Outside: 100%, Bottom: 50% of one, 5-10% of other.
1-G	.021,7000,100,5	3/10 1997	3:40		Pipes set for 30 min. Top: 100%, Inside: 100%, Outside: 70%, Bottom: 70% of one and 20% of other
1-H	.021,7000,100,10	3/12 1997	2:50		Pipes set for 30 min. Top: 100%, Inside: 100%, Outside: 10%, Bottom: 80% of one and 50% of other
1-I	.021,5000,200,0	3/10 1997	2:20		Pipes set for 40 min. Top: 100%, Inside: 50%, Outside: 35%, Bottom: 10%
1-J	.021,5000,200,5	3/11 1997	2:50		Pipes set for 30 min. Top: 100%, Inside: 15%, Outside: 15%, Bottom: 20%
1-K	.021,5000,200,10	3/12 1997	3:25		Pipes set for 35 min. Top: 100%, Inside: 100%, Outside: 5%, Bottom: 50%
1-L	.021,7000,200,0	3/10 1997	2:40		Pipes set for 35 min. Top: 100%, Inside: 90%, Outside: 75%, Bottom: 50%
1-M	.021,7000,200,5	3/11 1997	3:15		Pipes set for 30 min. Top: 90%, Inside: 95%, Outside: 95%, Bottom: 30%
1-N	.021,7000,200,10	3/12 1997	3:40		Pipes set for 40 min. Top: 100%, Inside: 100%, Outside: 5%, Bottom: 15-20%

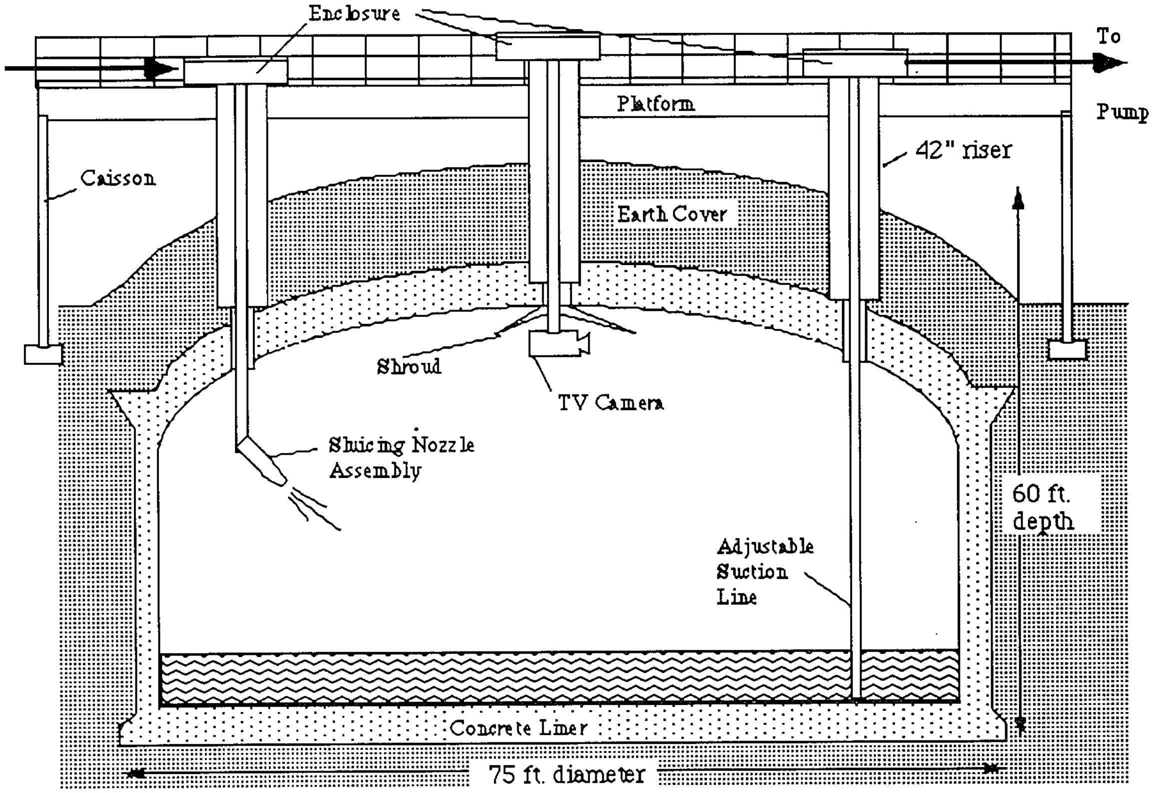


Figure 1. Dimensions of a Typical Tank.

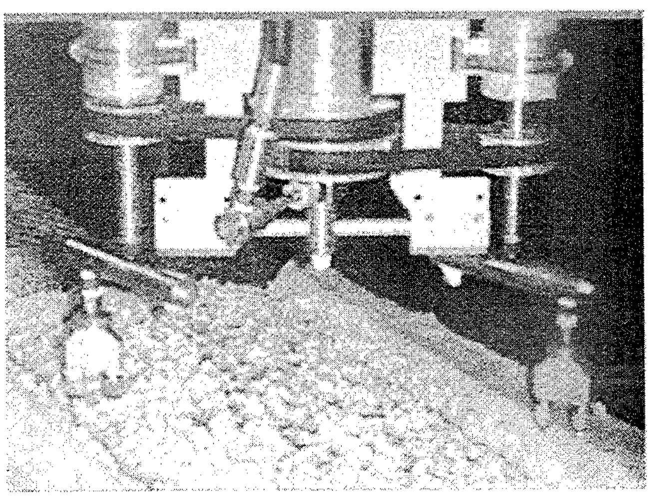
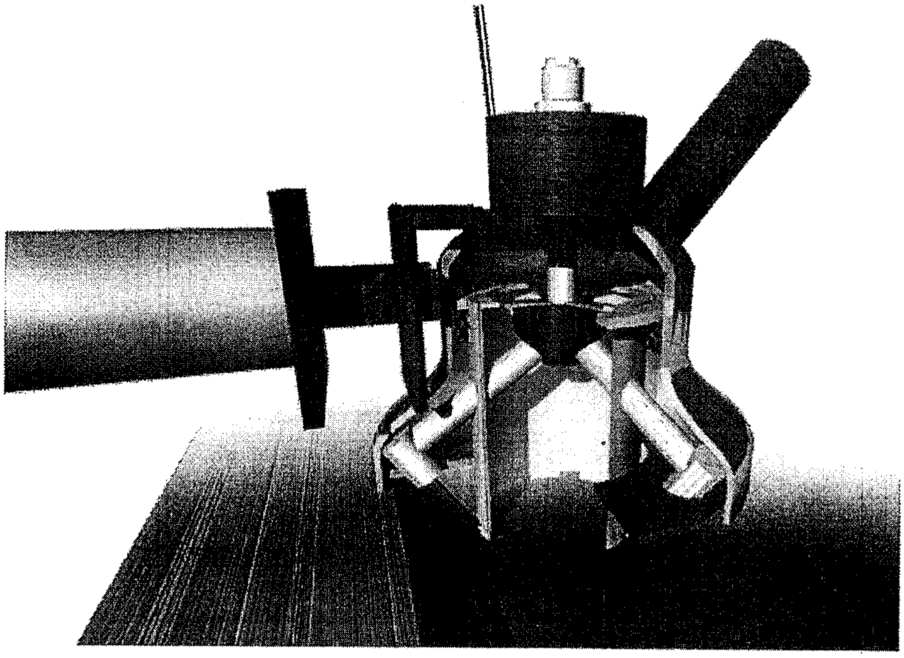


Figure 2. PNNL Prototype End Effector.



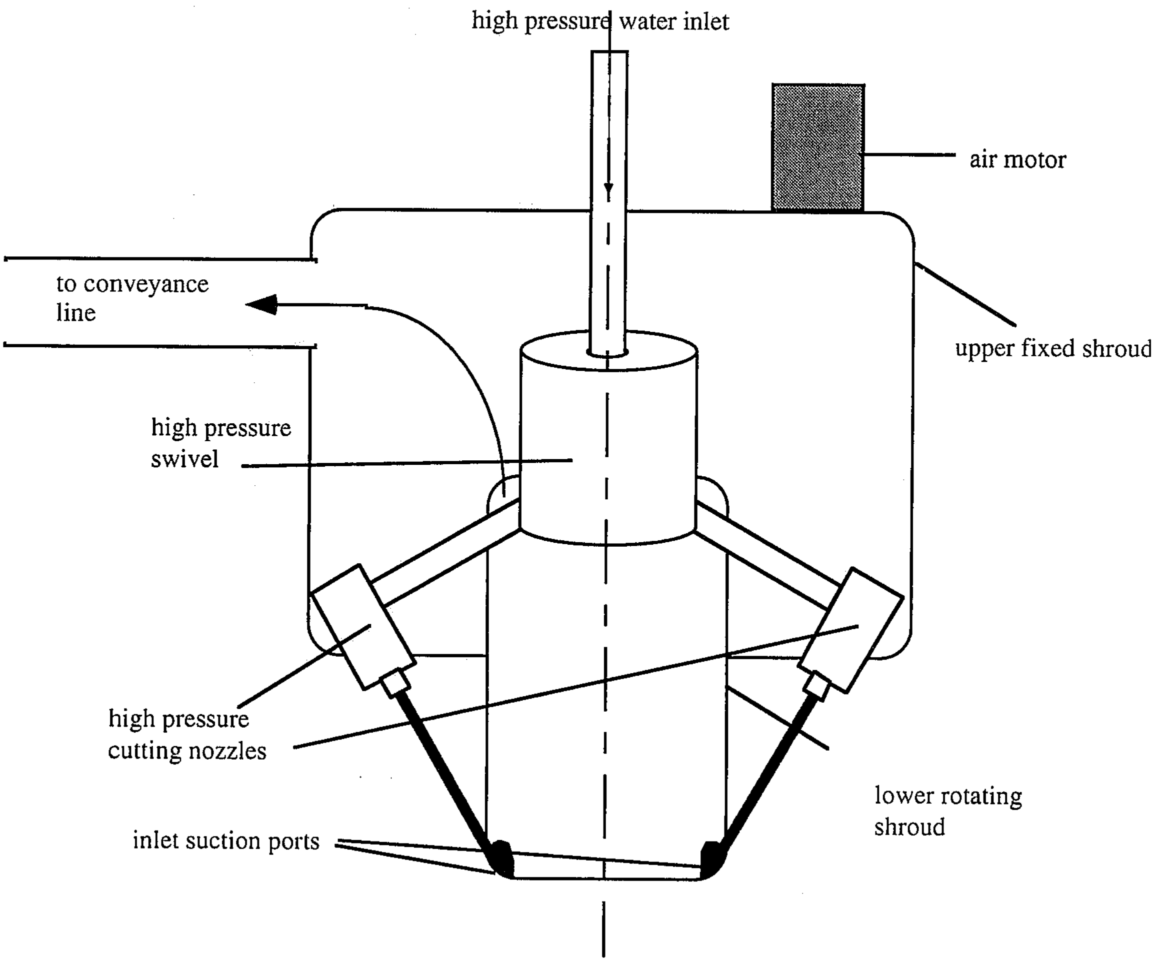


Figure 3. Artist's Concept of the ORNL System: a) In a Rendering, b) Showing the Relevant Parts.

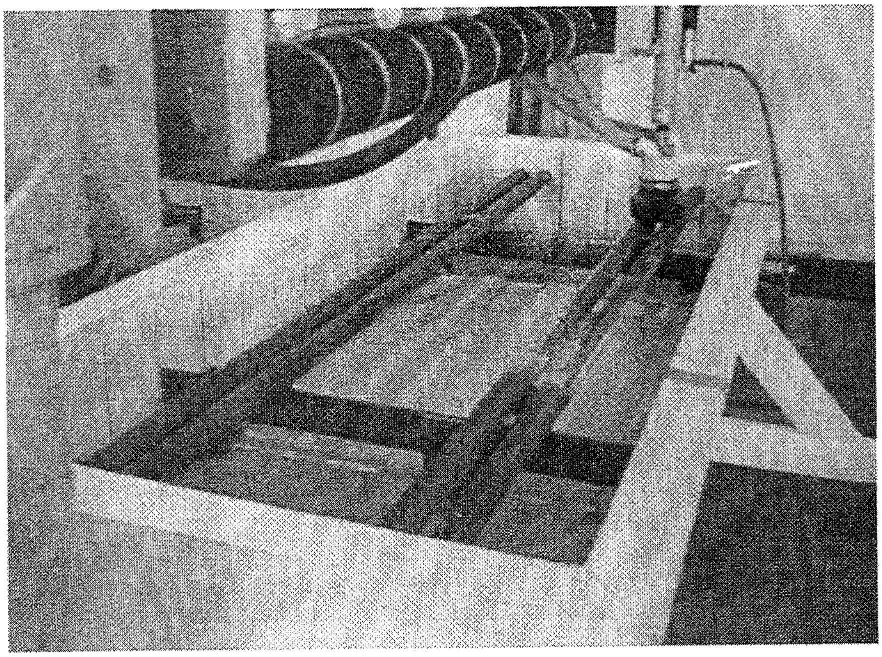
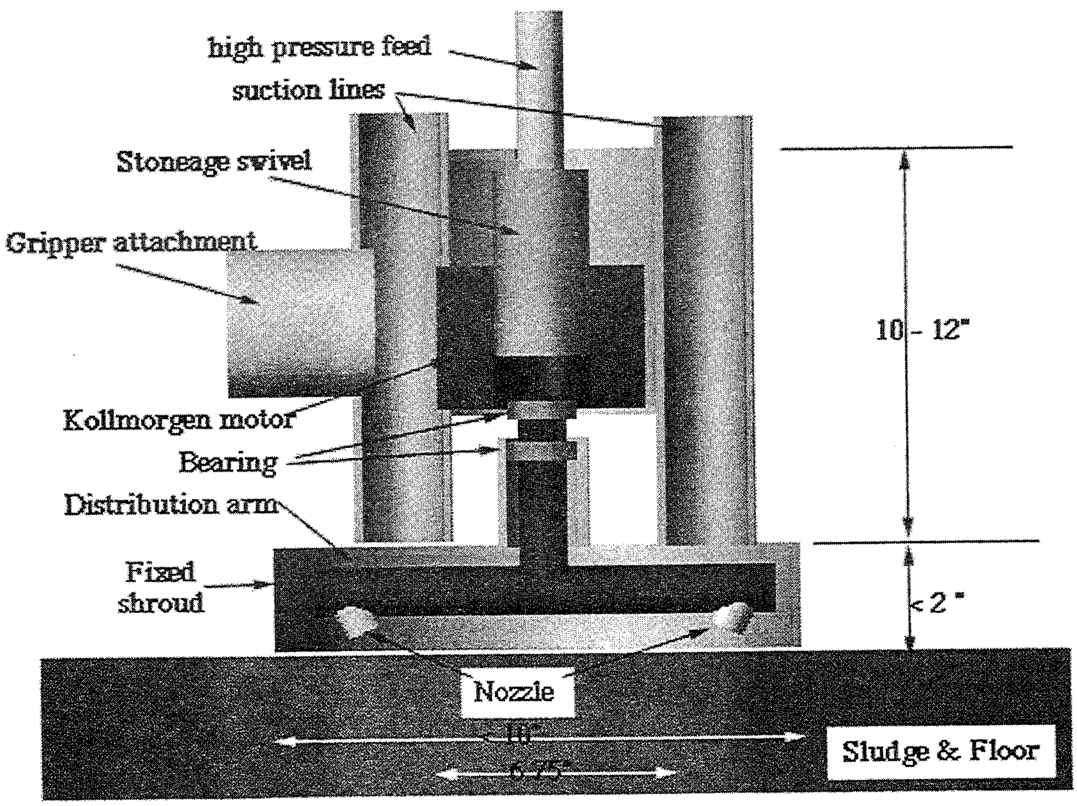


Figure 4. Geometry of a Section of the INEL Tank Hardware.



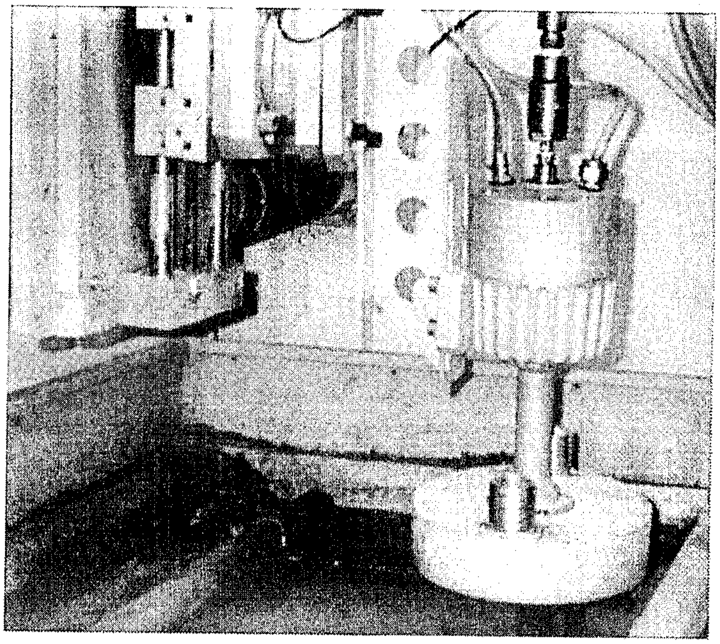


Figure 6. INEL Head Shown Relative to the Test Pipes in the Experimental Tank.

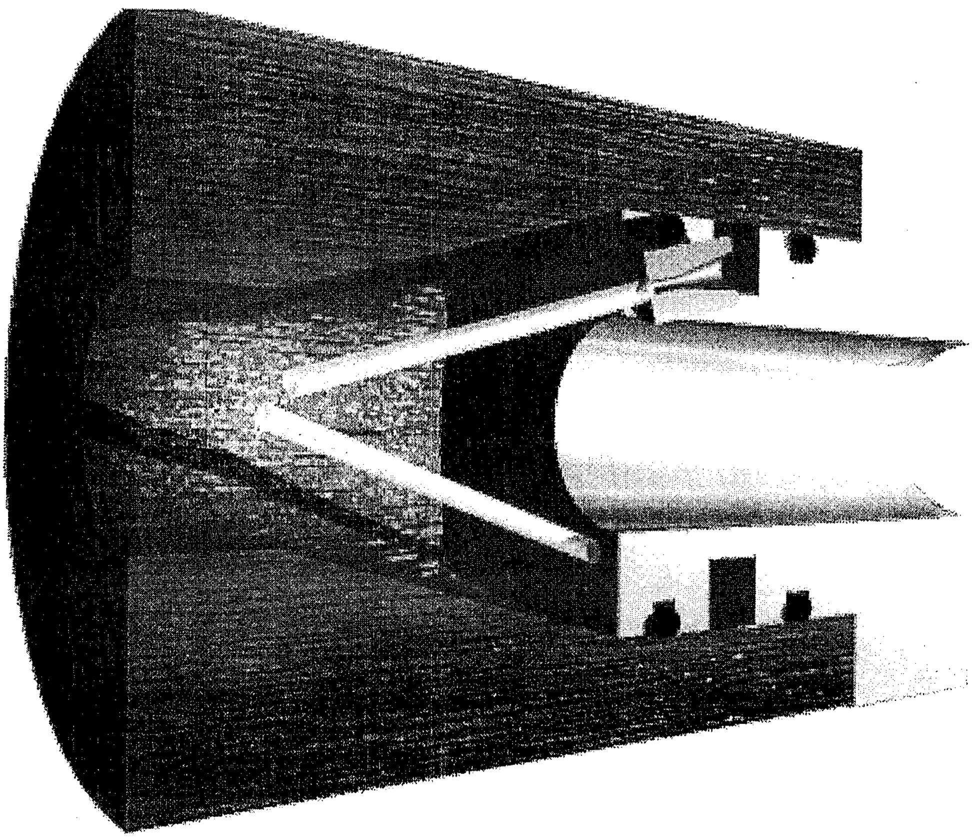
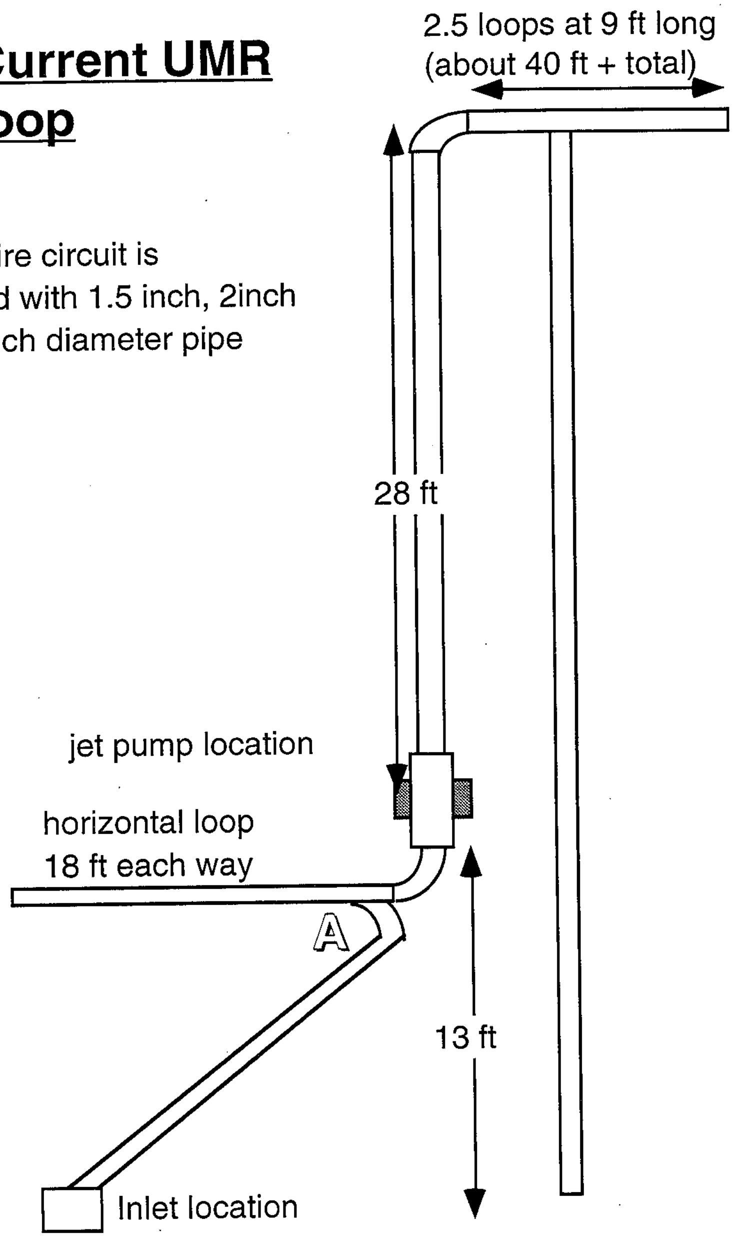


Figure 7. Artist's Concept Showing the Jet Pump Internal Geometry.

The Current UMR test loop

The entire circuit is plumbed with 1.5 inch, 2inch and 3 inch diameter pipe



Note that on the hose connection the inlet distance can be reduced below the 13 ft which is the maximum height. Above the connection at A, there are six hard pipe circuits, which can be interconnected nine ways. These are inlet horizontal loops (1.5, 2.0 and 3.0 inch dia) and delivery vertical loops (1.5, 2.0 and 3.0 inch diameter).

Figure 8. Test Loop Over Which the Jet Pump was Evaluated.

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Paper 53

CONTINUING IMPROVEMENT INITIATIVES OF SURFACE PREPARATION WITH WATERJETTING

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ABSTRACT

Surface preparation of concrete, steel ,and other metals and coatings removal is considered to be a large potential market for waterjet systems. In order for this process to be widely accepted, standards which provide a common language to define problems must be issued. The standards of third party organizations such as NSRP, SSPC, NACE, ASTM, ISO, and the proprietary specifications of private companies will be compared and discussed. It is vital that the coatings industry understand what the waterjetting industry has to offer and the waterjetting industry understands what the coatings industry demands in substrate characteristics.

Organized and Sponsored by the Waterjet Technology Association.

1. INTRODUCTION

Water has been used historically since the 1960's to clean surfaces of loose dust, chalking, and dirt, and to repress dusting in conventional air/abrasive systems. With the pressure of environmental concerns and the evolution of new equipment which is cost effective and reliable, high pressure waterjetting is more popular than in earlier years.

Water by itself, or with soluble abrasives is used predominantly in maintenance to remove heavy rust, old coatings, rubber, salts and other invisible contaminants, not in new construction. Water and hard abrasives can be used in new construction, particularly where there is a concern about the dust levels. The Foreword to the joint NACE/SSPC Surface Preparation Standard says: "Because water jetting does not provide the primary anchor pattern known to the coatings industry, this standard recommends its use primarily for recoating or relining project where there is an adequate preexisting profile."

Never the less, waterjetting without abrasive does provide a 10 - 75 micron (0.5 - 3 mil) profile on aluminum and is the subject of US Patent 5,380,564. Thermal spray coatings on a conventional grit-blasted surface have a tensile pull adhesion of 3,000 psi; on the surface profile prepared by 50,000 psi waterjetting, the surface pull adhesion is 6,000 psi.

For surface preparation using water, the current definitions which are found in prevalent use in commercial applications are:

A. Joint standard NACE No. 5- SSPC- SP- 12
B. SSPC- Technical Update Report. Wet Abrasive Blast Cleaning
C. The Navy Interim Guidelines
D. Schiffbautechnisch Gesellschaft Guide No. 2222 (referred to as STG 2222)
E. The International Coatings Visible Photographs on Hydro Blasting and Slurry Blasting
F. Cavi-Tech written definitions and visual photographs.
G. Jotun Valspar Group Visual Photographs
H. Hempel's Paint visual Photographs- issued in late fall, 1996.

Currently NACE No. 5- SSPC- SP-12 is the joint written standard. NACE written Standards take precedence over visual photographs (or standards) which are used to supplement the written material. NACE visual standard shall not conflict with NACE written standards.

1.1. Surface Preparation and Cleaning of Steel and Other Hard Materials By High and Ultra-High Pressure Water Jetting Prior to Recoating NACE -5, SSPC-SP 12

NACE No. 5- SSPC SP-12 is unique in that it addresses both the Visible Surface conditions, as is found in all the other blast cleaning standards, and the Non-Visible Surface conditions which is designated as Surface Cleanliness. This joint standards has undergone rigorous consensus scrutiny during preparation. The four visible conditions WJ-1 to WJ-4 are parallel in construction to the NACE No. 1, 2, 3, 4 or SSPC- 5, 10, 6, and 7. Definitions for the various levels of cleaning are consistent with the terminology of the industrial waterjetting community.

- WJ-1 surface shall be free of all previously existing visible rust, coatings, mill scale, and foreign matter and have a matte metal finish.

- WJ-2 surface shall be cleaned to a matte finish with at least 95 percent of the surface area free of all previously existing visible residues and the remaining 5 percent containing only randomly dispersed stains of rust, coatings, and foreign matter.

- WJ-3 surface shall be cleaned to a matte finish with at least two-thirds of the surface free of all visible residues (except mill scale), and the remaining one-third containing only randomly dispersed stains of previously existing rust, coatings, and foreign matter.

1. WJ-4 surface shall have all loose rust, loose mill scale, and loose coatings uniformly removed.

The three non-visible conditions do not have any guidance as to the suitability for service conditions. When the available papers were reviewed, it would appear that the SC-2 condition was the area of concern in which coatings would start to experience blistering or failure during testing. At the SC-3 condition, most coatings failed during testing.

2. SC-1 The surface shall be free of all detectable levels of contaminants as determined using available field test equipment with sensitivity approximating laboratory test equipment.

3. SC-2 The surface shall have less than 7$\mu g/cm^2$ chloride contaminants, less than 10 $\mu g/cm^2$ of soluble ferrous ion levels, and less than 17 $\mu g/cm^2$ of sulfate contaminants as verified by field or laboratory analysis using reliable, reproducible test equipment.

4. SC-3 The surface shall have less than 50 $\mu g/cm^2$ chloride and sulfate contaminants as verified by field or laboratory analysis using reliable, reproducible test equipment.

1.2. Wet Abrasive Blast Cleaning SSPC- Technical Update Committee Report.

This technical committee report has been in preparation since 1985 and describes sir-pressurized abrasive, water/abrasive, and water-pressurized abrasive blast cleaning systems. Procedures, equipment and materials are discussed and common consensus language is suggested. Because abrasives are doing most of the work in the cleaning process, the demand for a set of visual photographs is not as great as for waterjetting.

This document covers processes which extend from almost all abrasive which is just wetted with a little water to processes which are mostly water with a little entrained abrasive. In the former, the water is acting as a dust suppressant; in the latter, the cleaning is done by both the water and abrasive. It is felt that SSPC- SP 5, 10, 6, and 7 can serve as an accurate definition for these cleaning processes. The major visible difference is that the surfaces look darker. Flash rusting from the water may sometimes develop.

This document has been balloted and final editorial negative comments are being resolved. It should be published in final form in late 1996 or early 1997.

The International Coatings slurry blasting photograph should be sufficient to provide companion reference guide.

1.3. U.S. Navy Interim Guidance for Surface Preparation by Hydroblasting

The U.S. Navy funded a robotics controlled ultra-high pressure waterjetting system which was integrated by Waterjet Systems, Inc. The Ship-ARMS™ was field tested starting in July 1994. Ultra High Pressure Water Jetting (UHP WJ) is thought to be an economical, practical solution for compliance with environmental regulations promulgated by the Federal Clean Air and Water Acts. Open air abrasive blasting will essentially be no longer permitted under the Federal Clean Air Act. The adoption of Ultra High Pressure Water Jetting (UHP WJ) to strip paint decreases or eliminates the used abrasive grit which is the largest waste stream for many shipyards.

The Navy Sea Systems Command, Washington, D. C. , material branch has responded to the immediate need for guidance to the shipyards using waterjetting by issuing an interim guidance document in December, 1994. This conservative document incorporates the language of the International Coatings Hydroblasting Visual Standards and limits the acceptance of surface preparation to one visual specification- C HB 2.5 L. The hydroblasting method can be used on all areas of the U.S. Navy vessels, but the document specifically addresses underwater hulls as this is a very critical area. An epoxy primer coating system is recommended for the underwater hull area. The level of chloride contamination is limited to 3 $\mu g/cm^2$ Chloride for immersion areas and 5 $\mu g/cm^2$ Chloride for non-immersion areas. A minimum adhesion pull test is specified for the epoxy primer coating system. The amount of flash rusting is limited to light flash rusting.

The initial requirement for 1000 psi adhesion pull test was modified in August, 1995 to 500 psi, because the glue was failing between the dolly and the coating above 500-650 psi. The pneumatic adhesion tester level is still set at 1000 psi. In October, 1995, Ultra High Pressure Water Jet Paint Non-Skid Removal Approval was issued for use as a surface preparation for non-skid installation.

The Navy felt that they wanted to use the waterjetting process for waste minimization and environmental considerations. They could not wait for a third party consensus process to develop language. Currently an in-house Navy Process Instruction and Process Standard for the Use of Closed Loop Hydroblasting Equipment in Preparing Ship's Hulls for Painting is in preparation. It is anticipated that this guidance will be ready in late fall, 1996. This will provide yet more photographs of partial and complete removal of coatings with remotely and manually operated equipment.

At the NPCA meeting in June, 1996, the NAVSEA discussion on this subject indicated that the Navy will adopt consensus language and reference photographs as they become available.

1.4. **Definition of Preparation Grades for High-Pressure Water Jetting**, Schiffbautechnisch Gesellschaft Guide No. 2222 (referred to as STG 2222)

This guideline is a visual standard for marine application. The STG 2222 Guide was drawn up as part of the research project "Development of a high-pressure waterjetting tool, definition of surface standards for steel surfaces prepared by high-pressure waterjetting and development of coatings systems compatible with that method" and was sponsored by German Federal Ministry of Research and Technology. STG 2222 provides definition of preparation grades for high-pressure waterjetting without addition of solid abrasives, of corroded and coated steel surfaces, and at different initial conditions. STG 2222 consists of a series of photographs taken on the hulls, decks, and tanks of ships. It is intended to be used with DIN 55 298 Part 4 & ISO 8501-1

Adherent black iron oxide is left on the surface after the coatings are removed. G.C. Soltz showed that when salts are present, DAMAGING UNDER-FILM CORROSION WILL QUICKLY FORM UNDER THE PAINT FILM, EVEN IF THE CONTAMINATED SURFACES WERE TOTALLY RUST FREE WHEN IT WAS BEING COATED.(1) The European marine community uses the STG visual document which clearly shows black oxides under the existing coatings.

Definitions and visible photographs are given without requiring a specific type of process or equipment, there is a limiting pressure called the "threshold pressure" below which a substance is not removed. Tightly adherent black iron oxide is difficult to remove at pressures below 15,000 psi. The primarily difference in this set of pictures compared to those of International Coatings are related to the threshold pressure and the acceptance of a black appearance. In the pictures, it is difficult to determine if black staining or black oxide is present. The former is acceptable to many coatings manufacturers; there is no consensus on the presence of a black oxide layer.

None the less, this set of definitions has been accepted by some paint manufacturers for the use of surface tolerant coatings in marine applications. Visible water-insoluble foreign matter such as oil and grease shall have been removed prior to high-pressure waterjetting.

Dw 1 Only poorly adhering mill scale, poorly adhering rust and poorly adhering coatings are removed. Visible water-insoluble foreign matter such as oil and grease shall have been removed prior to high-pressure waterjetting. Previously coated surface are generally still predominantly covered with remaining coatings or parts of old coating systems.

Dw 2 Poorly adhering mill scale, poorly adhering rust and poorly adhering parts of coatings are removed. Firmly adhering mill scale is still present. From firmly adhering old coatings, various spots, and in part, also larger areas of the old systems or individual coats are present. Thin coatings on previously blast-cleaned surfaces (shop primer) are predominately removed. Generally, at least a weak sheen arising from the metal is perceptible outside firmly adhering residues before drying. However, this sheen disappears with the beginning formation of flash rust.

Dw 3 Poorly adhering mill scale, poorly adhering rust and poorly adhering parts of coatings are removed. Firmly adhering mill scale is still present. From firmly adhering rust, at most thin dark oxide layers and/or slight residues in the roughness valleys are present. From firmly adhering old coatings, residual areas having spots with damages, various scattered small spots and residues in roughness valleys may be present. These then lead to a slight cloudy shade of the same color as the old coatings. Thin coatings on previously blast-cleaned surfaces (shop-primer) are predominantly removed. Visible water-insoluble foreign matter such as oil and grease shall have been removed prior to high-pressure waterjetting. Generally, a distinct sheen arising from the metal is perceptible outside firmly adhering residues before drying. However, this disappears rapidly with the formation of flash rust.

1.5. Slurryblasting and Hydroblasting Visible Standards, International Coatings

Courtaulds Company International Coatings has prepared two visual sets of photographs to assist their technical service representatives in assessing the adequacy of surface preparation by slurry blasting and hydroblasting (waterjetting) for their coating materials. The international coatings community is adopting the use of water in surface preparation faster than consensus standards can be developed. The International Coatings definitions and pictures follow the ISO and Swedish Standards Institute definitions for surface preparation. The visual standards use grade C and D steel surfaces for the photographs. The International Coatings Marine Handbooks provide a very thorough treatment of flash rusting and provides guidance for the use of International Coatings over flash rust.

The four degrees of cleanliness are:

5. SB 2- Thorough Slurryblast Cleaning - When viewed without magnification, the surface shall be free from visible oil, grease, dirt, most paint coatings and foreign matter. Any remaining contamination shall be firmly adherent.

6. HB 2- Thorough Hydroblast Cleaning - When viewed without magnification, the surface shall be free from visible oil, grease, dirt, and from most paint of the rust, paint coatings and foreign matter. Any remaining contamination shall be firmly adherent.

7. SB 2.5 - Very Thorough Slurryblast Cleaning - When view without magnification, the surface shall be free from visible oil, grease, dirt, rust, paint coatings and foreign matter except for slight staining. Slight staining shall be limited to light shadows, streaks or minor discoloration.

8. HB 2.5 - Very Thorough Hydroblast Cleaning - When view without magnification, the surface shall be free from visible oil, grease, dirt, rust, paint coatings and foreign matter except for slight staining. A brownish-black discoloration of ferric oxide may remain as a tightly adherent thin film or corroded and pitted steel.

An important property of the waterjetting process is that it can emulsify and remove oil and grease from a surface as it is blasted. However, this does not preclude the need for proper degreasing procedures as specified in SSPC-SP 1, prior to waterjetting. The gray, brown to black discoloration seen on corroded and pitted steel after hydroblasting cannot be removed by further waterjetting. Analysis shows that this thin film consists mainly of ferric oxide, which is an inert material. As it is tightly adherent, it does not present a serious contamination problem.

Steel will rust when water is used in the cleaning process. The International Coatings Marine Handbooks also define flash rusting. The photographs are of a yellow-brown rust which is uniform over the whole surface. It is not the black, non-uniform rust which is indicative of active, local corrosion cells.

9. Light Flash Rusting - When viewed without magnification, small quantities of light tan-brown rust will partially discolor the original metallic surface. This discoloration may be evenly distributed, or in patches, but it will not be leave enough to easily mark object brushed against it.

10. Moderate Flash Rusting - When viewed without magnification, a layer of light tan-brown rust will obscure the original metallic surface. This layer may be evenly distributed or patchy in appearance, but it will be heavy enough to mark objects brushed against it.

11. Heavy Flash Rusting - When viewed without magnification, a heavy layer of dark tan-brown rust will completely obscure the original metallic surface. This layer of rust will be loosely adherent and will easily mark objects brushed against it.

The International Coatings definitions have provided the initiative for other coatings manufacturers in the world market to adopt and issue new product material data sheets incorporating these definitions of flash rusting.

1.6. Cavi-Tech Specifications for Partial Removal of Coatings and Corrosion

Cavi-Tech Inc., Kennasaw, Georgia, is one of several contractors who have been using waterjetting in surface preparation. Cavi-Tech is particularly competitive in maintenance where spot blasting is prevalent or where only part of the existing coating is removed. They have defined seven stages from brush blast cleaning to bare metal. They provide generic written descriptions and visual photographs, which are prepared for specific industries. These proprietary specifications are very useful in projects where economics is the driving force. Development of industry-wide consensus specifications for situations in which the individual coatings manufacturer has to agree that the new coating will be compatible with existing material on the surface is almost impossible. Cavi-Tech, as does other contractors skilled in waterjetting, uses equipment ranging from 15-20,000 psi to 30-35,000 psi to obtain the various levels of cleanliness.

The Cavi-Tech blast cleaning specifications are numbered CB-1 to CB-4. Some are closely equivalent to SSPC/NACE surface preparation specifications. Most of the definitions fall within the "brush-off" or WJ-4 blast cleanliness specification because they leave portions of the existing paint system on the substrate

12. CB-1 Sweep Off Blast. Removal of loose mill scale, loose rust, and loose paint to the degree hereafter specified. Leaves on tightly adherent material. The surface should be abraded for adhesion. The tight paint is feathered. The entire surface is stressed.

13. CB-1.5 Sweep Off Blast- Modified to remove all Corrosion. All rust, mill scale- except for carbon shadows-, streaks or discoloration caused by rust stain, mill scale oxides, or slight tight residues of rust may be found in bottom of pits. Loose paint & coatings are removed completely.

14. CB-2 Blast and Sweep Cleaning-Loose paint shall be completely removed. Tight Coating will be blasted back to show an underlying film surface evenly abraded.

15. CB-2.5 Control Blast and Sweep Cleaning-Tight coatings will be blasted back to a specified intermediate coat film surface. Evenly abraded over the surface to provide good adhesion and bonding of paint.

16. CB-3 Blast and Cutback Cleaning-Old paint is removed down to existing primer paint. Prime coating shall be reduced to a dry film thickness, whereby all degraded coating film has been removed. Remaining prime coat shall be tight and evenly abraded.

17. CB-3.5 Control Blast and Cutback Cleaning- All old paint is to be removed down to the existing primer. The prime coating shall be removed to a dry film thickness of not more than 0.8 mils.

18. CB-4 Full Blast- At least 95 of each square inch of surface area shall be free of visible coating residues, and the existing profile of the surface shall be clearly evident.

1.7. Jotun Valspar Group

Jotun Valspar has issued photographs for four grades of flash rusting- none, slight, moderate, and considerable on a single, uniform steel panel. Flash rusting is defined as rusting which occurs on metal within minutes to a few hours after cleaning has been completed. The speed with which flash rusting occurs may be indicative of salt contamination on the surface, high humidity, or both. The surface is of a blasted Grade A steel and the guide is intended to be a tool for visual assessment . The Guide is not restrictive to the use of water in the surface preparation.

All the photographs are of a uniform, yellow-brown rust. They are NOT the splotchy, non-uniform, black rust which is indicative of active, local corrosion cells.

JG-2 Slight flash rusting. The Steel surface shows a clearly perceptible change in color, but the original metal surface is clearly visible under normal vision. The surface exhibits a clearly visible metal shine when viewed at different angles.

JG-3 Moderate Flash rusting. The steel surface shows a very clearly perceptible change in color, but the original metal surface is still visible under normal vision. The surface exhibits moderate metal shine when viewed at different angles.

JG-4 Considerable flash rusting. The steel surface shows a pronounced change in color and the original metal surface is completely covered by flash rust and not visible under normal vision. The surface is characterized by a matte finish.

1.8. Hempel

The fall, 1996, issuance by Hempel of their "Photo Reference for Steel Surface Cleaned by Water Jetting" further emphasizes the urgency of intervention of the third party consensus process. Each coatings manufacturer, contractor, or operator, does not wish to refer to proprietary material which is issued by a potential competitor. The Hempel series includes painted and unpainted surfaces, with varying degrees of flash rusting, depicting WJ -1 to WJ-4.

2. DISCUSSION

There are THREE components for successful surface preparation. The first two everyone knows about.

19. Visible Cleanliness and
20. Anchor Profile
21. Invisible Contaminants

The third component, **Invisible Contaminants,** is one that people are still unaware of. ALL THREE COMPONENTS are all equally important as shown by Dr. Soltz and Ben Fultz in NSRP publications. IN fact a 1996 National Shipbuilding Research Program on less than ideal surfaces would suggest that salt levels may be more important than visual cleanliness on coatings performance.(2)

While all three are necessary for good coatings performance. It is the last component, the removal of invisible contaminants and removal of detrital material, that demands water and which requires REFORM and CHANGE.

Waterjetting CLEANS THE EXISTING PROFILE AND OPENS IT.

Coatings manufacturers understand that when you use water you get better adhesion. In addition, the removal of the invisible contaminants gives you better performance.

Water cleans from the bottom up. Dry Blasting makes changes the surface from the top down. This leads to two distinct visual appearance.

Abrasive blasting changes the surface from the top down; water cleans the surface from the bottom of the pits up. The micro profile is fractal for waterjetting. These two cleaning methods produce very different visual appearances. The industry has long accepted that the bottom of pits and crevices will contain contaminants. With the advent of competitive waterjetting and water/abrasive systems, the surface can be opened for coatings and the crevices can be cleaned.

2.1 Areas which require resolution

How much black oxide, carbon stain, or adherent coatings can be left on the surface after cleaning is to be determined by agreement between the owner/operator, contractor, and coatings manufacturer. The economics of the project forces discussion of compromise. Marginal projects may just not justify removal of all of the coatings. The economics force adoption of some level of cleanliness between the brush off blast and the commercial blast definitions. Waterjetting can selectively remove coating layers.

The use of both terms "hydro blasting" and "waterjetting" causes some confusion. Waterjetting is defined for the Water Jet Technology Association (WJTA) and the NACE/SSPC. Hydro blasting is a generic term used for processes ranging from low pressure water cleaning to ultra high pressure waterjetting.

The biggest hurdle of using the written and visual standards throughout the international commercial community is the use of conflicting numbering systems and the difference in the details of the written definitions. Coatings manufacturers are asked to warrant their product throughout the world. Not withstanding that the details of the definitions vary, it is a practical matter that coatings manufacturers have adopted nominal equivalency between the various standards. (Table 1) This "equivalency" table is <u>not</u> adopted by any of the standards agencies.

3. OTHER CURRENT ACTIVITIES

NACE and SSPC are working to adopt and finish their limited reference photographs for water jetting surface preparation. As an initial step, the joint SSPC/NACE Task Group is balloting the International Coatings photographs. Appropriate language modification has been made to resolve the difference between the written definitions for WJ-2 and WJ-3 and the visual appearance which were prepared with ISO 8501 definitions.

ISO has designated the Task Group chaired by the United States and NACE as the site for future standards concerning waterjetting.

4. ECONOMICS

It is a false assumption that waterjetting will cost more money than abrasive blasting. Let me share with you a three examples of **cost savings** which were reported in recent publications.

These examples represent three different ways water can be used.

4.1 Slurry Blasting

In a Navy Trident Submarine refit yard, when removing lead based paint, a modern SLURRY Blasting system was used to remove lead paint. The nearly complete elimination of fugitive dust emissions has allowed TRF, Bangor, 100 percent capabilities for open blasting in dry dock. "We were able to finish the project in just 14 days. This saved 10,000 man hours and nearly half a million dollars."(3) TRF commented after the USS Michigan was blasted with slag and Blastox® using the Torbo® System. Taking lead based paint off a submarine.

4.2 20,000 psi Water Jetting- HP Water Jetting(4)

On a lead based paint removal job off a dam for the Lower Colorado River Authority in Texas- the bid estimate for dry abrasive blasting was $700,000; the water jetting bid was $400,000. It was completed for $411,000 because of bad weather.

4.3 UHP Water Jetting

The ability to have painting, welding, and engine repairs occurring at the same time as the coatings removal is a major economic benefit. In a recent experience at Detyens Shipyards Inc., the *Sirius* was stripped with UHP WJ (WOMA equipment)..... Jack Smith of Detyens estimated that the UHP WJ saved Detyens approximately 560 hours of cleanup wages. Detyens did not have to purchase abrasives at $30,000. Detyens did not have to pay for disposal of the abrasives at $14,000. They did not have to spend 5-7 days to wrap the vessel, They did not have to spend 4-5 days unwrapping the vessel.(5)

These are THREE different processes for using water, each of which is providing costs savings.

5. ENVIRONMENT/ HEALTH AND SAFETY ISSUES

5.1 Lead Based Paint (LPB)

These are the base reference points used by OSHA in 29 CFR 1926.62.

Representative TWA (8) Exposure Levels in $\mu g/m^3$
Absent Engineering Controls and Respiratory Protection by Construction Industry(6)

Construction Activity	Exposure Level Used to Specify Controls ($\mu g/m^3$)
open abrasive blasting	23,680
open abrasive blasting in full containment	37,300
vacuum blasting	558

hand scraping	96
Removal and replacement of Building Components	9

The Action Level (AL) is 30 $\mu g/m^3$. If you work in an area at or above 30 micrograms per cubic meter of air, your employer must give you medical surveillance and training in the hazards of working with lead.

The Permissible Exposure Limit (PEL) is 50 $\mu g/m^3$. Your employer is not allowed to let you breathe in more that 50 micrograms of lead per cubic meter of air. This limit is for the average amount of lead in the air over an 8-hour day (TWA). If you work in an area with more lead in the air than the PEL, your employer must reduce your exposure. Work practice controls and engineering controls must be used to reduce the airborne lead exposure, prior to relying on respiratory protection.

When dry abrasive blasting is being used in lead-based paint (lbp) activities, toxic respirable dust is a major culprit. Precautions are taken to take control dust and protect the workers from ingesting the lead. When water is used, the particles are wetted, and fall down to the lowest spot. Containment is used to direct the water to the impermeable collection areas. Water really excels in industrial lead hazard control. Air monitoring is replaced by water containment.

5.2 Removal Methods Incorporating Water

Many paint removal methods incorporate water usage. These range from mostly solid abrasives with very little water to those with is richer in water/abrasive mixture to methods utilizing water alone.

The first method, to examine is an abrasive process which uses equipment that just wets the abrasive, consuming less than a pint of water per minute. The wetted abrasive is moved through the blast hose and nozzle by compressed air. The objective is to wet the particle, not wash the surface. This is commonly called WET ABRASIVE BLASTING, or Slurry Blasting. To demonstrate this further, two project examples are provided.

5.2.1 Wet Abrasive Blasting in U.S. Navy Trident Refit Facility Bangor(7)

In 1994, both dry abrasive and Torbo® wet abrasive blasting were performed at the Trident Refit Facility (TRF) Bangor in Silverdale, Washington. The exposure potentials adjusted for 12 hour shifts are below the time weighted average (TWA) and associated Actions Levels (AL) for Lead at 7$\mu g/m^3$ maximum, Copper, Chromium, and Cadmium. Both personal and area monitoring results was conducted. The spent grit with Blastox® was non-hazardous. In dry abrasive blasting, the exposure potentials adjusted for a 10 hour shift are above the (TWA) and associated AL for lead at 540 - 6,352 $\mu g/m^3$, copper, chromium, and cadmium.

The Torbo® System has been used to remove paint containing in excess of 1% lead on the exterior hulls of submarines in 1994. The nearly complete elimination of fugitive dust emissions has allowed TRF, Bangor, 100 percent capabilities for open blasting dry dock. They sand blasted and painted approximately 70,000 square feet surface area in a 15 day time frame- a significant event achieved by using the Torbo® System. The removal rate varied between 120 to 150 square feet per hour. The consumption rate of blast media per square foot was approximately 4 pounds of blast media in place of the normal blasting condition of 10-12 pounds. A significant reduction in the waste stream is realized.

"We were able to finish the project in just 14 days. This saved 10,000 man hours and nearly half a million dollars."(8) TRF commented after the USS Michigan was blasted with slag and Blastox® using the Torbo® System.

5.2.2 Wet Abrasive Blasting- Huey P. Long Bridge- New Orleans, demonstration.

On December 4 through 7, 1995, Torbo Tech, Inc. demonstrated lead based paint (LBP) removal on the Huey P. Long Bridge in New Orleans. The cleaning averaged 125 square feet/hour even on lattice work. Ground containment was impervious black plastic sheets. 85% Geoscreen Containment tarps, supplied by Eagle Industries, were draped from the structure to direct the wetted abrasive/paint chips into the ground containment. The containment is best described as permeable materials, flexible containment, natural input air, open seams, with no controls on exhaust-- not the expensive, rigid, full containment system used in open air abrasive blasting. The wetted grit and paint debris was dry by the time it fell from the superstructure to the ground collection site.

SiteAir	Monitoring Results (μg/m3)
Blaster, inside containment	45.7, 159.6, 224.2, 305.2
Laborers, outside containment during blasting	16 samples, 14 are below the AL, two samples at 40.1 and 52.7 $\mu g/m^3$
Laborers, during clean-up	10 samples, 8 are below the AL two samples at 42.0 and 135.4 $\mu g/m^3$

Though not as good as in the first example these numbers are still are impressive compared to dry abrasive blasting. There was more exposure during sweeping and removal of the tarps and screens as the spent paint and abrasive were dry. Clean-up was performed by rolling the plastic sheet to gather debris to one area and then dry sweeping and shoveling. The increase in air borne particle indicated that the dry spent abrasive/paint should be wetted while sweeping and cleaning was occurring.

Essentially these airborne lead exposure numbers for wet abrasive blasting are comparable to vacuum blasting. The generated paint chips and abrasive was approximately 3 pounds/ square foot. Regulated area samples were collected at the edge of the work area in the direction of the prevailing wind. All results were below the Action Limit for airborne lead., so that workers and observers outside the regulated areas were not impacted.

The TCLP testing results indicate the waste generated was non-hazardous. This waste was beneficially reused in cement kilns.

5.3 Air/water/abrasive blasting

Air/water/abrasive blasting is a cleaning method in which water is injected into the air/abrasive stream generated by conventional air-pressurized abrasive blasting equipment. Water/abrasive blasting is a cleaning method in which the abrasive is injected into the water stream of a hydraulic pump. All of these methods are sometimes called Slurry or Wet Abrasive BLASTING. The abrasives can range from hard grit and sand to soft, soluble media.

22. Wet Abrasive Blasting with Soft Grit (Bicarbonate or other soluble abrasives)

A popular method LBP removal combines water and soluble soft abrasive such as sodium bicarbonate. The abrasive dissolves to leave just the water and paint for collection and disposal. The paint is removed from the water during the collection. The water must be tested for lead levels, but typically only the paint solids (and filters) are hazardous waste. Water is disposed as industrial waste water.

These systems can be configured as water systems to which abrasive is added at the nozzle or as dry abrasive systems where the water is added at the nozzle. Several different configurations are available ranging in water consumption of 1 quart to 8 gallons per minute and water pressures of 25 to 4500 psi.

As a particular example, the Jet Stripper® soft abrasive blasting systems uses a water input of 200 to 5000 psi at a rate of 0.5 to 1 gallon per minute and 0.5 to 1 pound/minute of grit. It is a coaxial arrangement with the water being added at the nozzle. The abrasive is carried to the nozzle by compressed air. In 1991, a Jet Stripper® system using EcoShield™ was used to remove red lead primer and alkyd paint (average thickness eight - twelve mils) from an oil storage tank. Commercial hard grit at 5-10% addition was added to remove mill scale and achieve an anchor pattern. No enclosures were used. Samples sites were located downwind from the work area. Total solid particulates were collected. The results were 2.6 $\mu g/m^3$ for a 4 hour period on one day and 1.3 $\mu g/m^3$ which is well below the PEL and AL.

White Metal also supplied data for November, 1993, in removal of LBP from a generating station. The personal levels ranged from <2 to 3 $\mu g/m^3$. " At these exposure levels, the painters are adequately protected with half-mask respirators with HEPA filter cartridges and disposable rain suits." states the manager of industrial hygiene. "Plant employees working around the blasting area are not exposed to any dangerous levels of lead. In addition, paint debris landing in areas outside of the polyethylene-lined containment area are promptly picked up by sweeping with water mist to suppress the dust."

5.4 Low-Pressure Water Cleaning

Low-Pressure Water Cleaning (LP WC) is cleaning performed at pressures less than 5,000 psi (power washing).

Although I do not have direct knowledge or field case histories LPWC (power washing) for LBP activities, I am aware that in Canada, LPWC is used to wash bridges, plants, and tanks where LBP is present. The loosely adherent paint comes off in larger chips, rather than as small particles.

In some cases where the chips are large, the governing body has ruled that this is an acceleration of the natural weathering process and the effluent water/paint does not have to be captured. If the removed paint is powdered or small so that there is a clear action that the water flow is removing more than the loosely adherent paint, then it must be contained.

LPWC is an excellent way to remove loose paint. Even if no LBP is present, the Pollution Prevention Act requires that the run-off water from industrial activities be tested for oil/grease and suspended particles. A sump pump, filter unit, and holding tank might be required to prepare water for discharge into a sanitary sewer or for reuse.

In cases where oil and grease could be a problem, an oil/water separator might be required. The water must be tested for lead if lead is suspected. Approximately 90 percent of the heavy metals are contained in the solid particles. The Federal hazardous limit for the water is 5 milligram/liter (5 ppm), but different municipal requirements vary. For example, the Seattle Metro Sanitary Sewer permit limit is 2.0 mg/L;(9) The Los Angeles County Sanitation District has a limit of 40 mg/L for a discharge going into the sewer which will lead to the treatment facility which is over the Federal hazardous limit.

5.5 High-pressure Water Jetting

High-pressure Water Jetting (HP WJ) is cleaning performed at pressures from 10,000 to 25,000 psi. In most pump configurations the velocity increases to the speed of sound at 10,000 psi. A true fluid jet is being formed. This velocity increase starts to change the amount of cutting and cleaning which can be accomplished by water alone.

Several contractors use HPWJ around 20,000 psi to remove LBP in varying amounts. The LBP is often removed from a tank in a plant facility. In this case, the effluent water can typically be commingled with all the other industrial water being used in the plant and sent to the plant treatment facility.

Petrochemical Tank Cleaning Cavi-Tech[5] owns and operates several different pressurized water cleaning systems. As a contractor, Cavi-Tech matches the equipment to the job specification, and has cleaned millions of square feet of coatings. Two LBP projects are described in which Cavi-Tech used water alone with cavitating, rotating nozzle with multiple orifices, around 20,000 psi at six - ten gpm.

In April, 1995, Cavi-Tech removed eight mils of lead primer coat and top coat from a petroleum storage tank near Los Angeles,. Minimum scaffolding was required, with two blasters on a mobile unit. This petroleum tank was located in a yard with several other storage tanks.

The first two days, general air monitoring was conducted up and down wind, with a result of < 0.25 $\mu g/m^3$. There was no need to erect containment screens around the tank. (See Picture 1). No paint dust is in the area, just water mist. Personal monitors on the blasters had a level of 3.31 $\mu g/m^3$ lead on an 8 hour TWA. The blasters wore half mask respirators.

The spent water was collected in a berm extending about 20 feet from the tank's edge. The effluent water was immediately filtered through a coarse bag filter and placed into a 6,000 gallon tank. Two tanks were used for filtered, reclaimed blast water which was allowed to settle in one tank and used for blasting on alternate days. It was filtered further to protect the pump from solids. After three days, the filtered blast water contained 0.17 mg/L; at the end of the job, the level was 0.32 mg/L lead-- well below the hazardous level of 5 mg/L. Less than 8,000 gallons of effluent water was disposed as industrial water by a waste hauler at around $0.20 /gallon. The total footage is estimated at 5,200 square feet. Under Cavi-Tech's procedure, they would have about 12,000 gallons of effluent industrial water, even if the job were several times larger.

The water had to be hauled from the site as there was no connection to the L.A. County Treatment facility; otherwise, it could have been sent directly to the POTW. The only hazardous material for disposal was the filter cartridges.

Lower Colorado River Authority Dam.(10) HPWJ was used to remove the LBP on the Wirtz Dam in Marble Falls, TX in June, 1995. This job essentially have to be completed during the month of June. The Lower Colorado River Authority rejected dry abrasive blasting because the low bid was nearly $700,000 which was nearly twice the project budget. An air tight containment would have been required.

The LCRA considered HPWJ at 20,000 psi as it could remove the loose coatings; would profile the remaining primer to two mils; and would permit intercoat adhesion value of 400 to 600 psi.

Suspended scaffolding and containment was erected in three sections--- partial erection in the first section for worker comfort, rest, and "clean" area; water jetting in the second section; and painting and priming in the final section. Most of this HP WJ was done when the weather was around 100 ° F, so heat stress was monitored.

The working configuration was engineered in a "closed-loop" system so that blasting water was recycled after filtration and settling. The spend blast water and paint entered a sump, was pumped through filters to a settling tank, then through three micron filters before going back to the water blasting pump. The daily averages for lead in ambient air were less than 0.18 $\mu g/m^3$ lead on an eight hour TWA, well below the NAAQS. Soil sampling indicated no increase in the levels of lead particulate. Personal air monitoring ranged from 0.00 to 19.8 $\mu g/m^3$ lead on an eight hour TWA. The workers wore half-mask respirators with HEPA filters. The final filtered water was non-hazardous at 0.306 μg/L lead level. The water was disposed at a publicly owned water treatment facility.

The original estimate of less than 1 ton of hazardous waste from the paint and filters rose to 5 tons by the end of the HPWJ project. The water was drawn from the lake for use in the closed-loop system. A flash flood during the project stirred up silt in the make-up water. The silt clogged filters that separated LBP debris from the recirculated water, necessitating more filter changes than originally anticipated. The filtered solids were disposed as hazardous waste.

The total cost of the surface preparation and coatings application was $411,235 with an average cost per square foot of $7.48. The original project budget was $400,000.

6. ULTRA HIGH PRESSURE WATER JETTING

Ultra High Pressure Water Jetting (UHP WJ) is cleaning performed at pressures above 25,000 to 30,000 psi. Although the UHP WJ operates at a higher pressure than HP WJ, it uses less gallons per minute. The choice is to let the mass of the water (gpm) or the pressure do the work. The cost for equipment increases as the horse power and pressure increases. Contractors use both HP WJ or UHP WJ for paint removal.

UHP Projects, Inc. and Valley Systems, Inc. are two contractors who have removed millions of square feet of coatings with 35,000- 40,000 psi water jetting with nozzles operating around two to three gpm.(11)

UHP Projects, Inc. can reclaim and process the water in a system that can be tailored to the client's specific needs. The reclamation system captures the removed coatings, rust scale, and solids for disposal. On one project each employee averaged 892 hours. The prejob blood lead level averaged 4.77 μg/dL; the post-job blood lead level averaged 6.76 μg/dL. The OSHA permissible Blood Lead Level is 40 μg/dL. Ambient air monitoring averaged .17 $\mu g/m^3$.

After recirculation and filtration of the jetting water for ten day, the lead level was 0.473 mg/L, compared to the RCRA defined level of 5 mg/L. The filtered water can be disposed into a publicly owned waste treatment facility.

Lead Paint Removal From Cranes in a Marine Port.(12) The Port of Houston has six gantry cranes which are 12-15 years old. The existing coating contains 0.1 to 20 percent lead. Hard abrasives were excluded because of the potential for damage to bearings and motors, and the labor associated with changing them and the revenues lost during unloading operations while a crane is out of service.

Sodium bicarbonate was the initial choice for blast media and would most likely have performed adequately. Circumstances, however, dictated UHP WJ at 40,000 psi to be a clear choice for removing paint from these 60 feet tall cranes due primarily due to the lessened containment requirements. Flash rusting was removed by pneumatic angle sanders and abrasive pads. Approval was granted for the use of a rust inhibitor during the preparation of the second crane.

The outer containment consisted of shrinkable plastic wrap anchored by wood ties. A dike of approximately 50 ft by 100 ft was used on the ground as primary containment for water and paint chips. No walls or ceiling were used because the water weighed down the paint chips so they didn't drift. Air borne lead monitoring for the blaster was $<0.99\ \mu g/m^3$, which is well below the OSHA permissible level of 50. Airborne lead and nuisance dust monitoring were below requirements.

The water and sludge (4.4 mg/L lead) were vacuumed daily with HEPA filters and pumped into a three-stage, 3,200 gal water separator to remove the lead paint chips. Then the water is pumped through a resin filter, pH neutralized and transferred to a covered holding tank (0.26 mg/L lead, 4,600 gallon) before discharge to a waste treatment plant. The paint chips in the waste collection tank sludge contained 0.41 mg/L lead - which is non-hazardous. The waste containment in the soiled area of the containment floor was 4,000 ppm. That waste was assumed and disposed of as hazardous. The shredded plastic in the primary and secondary containment, and the heavy metal filter catalyst was below 5 mg/L and considered non-hazardous.

7. ACKNOWLEDGMENTS

The mention of specific products or companies by name does not represent, nor is it to be construed, as an endorsement of any individual company or product. The material is provided for illustrative purposes only. The opinions expressed in this paper are not intended to be, nor should they be interpreted as a replacement for professional legal advice. Data, literature, and examples have been generously supplied by several individuals and companies. Dr. Frenzel extends her thanks to the water jetting industry for their assistance and cooperation.

Dr. Frenzel would like to acknowledge the continuing support by, and discussion with: Aqua-Dyne, Inc., Butterworth Jetting Systems, Flow International, NLB Corporation, WOMA Corporation, Aulson Co., Cavi-Tech Inc., Fluidyne, Resto Tech Ultra Pressure Systems Ltd., UHP Projects Inc., Valley Systems, Dr. Brenda Holmes- NAVSEA, and Mr. Eugene Bossie-SUPSHIP-San Diego.

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Table 1

Nominal Equivalency of Blast Cleanliness Standards for Visual Contaminants

	NACE	SSPC	ISO	NACE/SSPC
"White Metal"	No. 1	SSPC-SP-5	Sa 3	WJ-1
"Near White"	No. 2	SSPC-SP-10	Sa 2.5	WJ-2
"Commercial"	No. 3	SSPC-SP-6	Sa 2	WJ-3
"Brush-Off"	No. 4	SSPC-SP-7	Sa 1	WJ-4
Solvent Cleaning		SSPC-SP-1		
Hand Tool Cleaning		SSPC-SP-2		
Power Tool Cleaning		SSPC-SP-3		
Pickling		SSPC-SP-8		
Power Tool Cleaning to Bare Metal		SSPC-SP-11		
Visual Standards for Abrasive Blast Cleaned Steel		SSPC VIS 1-89		
Visual Standards for Power Cleaned Steel		SSPC VIS 3		

Nominal Equivalency of Blast Cleanliness Standards for Visual Contaminants (cont.)

	Navy	NACE/SSPC	Int. Paint		Cavi-Tech
"White Metal"		WJ-1			
"Near White"	C HB 2.5	WJ-2	SB 2.5	HB 2.5	CB 4
"Commercial"		WJ-3	SB 2	HB 2	
"Brush-Off"		WJ-4			CB 1 to 3.5

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Paper 54

BUILDING A BUSINESS IN WATERJET CUTTING/MACHINING

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ABSTRACT

Waterjet technology offers a variety of new solutions to old cutting problems. But Waterjet technology is not simply technology for technology's sake. New and existing applications are pursued for economic purposes, the intent being to profit from the operation of waterjet cutting equipment. Intense competition among various new and traditional cutting methods results in the survival of the fittest, the fittest being those companies that develop a strategic plan, including a sound business plan, product development strategies, and appropriate training on the equipment. In unique applications, research is required to obtain maximum cutting efficiency. The owners of an existing business, as well as those contemplating a new venture usually have general machining expertise. This paper examines the other strategic areas that comprise the comprehensive business plan.

Organized and Sponsored by the Waterjet Technology Association.

1. INTRODUCTION

The cutting industry, although seemingly very specific, has a vast array of applications. Cutting needs range from the sculpting of a delicate glass mosaic to the stalwart shearing of armor plating used in the manufacture of tanks. Within the cutting industry, waterjet cutting is steadily increasing its viability (Summers, 1992).

Waterjets, noted for their ability to cut quickly and with a high rate of accuracy, also reduce the cost of materials as a result of nesting capabilities. The waterjet's quick and effective setup allows for rapid production of prototypes and problems associated with heat affected zones are eliminated. Savings are realized with a reduction in secondary operations, often with little or no finishing operations being required. And because the technology is machine driven, rather that labor intensive, savings result from a reduction in the labor force.

These advantages are some of the major reasons that the waterjet cutting industry is experiencing such dynamic growth. It is an industry within an industry and has the potential for rapid growth and a vast client base. It is expected that over one thousand waterjet systems will be introduced in the next year. To seize these opportunities requires business planning, as well as specific training in waterjet technology.

Attention to a myriad of details is required before the first drop of pressurized water jettisons forth from the cutting head. Depending on the size of the shop, a mechanism and the expertise to collect and analyze these details may or may not exist. Regardless, it is critical that the business function of waterjet cutting be addressed.

2. THE BUSINESS PLAN

The purpose of any business plan is to examine a wide variety of parameters that determine the success, or failure of any venture. Very few success stories are a result of pure luck. Instead, appropriate planning and foresight are required, particularly in this industry where technological advances are realized each day.

2.1 Market Research - The Four P's

Critical to any marketing plan are Product, People, Place, and Price. An investor must be aware of; the product or the particular cutting application for which the waterjet will be used; the people seeking cutting services; the place, or location, of the cutting service; and the price of the cutting service. This information provides an organization with a map, or an understanding of their goals.

Understanding this same information with respect to a competitor is also advantageous. When compiled and analyzed properly, this information becomes a viable predictor of the organization's competitive position. The answers to questions such as, "What will increase/decrease my market share?" and "How quickly can they react to my changes?" become more apparent.

2.1.1 Product and People

The wide variety of applications for waterjet cutting brings to the investor a wide range of potential clients. A conscience decision is required on whether to focus on a specific cutting need, such as cutting stone, paper or rubber, or targeting a broad spectrum of clients.

There are two critical reasons for targeting a particular subset of the cutting industry. The first relates to the type of equipment which will eventually be purchased and the environment in which it will be set up. The second reason relates to the client base and how they will be targeted.

Waterjet cutting systems fall into two categories, abrasive waterjets and waterjet only (no abrasives). Abrasive waterjet systems are appropriate for materials such as alloys, glass, tungsten, wood, composites, invar, steels, laminates, stone, plastics, stainless steel, and Inconel. Waterjet only is utilized to cut softer materials such as carpet, foam, rubber, plastics, wood, food, and leather. It can also be used in blasting, or coating removal. Targeting one type of cutting simplifies startup time. The time spent in becoming proficient at cutting particular materials is reduced when fewer materials are used. This does not eliminate the opportunity for diversity in the future. Water only waterjet cutting systems can be upgraded to included cutting heads and abrasive delivery systems that allow the machine to cut harder materials. The converse also holds true, abrasive cutting heads can be replaced with water only and the abrasive can be eliminated to cut those materials that require only pressurized water.

The selection of a target group of clients, or people, also determines the manner in which your product will be conveyed to consumers. Communication with potential clients is one of the most important and flexible links between an organization and its markets according to Bagozzi (1986). In other words, how you will advertise. Knowing the materials to be cut allows companies to effectively channel their efforts into activities such as direct mailings, personalized phone calls and faxes, as well as tailoring incentives. It also assists in selecting purchased databases and in advertising strategies for industry papers and magazines.

2.1.2 Place

The location of the waterjet cutting facility is also critical, particularly for materials that are large or heavy and where shipping is a major component of the cost of producing an item. If the location is close to the targeted clients and/or close to the delivery location, significant costs are saved as well as time. Storage of materials before and after processing can also be an issue related to the placement of the facility.

Marketing decisions can be made with the help of economical Geographic Information Systems (GIS). Such a project requires collection of appropriate data and plotting it for a specific geographic location. Philadelphia and its surrounding cutting industries was used as an example. A survey of cutting facilities in the selected area (eastern Pennsylvania) and their locations was compiled. There were over 40 types of businesses identified. Table 1 lists fifteen of these along with their locations. The information from that survey comprised the database that was accessed by the mapping programs in the GIS. A map was generated marking each facility. Further analysis was enabled by limiting the geographic area under consideration. In Figure 1, Philadelphia is shown, as well as the area within a radius of 25 miles. All potential competitors appeared on the map.

Compilation of this information is time consuming, but the final graphic representation is undeniably helpful in assessing issues related to competition. It provides information on "who" the competition is, as well as where they are.

2.1.3 Price

A desirable product, potential clientele, and an enviable location comprise much of the picture, however, pricing remains a key factor. Costing information must include CNC drafting time, material costs, shipping costs, actual cutting time as well as the overhead cost associated with the facility. Additional details are examined in the Financial Plan section.

2.2 Environment Evaluation

Once an investor/owner has decided the basics of Product, People, Place and Price, it is time to address the physical aspects of production. The site may be an existing facility that already has a waterjet, an existing company that has no waterjet, or a new site currently being designed or built. The critical factor in each case is to maximize the potential of a waterjet machine.

2.2.1 Site Evaluation/Preparation

A concise analysis of an existing site requires as much time and thought, if not more, than of a potential new site. Existing sites often have constraints that are costly to correct and can potentially result in increased operating costs. New sites benefit from well designed placement of both the main and peripheral waterjet equipment. Areas to examine in a new or an existing site include: power requirements; water supply; drainage; computers; room environment; and sundry equipment and tools.

The subject of power is comprised of several components. The availability of power and location of the power points are the most obvious considerations. It is critical however, to also consider backup power supplies for both computers and CNC controls as well as protection of all units from power surges. Future power requirements should also be anticipated.

As the term waterjet implies, a water supply is a vital element. Water must be readily and economically available or consideration must be given to a closed loop system. Evaluating which method is most appropriate allows for the cost associated with the water to be included in the fixed and variable costs of operating the system.

Where water is relatively accessible, heated water from the cooling system can be cooled and discharged into the facility's normal sewer system. Water from the cutting process requires removal of solids which may include abrasives and particles from the material that was cut. Disposal of this water is subject to local ordinances and normally requires testing before it is eliminated. Closed loop systems reuse the water. Although more expensive, they eliminate problems associated with restricted water supplies and disposal.

In addition, the water supplied to the waterjet system must meet certain standards which are specified by the manufacturer of the equipment. Waterjet systems require water that is free of any type of foreign substances. Treatment of the water may require the use of a softener, or subjecting the water to reverse osmosis or a deionization process. Testing the water, often done at no cost by the manufacturer, eliminates the risk of incurring additional unknown costs prior to using the equipment. Failure to meet these standards will cause an increase in maintenance time and costs, as well as downtime.

An integral part of the waterjet technology is the computer which controls it. Consideration must be given to is physical location in respect to the cutting table. It too, requires a power supply, should be readily accessible and located in a place that offers protection. Issues arise regarding the existence of appropriate computer software or the necessity of purchasing new CAD/CAM software. Configurations for the computer presents all types of options, from the stand alone application to networks of systems. Thought must also be given to backup methods. Operating any computer system without an effective backup procedure poses a serious risk to the integrity of the software.

The physical environment is critical. A clean room and adequate space surrounding the CNC table, pumps and bulk feed hopper is preferred. A lack of space can cause major delays in maintaining equipment, loading abrasives, and setting up and removing material before and after the cutting process. Tools for the maintenance of the equipment must be available as well as apparatus to clean the machines and materials when necessary.

As in any machining project, there are sundry equipment and tools that are a requirement. So too with a waterjet system. Although waterjet systems are noted for their ability to cut a finished edge, there are still cases where materials need to be handled and prepped before and after the cutting occurs. A basic list of associated tools would include: a compressor (30 - 40 cfm), a vice, overhead cranes, general hand tools, grinders, fork lift, welding machine, wrenches, a pallet jack, and a cutting torch.

2.3 Equipment

More often than not, equipment, rather than a comprehensive business plan, is the driving force behind the goal of establishing a waterjet cutting operation. In some cases, machines are already installed and under-utilized, in other cases, it is the allure of the technology of waterjet cutting that is drawing a potential buyer. Investors find themselves with an existing machine or the desire to purchase a new machine and then backstep to create the business plan around it. Whatever the case, the equipment is the heart of the plan. It is the engine in the car, it must provide the power needed to complete the task, be easy to operate and accessible for maintenance.

The type and capacity of the waterjet system will be determined by the main type of item to be cut. Obviously, larger, hard materials require larger cutting surfaces as well as the capacity to exert more cutting power. Consideration should also be given to the main secondary item that will be cut. A secondary item may be a major contributor to steady income. The number of machines required will depend on the desired production capacity and the ramifications of downtime on a machine. Assessing the desired cutting tolerances and the need for accuracy when making repetitive cuts will aid in selecting an appropriate machine.

Attention must also be given to peripheral equipment, including clamps and jigs required while cutting an item, and clamps, forklifts, or cranes needed to handle material before and after cutting.

3. THE FINANCIAL PLAN

The best of marketing strategies and product innovations comes down to the financial elements. In order to accurately assess the feasibility of waterjet applications, a detailed investigation of the associated cost must be developed.

3.1 Financial Analysis

Operation costs of the waterjet systems include both fixed and variable costs. Fixed costs are those costs that are one-time expenditures or those that remain constant regardless of the level of utilization of the machinery. Table 2a lists fixed costs that require consideration. Table 2b provides variable costs, those costs which vary depending on the use of the machine.

3.2 Pricing and Cost Generation

Pricing is a key consideration in maintaining a profitable, yet competitive profile (Dudick, 1991). Fixed and variable costs can be summarized to produce an hourly rate for a waterjet machine. In addition to that cost, consideration must be given to job specific costs. A comprehensive quotation form should be developed to collect the job specific costs.

The form should specify the quantity of the item to be produced, the size of the item, the material to be cut (including thickness), the supplier of the material (will the shop or the customer pay/provide the material), and the time frame in which the job needs to be completed. Details must include any special aspects of the material and finished product such as cutting tolerances, polished surfaces, frosting limitations, importance of vertical edges, the quality of the edge finish, and the susceptibility of the material to rust or distortion by water.

CNC drafting time needs to be determined and will vary depending on whether the CAD work is done in-house or contracted out. Cutting time for a product must also include the time for pierce and lead-in cuts. Add to the cost, the time spent handling the materials before and after cutting, as well as packing and shipping costs and the time and cost spent on secondary work.

It is prudent to request sample materials prior to the start of the project. The quote can be made contingent upon approval of the sample material test results. On any quotation, reserve the right to modify the price if any of the parameters change. Also include in the price shipping costs if appropriate and tax. Explicitly state the payment terms and provide an expiration date for the quote.

3.3 Cash Flow Analysis

Cash flow, often one of the last factors to be examined, can be the most devastating blow that results in the failure of a business. Cash flow, the ability to have cash on hand to meet immediate needs, must be assessed. Using the information from much of the aforementioned analysis, the investor can evaluate the rises and falls of income and expenses. Simple, economical software can be purchased to assist in the collection and analysis of proposed cash flows.

4. OPERATIONAL STRATEGIES

Waterjet cutting jobs are classified into two types, repetitive jobs and custom work. Both provide benefits, as well as limitations.

Repetitive jobs, those materials and parts that are cut in large quantities or on a repeated basis, are associated with certain savings. There is little effort in the CAD stage and limited testing time after the initial setup. The risk of unknown factors that might interrupt production, such as difficulty cutting a new and untested material are significantly reduced. Often repetitive jobs are ideal candidates for nesting of parts. The repetitive nature of the job results in lower supervision of the material being cut, thereby reducing manual labor. Production then becomes machine driven rather than relying on labor.

In terms of income, the repetitive job is a major contributor when used as fill-in work between other jobs. If repetitive work is the only work, it provides a steady contribution to income. The limitation is that the income generated is based on an hourly rate and obtained only when the machine is in operation. It is currently estimated to generate $120-$140/hr.

Custom work, on the other hand, allows for a very high rate per hour, in excess of $160/hr. Often the cutting is only ten to twenty percent of the value of the work. The high hourly rates contribute dramatically to income and the custom jobs are ideal when scheduled alongside repetitive work.

However, the nature of custom work has several deterrents. It normally requires substantial CAD time, as each job has to be programmed separately. It also consumes time in testing. Custom jobs often utilize expensive materials which greatly increases the risk if errors occur or problems arise.

Diversification, the ability to spread out your activities, is an often employed strategy in any industry. When implemented appropriately, it reduces financial risk, thereby helping to insure the viability of the operation. When done incorrectly, resources are often spread so thin that the risk of insolvency is increased. Waterjet technology allows the security of specialization, an operation can become proficient in the specifics of waterjet cutting, yet the flexibility of the technology allows for diversification. A waterjet shop could service a variety of cutting needs, fully optimizing their equipment. This variety could include cutting diverse types of materials and/or combining repetitive and custom work.

5. STAYING ON TOP

Three options in the dynamic waterjet industry are; to lead, to follow, or get out of the way. It may appear as flippant advice, but careful consideration shows its merit. Just "following" is a job in itself. It requires someone to keep abreast of new applications and improved methods in an industry where technological advancements are routine and new applications are continually forthcoming. To actually lead necessitates even more effort in research and development, and foresight. It implies risk and with it the potential for economic success or failure. At a bare minimum it requires basic training to acquire the skills necessary for a waterjet operator.

Training for the technology comes from two major sources, the manufacturer and privately owned waterjet technology consultant services. The training furnished by manufacturers provides overall instruction in the operation and maintenance of the purchased machine. Discussions and demonstrations are directed at the machines and materials specific to the waterjet site. Such training is an investment of time that should rate as a high priority. Without it, the key asset, the waterjet system, may not be used effectively.

Contracted training services provide a broader spectrum of services for both the business administrators and equipment operators. Seminars for administrators includes all aspect of profitably managing a waterjet business. Technical workshops are also provided. In most cases the additional training allows operators to circumvent much of the learning curve associated with the operation of new equipment. The training focuses on optimizing all aspects of an operation.

6. CONCLUSION

Some of us are lucky, fewer of us are not. And surprises, although sometimes enjoyable, often harbor demise. The investor of today requires information, and the ability to assimilate a variety of factors that are well beyond the actual technology that drives a waterjet system. A comprehensive business plan is critical in order to be "a Cut above."

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Table 1. Subset of data used in mapping the cutting facilities in and around Philadelphia, PA.

Type of Business	Pennsylvania							
	Lancaster	Chester	Delaware	Montgomery	Bucks	Berks	Philadelphia	**TOTALS**
Metal Stamping	11	11	5	26	18	9	17	**97**
Steel Fabricators	22	16	12	35	28	28	21	**162**
Machine Shops	84	59	55	118	151	54	71	**592**
Lasers	0	1	0	1	1	0	0	**3**
Marble Natural	0	3	2	1	2	3	7	**18**
Flat Glass	0	1	0	2	1	0	0	**4**
Alloys	0	0	0	2	1	4	0	**7**
Titanium	0	1	0	0	0	0	0	**1**
Aluminum Sheet Plate & Foil	1	2	0	0	0	0	0	**3**
Foundries- Aluminum, Brass, Bronze, Etc.	12	3	1	3	1	5	4	**29**
Aluminum	8	5	1	4	2	4	9	**33**
Plastics-Rods, Tubes, Sheets, Etc.	1	3	1	7	3	5	3	**23**
Aircraft Manufacturers	0	3	1	0	3	0	3	**10**
Plastic High Press Laminates	1	2	0	2	0	1	2	**8**
Gasket Manufacturers	0	0	1	1	0	0	2	**4**
TOTALS	**140**	**110**	**79**	**202**	**211**	**113**	**139**	**994**

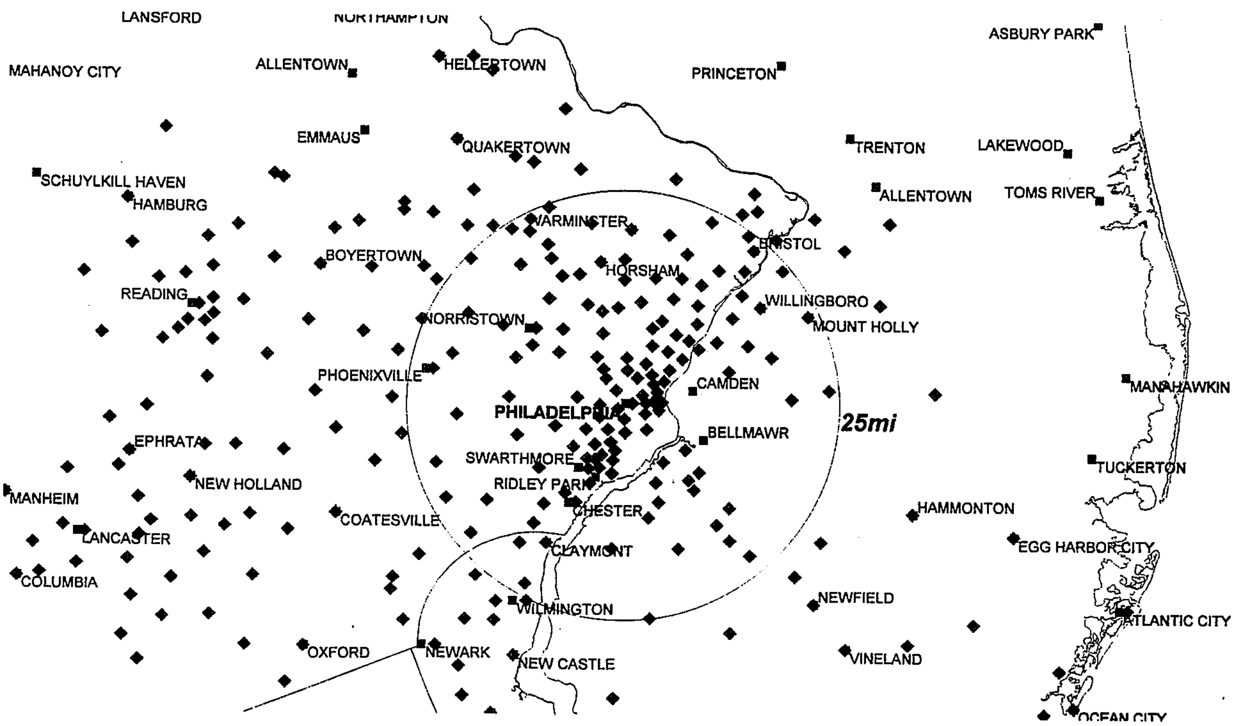

Figure 1. Cutting Facilities in and around Philadelphia, PA. The circle indicates a 25 mile radius.

Table 2a. Fixed Costs associated with the operation of a waterjet cutting system.

Advertising	Installation and Commissioning
Administration	Marketing
CAD Programs	Network
CNC Table	Pump
Computer hardware	Rent
Computer software	Salaries
Compressor	Sludge removal
Electrical Connections	Spare parts
Fax	Tank
Hopper	Water Purification System

Table 2b. Variable Costs associated with the operation of a waterjet cutting system.

Abrasive	Marketing
Abrasive cutting head	Orifices
Abrasive focusing tubes	Phone
Abrasive removal	Power
Abrasive spare heads	Wages
General Administration	Water
General Maintenance Items	

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Paper 55

COMPUTER AIDED MANUFACTURING FOR THREE-DIMENSIONAL ABRASIVE WATER JET MACHINING

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ABSTRACT

This paper presents a systematic approach to computer aided manufacturing for two and three-dimensional abrasive water jet applications. On the turning point to using the abrasive water jet in industrial production lines e.g. in automobile or aerospace industry as well as in machine shops for high quality and precision machining further demands have to be satisfied. With the described system for water jet cutting the actual shape of the tool can be modeled and so the cutting edge contour can be simulated. Using the results of the simulation both linear and angular tool path correction can be realized and an optimized cutting path is generated. Also machining strategies to meet demands for high contour accuracy, high cutting speed and high surface quality are integrated. With computer aided manufacturing production cost can be decreased by reducing labor and machine resources spend for preparation, the machining process can be optimized, and industrial standards for accuracy, reliability and efficiency will be met.

Organized and Sponsored by the Waterjet Technology Association.

1. INTRODUCTION

Abrasive water jets have become a most recent tool in mechanical machining. With its great advantages of geometrical and material flexibility and its ability of cutting hard-to-machine materials the technology is more and more spreading among firms serving as job-shops many different fields of industry for two-dimensional cutting. Here the operators obtain a high level of operator's expertise and qualification. For two-dimensional machining tasks operators do all from programming and selection of the optimal cutting parameters to controlling the machining process with little external support (Henning, 1996)

In three-dimensional machining this can not be done manually. Here computer support is needed. Other than in two-dimensional machining the operator can not generate the tool path using drawing programs. With three-dimensional machining generation of the tool path and selection of the process parameters is much more complex. The cutting conditions in three dimensional machining vary over the entire cutting path with changing cutting angles and work piece geometry. Even when only cutting sheet metal with chamfers the actual cutting depth continuously varies with the angle of attack. Therefore process parameters must continuously be adapted to the actual cutting conditions which cannot be done manually.

For three as well as for two dimensional cutting computer support is necessary. Several applications for computers support in water jet cutting. With computer based process control systems the reliability and the roughness of the process can be improved (Kischkat, 1996). With such also labor cost can be reduced when controlling many machines by one operator. For three shift machining this may be essential. Another field for computer support is the generation of the CAD model. Here approaches to complete process cycles from scanning to machining can be found (Kille, 1995). The third major support for water jet machining is the use of data bases or expert systems to archive and cumulate knowledge and experience to ease the selection of the parameters (Singh, 1995).

The subject that is discussed in this paper deals with the computerized generation of the optimal cutting path with suitable machining strategies. Conventional machining strategies always meant to manually iterate experiments until the demanded accuracy was achieved. Today's approaches using numerical modeling and simulation of the process not only save plenty of machining time but also can optimize the process towards various criteria. With such a tool geometrical accuracy of the cutting edge can be improved and therefore new approaches to precision machining can be introduced.

2. COMPUTER AIDED MANUFACTURING (CAM)

In the last ten years, demands on production processes have severely changed. With the fast growing of global markets, product development delays and life cycles of the products have been reduced. This comes along with the development and using of computers in product development as well as in the production process itself. Besides computer aided design (CAD) that is used for creating computerized models of the work piece, more and more companies employ computer aided manufacturing (CAM) to support the actual production process (Schwarz, 1994)

2.1 What is CAM

There are many approaches to CAM available on the market. Depending on the expected use, they can cover a large variety of functions, from scanning of hardcopy plots or prototypes of the product (e.g. seals) and contour analysis over tool path generation with tool correction up to off-line programming. Other functions such as process simulation, logistic functions, nesting algorithms, and resource planning modules can also be integrated (Kille, 1995).

There is a large number of possible elements that can be integrated in such a CAM system. The most important function, though, is the generation of the tool path. In the past this has been a very time wasting and costly task for the operator. With the use of CAM systems the programming of the NC-code can be done off-line. This saves resources of labor and machining. Also, with simulation tools the accuracy of machining outcome can be improved.

2.2 Different Approaches to CAM

There are already many professional CAM solutions for all kinds of applications on the market. They can be divided into different categories due to the supplier on the market (Warnecke, 1989):

- machine orientated
- application orientated
- process orientated

Machine orientated CAM solutions are mostly sold by the machine suppliers to work with their own machines with their specific controls and specific NC-codes. This machine specific CAM is in many cases only designed to serve this specific brand-name. Adapting it to machines of other brand-names is very difficult or even impossible (Tönshoff and Kader, 1993).

Application orientated CAM solutions are designed to serve special jobs. They consist of modules that support the user with his special demands. Since they are designed for this application they can cover the whole process from design to manufacturing. For rapid prototyping e.g. all modules from scanning to programming and control of the machining process are available (Rauh, 1994).

Most CAM systems on the market consist of a basic program to supply the global functions as e.g. graphics or import and export devices and process specific modules. Often also associated with a CAD system, the program provides all functions the operator or programmer needs. Such solutions are also capable to serve as an integrated system for all tooling methods (milling, turning, cutting etc.) for a whole machine shop. The usability of the program here depends on the programming effectiveness and on the quality of the single process modules. CAM systems are often specialized on one special tooling methods as. Here, the program offers a large variety of items that can be used for this special technology. Although the programs offer modules for other tooling methods as well, they are often only added by using the functionality of the original modules. Therefore it is very important for the user to analyze which method he uses most when choosing a CAM system.

For tooling methods as water jet machining, that are not as widely spread as milling or turning, CAM solutions are mostly derived from conventional solution of other methods as e.g. EDM wire cutting. Machining with EDM is similar to water jet cutting by means of creating and controlling the cutting path. Yet there are major differences in geometric aspects and the influence and interaction of process parameters.

3. DEVELOPMENT OF A CAM SYSTEM FOR WATER JET MACHINING

3.1 Deficiencies of Conventional CAM Solutions for Water Jet Cutting

Conventional CAM solutions for cutting with the water jet are commonly derived from other machining methods like EDM, laser or even milling. These machining and cutting methods use very similar machine controls, so that programs can easily be converted. In many cases it might be good enough only to create the bare NC-code for the cutting task from a CAD-model. For high quality cutting more and specific functionality of the system is needed to compensate the effects of the jet lag or the taper of the kerf. This is not provided by conventional CAM systems, since those effects are unknown to the tooling method they were originally designed for. Working with milling tools e.g. will always lead to the same material removal. The radius and the shape of the tool are usually constant (see figure 1a). Changes of the shape due to alternating the velocity of the tool as we find it with water jet cutting, do not occur. Tool correction other than a linear offset is not necessary for milling technology.

With water jet cutting, the tools taper cannot be described like a milling tool with parallel edges. Depending on the speed and other parameters, changes on the shape do occur. In figure 1b, a schematic shape of the water jet beam being described as the 'tool' is shown. We do not only find non parallel edges as described by Guo (1994) but also an increasing displacement of the tool's center with increasing cutting depth.

With conventional 2D-CAM solutions, this changing jet tool shape has mostly been ignored. They assumed parallel edges and so the operator had to find the combination of parameters to fulfill these requirements. Doing so, the operator looses the possibility of optimizing the process regarding other important aspects as e.g. cutting speed or contour accuracy.

3.2 Approach to CAM for Water Jet Cutting

A specific CAM solution for water jet cutting has to cover a large variety of functions. It also has to take into account the real shape of the water jet tool as well as the critical points as e.g. corners and curves. The following specific functions have to be employed:

- Modeling of the tools taper
- Machining strategies
- Tool correction (linear, angular) with optimization
- Simulation of the machining process

According to usability studies, the CAM system has to meet industry standards. Therefore we have integrated users interface, where the operator or the programmer can e.g. select certain machining strategies that he considers the best solution. The program here serves as an advisory tool that proposes a choice from analyzing the situation. The decision though must be made by the operator from his expertise. Depending on the level of the operators experience and reliability of the system, these decisions can also be automated.

For the modeling the shape of the tool depending on the parameters the operator can feed the system with new data when using new materials or parameter combinations. For this, a user-interface was created where the operator enters data that he can measure directly like the top and bottom diameter of a circular or square cut.

3.3 Modeling of the jet tool shape

The most important module of the CAM system is the modeling of the tool's shape. It is used to simulate as well as to calculate amount and direction of the tool correction. In literature, many models for the cutting kerf can be found (Hashish, Kim and Zeng, Blickwedel, etc.). Most of them model the maximum cutting depth from the given parameters. The model that is used here, models the shape of the tool from the process parameters.

As shown in figure 2a, a geometric model of the tool water jet is created. It consists of two functions that describe the diameter and displacement of the tool against the moving direction (figure 2b). In figure 2c the side view of the tool gives an idea of the jet lag that occurs under these working conditions. The front view (figure 2d) shows the increase of radius with the cutting depth.

This model is based on empirical experience and functional dependencies of the parameters (e.g. Guo, 1994). From these data, significant codes are derived to set up a geometrical model that can be effectively used for tool correction and simulation. Since this is a semi-empirical model, the operator can easily enter new parameters for his working conditions (material, hydraulic parameters etc.).

3.4 Jet Tool Path Correction

As mentioned before tool path correction is one of the central elements of CAM systems. In two dimensional e.g. sheet metal cutting with two or three axis water jet cutting machines tool path correction can be achieved by simple linear offset. This can be done manually by the operator generating the NC code himself or with the support of the machine control. The most important part is here to find the right combination of cutting parameters. For three dimensional machining tool path correction is much more complex. Additional to the linear offset also angular corrections are possible. In all cases of 3D-machining though the correction is to be determined in vectorial manner with perpendicular displacement to the contour surface.

Three different methods of tool path correction are implemented in the CAM system:

- linear offset to compensate the top tool width
- angular correction to compensate the variance of tool width
- angular correction to compensate the effects of the jet lag
- adaptation of the feed rate

All different types of corrections can be implemented individually according to the needs of the actual machining job. Since all angular corrections do result in a slight increase of cutting depth little reduction of the feed rate might be necessary to obtain the required surface quality.
The basic tool correction that can be done in two dimensional machining as well is the linear offset. Here the cutting path keeps the distance of the tool top radius from the programmed contour (figure 3b). With this linear offset the contour accuracy can be improved very well compared to cutting on the very contour (figure 3a). In two dimensional cutting this kind of cutting path correction can be done by creation an equidistant to the contour. In three dimensional cutting the direction of the offset is normal to the contour and parallel to the work piece surface. With this method alone a moderate contour accuracy can be achieved when selecting the process parameters for parallel cutting edges.

In addition to linear correction of the tool path with angular correction the cutting process can be optimized in means of accuracy and cutting speed. For this, though, five-axis cutting machines are necessary. There are two angles that can be changed for compensating the shape of the tool. The first angle compensates deviations of the tool width in cutting direction (figure 3c). Using this kind of correction parallel cutting edges are not necessary, and the feed rate can be increased.

The second angle points in cutting direction. With this the effects of the jet lag can be minimized (figure 3e). This is very important at critical points such as e.g. corners and at critical contour elements as small radius curves. Here typical geometrical errors as e.g. overshooting can be avoided with the second angular correction.

3.5 Machining Strategies

The definition of machining strategies is another vital module of a CAM system. Here the machining process is optimized according to the given demands. Typical optimizing criteria are the following:

- high cutting speed (little machining time)
- high contour surface quality
- high contour accuracy (size, shape)

The cutting parameters and the cutting path have to be adjusted according to the optimizing criteria or weighted combination chosen. Strategies for compensation of geometrical errors do include more than only changing the given tool path and adding some angles to it. For best results also the cutting speed has to be adapted to the actual cutting depth and for the actual cutting situation. So the feed rate ought to be decreased before the process comes to a critical point. Thus adding a speed profile to the cutting path, it has to be split into smaller segments according to the actual needs.
As shown in figure 4 there are major differences between the top contour (figure 4b) and the shape of the bottom contour (figure 4c). Especially corners and small radius curves deviations from the expected contour occur. These critical points have to be treated separately at all machining strategies.

3.5.1 Corner

Corners are a very sensitive subject with water jet cutting. Due to the jet lag a deviation from the expected and programmed contour occurs. The deviation increases with the cutting depth and has the shape of an overshot (see figure 4b). This cannot be allowed for industrial cutting with exactly defined contours. Therefore the cutting path has to be changed in order to compensate this effect. As shown in figure 5, three different strategies are implemented into the CAM system. The easiest compensation strategy is to stop at the corner, waiting for the jet lag to catch up to the tool position (figure 5a). When starting off for cutting the next edge, damage on the outside edge will occur, though. Another strategy is to fillet the tool path at the corner with the radius of the tool and decelerating at the same time (figure 5c). With this strategy, the corner is most likely to be filleted as well due to the very low feed rate in the center point of the circle. At concave corners the same strategies are used (figure 5d). Here the minimum contour radius that can be achieved is the radius of the tool. Recent developments have shown that a radius of 0.2 mm and below can be realized. The sharpest corner and the best results can be achieved by doing the loop (figure 5b). The cutting contour for both edges is created by straight cutting of the edges before and after the corner. Therefore maximum contour accuracy at the corner can be expected by following this strategy. But this also means an extra need of space and machining time. With three dimensional tool path correction the geometric accuracy at the corner can be improved at minimum waste of machining time by compensating the effect of the jet lag through angular correction.

3.5.2 Curved Contour

Machining curves with the abrasive water jet is also a sensitive matter. Especially when machining curves with a small radius the cutting contour shows significant geometric deficiencies. Depending of the diameter of the cutting curve the cutting contour varies at the same cutting conditions (figure 6). The effect is bigger for smaller diameters. This can be explained by the constant jet lag that always points against the actual feeding direction. With small diameters at the same jet lag the radial deviation is larger than with bigger diameters (figure 7). Because of the non linear jet lag tool the contour at curved cuts also shows a curved shape. (figure 6). Conventional approaches to achieve high accuracy at curved cuts have mostly reduced the feed rate in order to abate the effect of the jet lag to a minimum. With the lower speed the shape of the tool will change again to a wider cutting shape at the bottom. To achieve high contour accuracy at an economical cutting speed three dimensional tool path correction both angular and linear is needed.

3.5.3 Straight contour

At straight contours conventional 2D cutting systems can achieve a high degree of contour accuracy as well. For this thorough selection and close control of the cutting parameters is necessary, though. With a certain combination of cutting parameters that depend on material properties, cutting depth, and other machining conditions parallel cutting edges can be realized. But this also means that there is only one feed rate that can be used for machining (Guo, 1994). Therefore optimization is only possible in one criteria. The operator has to consider which optimization criteria he will follow: contour accuracy or cutting speed. With 3D-angular tool path correction the maximum cutting speed can be used without loosing contour accuracy. The only limit is set by the minimal allowed surface quality of the cutting edge.

3.6 Cutting Edge Simulation

The major problem with water jet machining is to determine the cutting edge contour before carrying out the actual job. Thus high precision machining has always been dependent on the expertise of the operator and a matter of iterating approaches to meeting the demanded accuracy. With the previously described modeling of the jet tool shape (see chapter 3.3) not only correction of the cutting path is possible but also simulation of the actual cutting edge contour. With this the tool path can be optimized without wasting machine resources. The outcome can be simulated that in most cases tolerances are kept from the first piece without iterating experiments.

In figure 8 a sample of the simulation is shown. The work piece was to be cut with maximum possible speed. With angular correction of the tool path it was possible to obtain both demands for high accuracy and minimal cutting time. In figure 8b and 8c one part of the simulation is magnified. It is very good to observe in figure 8b that big deviations from the expected contour do occur. With angular correction in figure 8c the deviations are reduced to a minimum.

3.7 Data Import and Export

Import and export functions are vital for communication of the CAM with its environment. This being a stand alone solution it is possible for all users to adapt easily with standard file interfaces. Geometric data can be imported in many different formats like e.g. CNC, DXF. These data are converted to the internal used Vector-Point-Sets. After processing and simulation these can be exported to the machine control for machining. Most controls require machine specific NC-data, though. Here converter for most controls are available or can be added rapidly.

4. CONCLUSION

Water Jet technology has become one of the most recent technologies for machining metal and non-metal materials. Because of its unique features and its high flexibility, its use is more and more spreading not only among job-shops but as well in industrial machining. Thus having reached a turning point from laboratory use where the operator can control and optimize the process with his personal expertise to using water jet technology as an efficient and economical tool for manufacturing different demands have to be met. Here computer support is needed to reduce preparation time and optimize and control the machining process.

With this computer aided manufacturing system for abrasive water jet cutting high precision machining with the abrasive water jet can be realized in both two and three dimensional applications. On the base of three dimensional geometrical jet shape modeling tool path correction both linear and angular can be carried out for maximum precision of the cutting edge. Additionally the use of machining simulation replaces laborious experiments for optimization of the machining outcome. With the application of specific machining strategies the outcome can be optimized regarding machining time, contour accuracy and surface quality.

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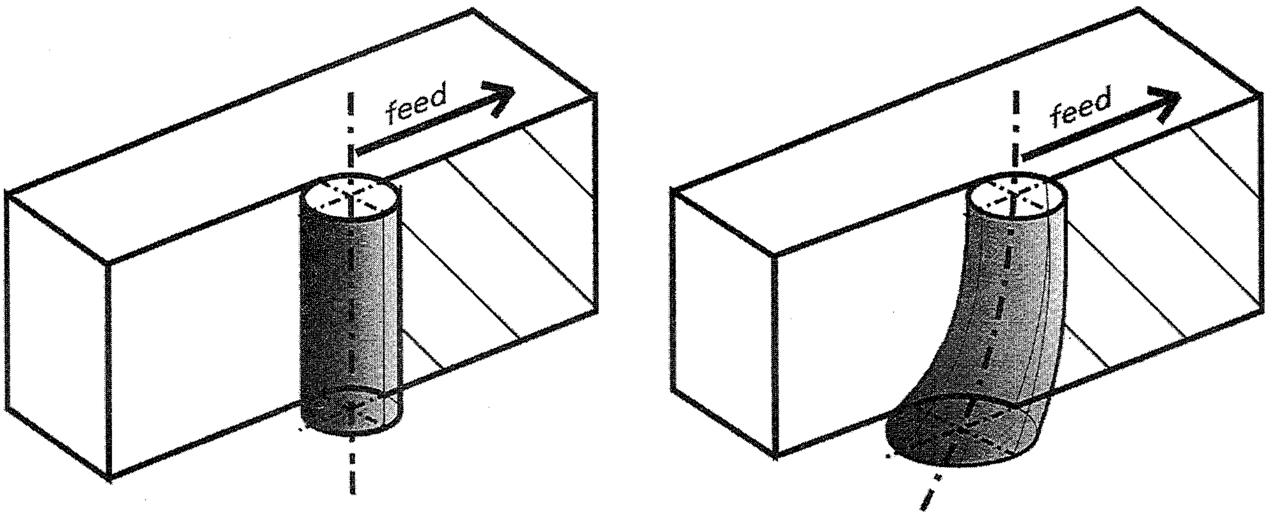
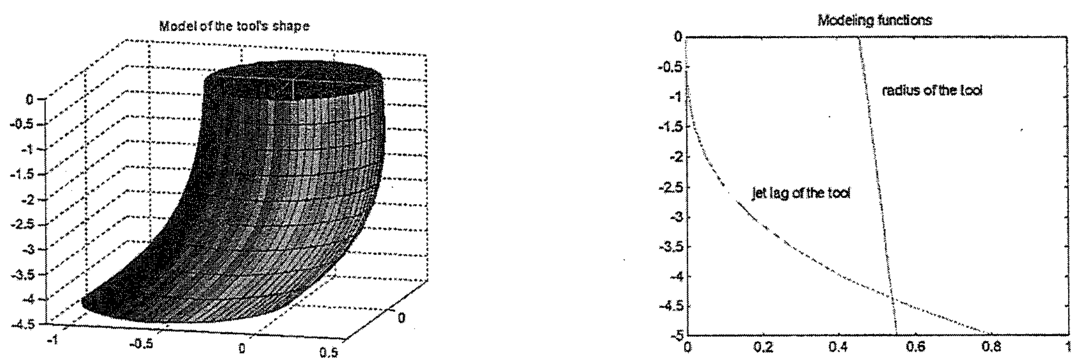
6. FIGURES



a) jet tool shape for conventional tool correction

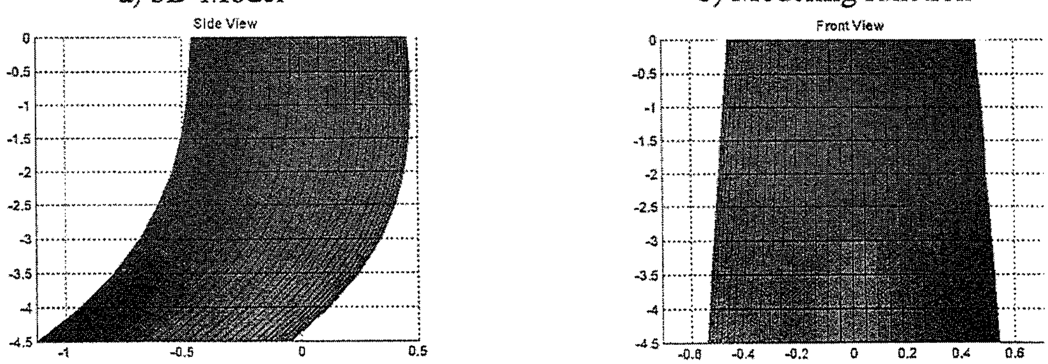
b) real jet tool shape

Figure 1: Deficiency of Conventional Tool Correction



a) 3D-Model

b) Modeling function



c) Side View

d) Front View

Figure 4: Modeling of the Jet Tool Shape

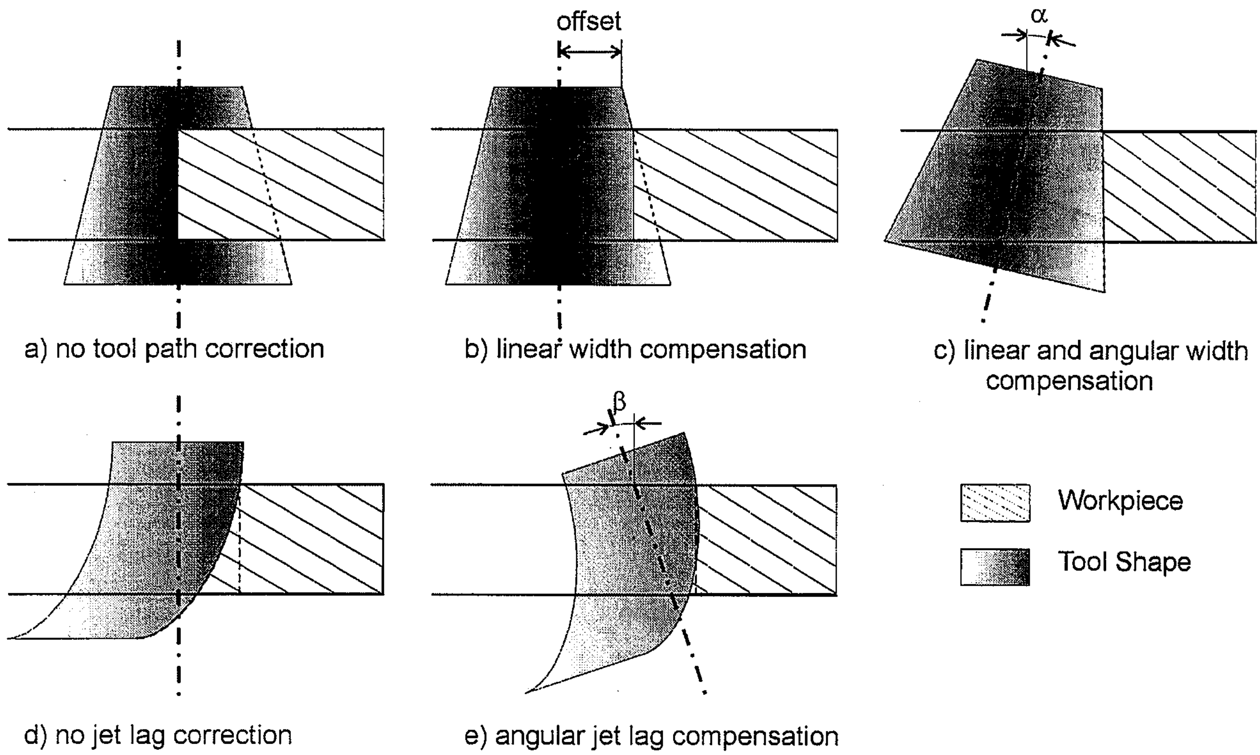


Figure 2: Linear and Angular Compensation of the Jet Tool Shape

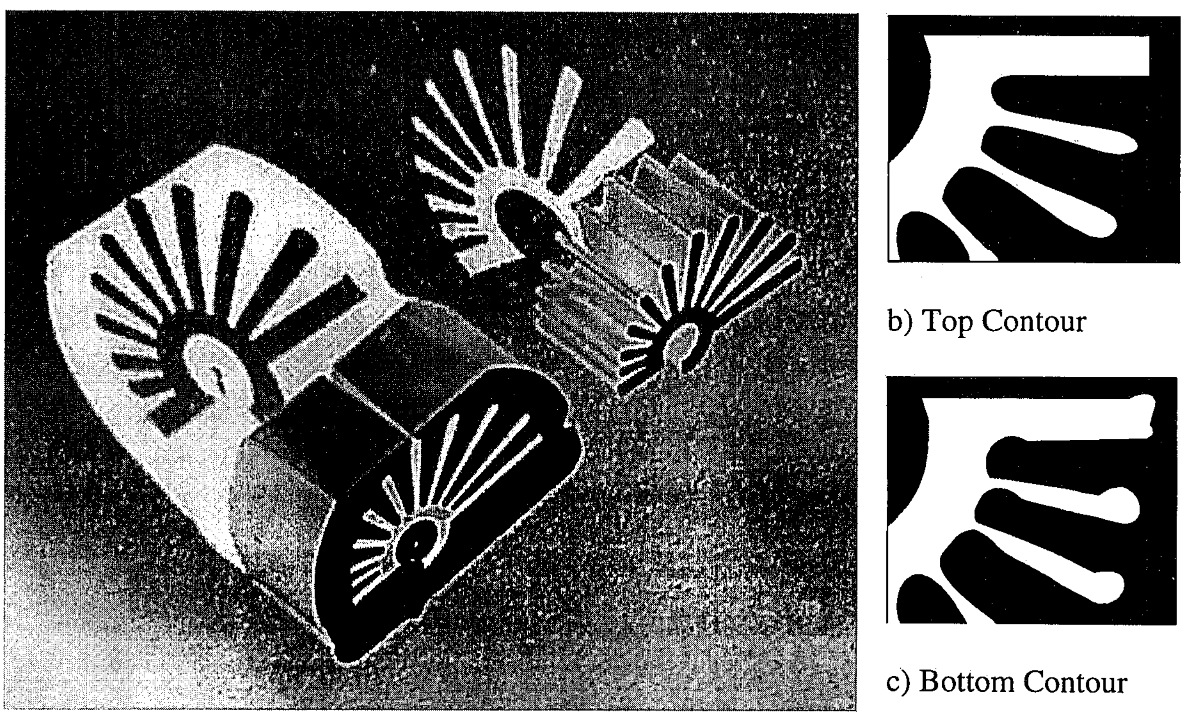


Figure 3: Sample for Precision Cutting with Contour Deficiencies (Henning, 1992)

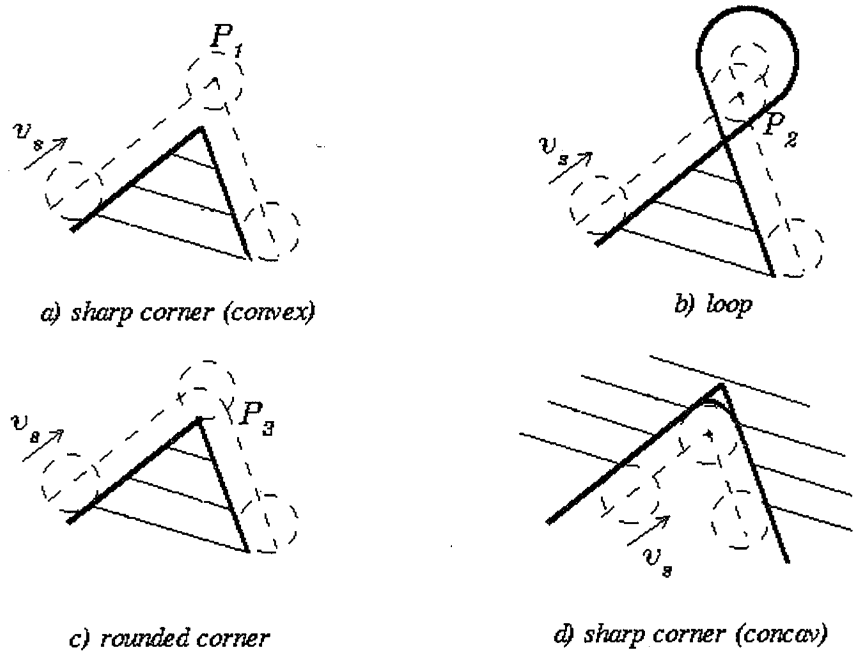


Figure 5: Machining Strategies for Corners

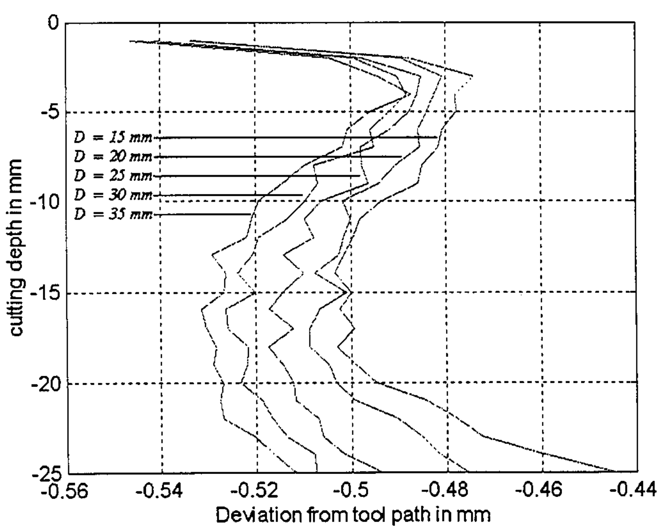


Figure 6: Deviation of Curved Contour with Variation of Tooling Path Diameter (D)

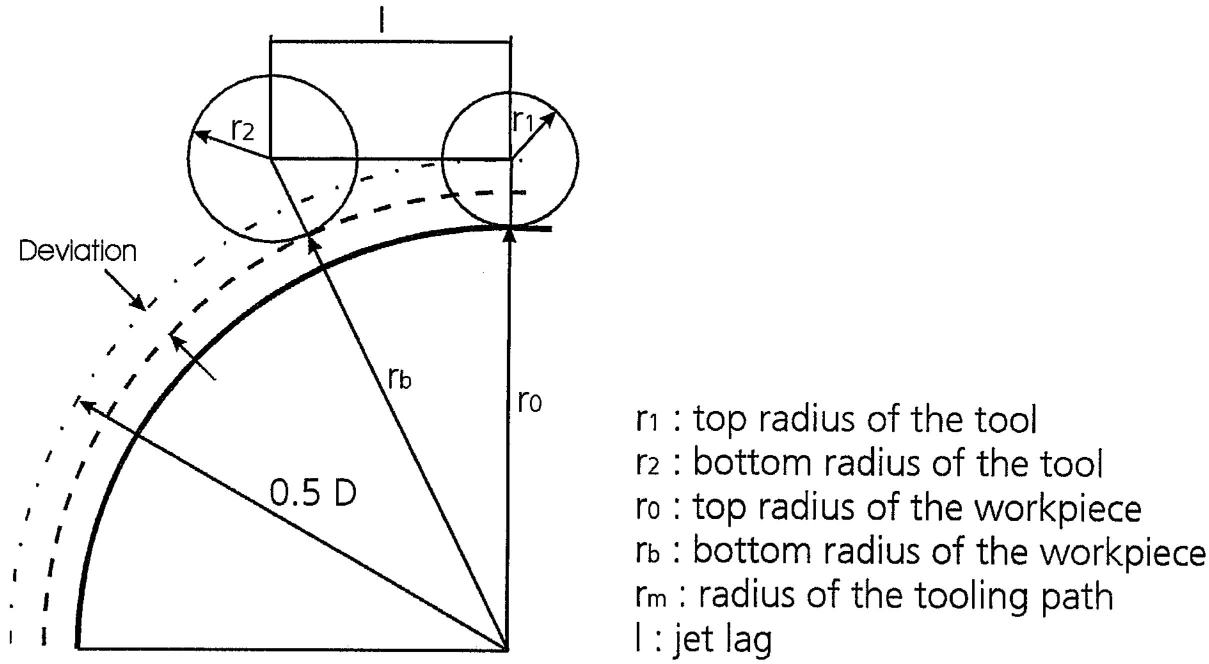


Figure 7: Analytical Description of Curved Contours

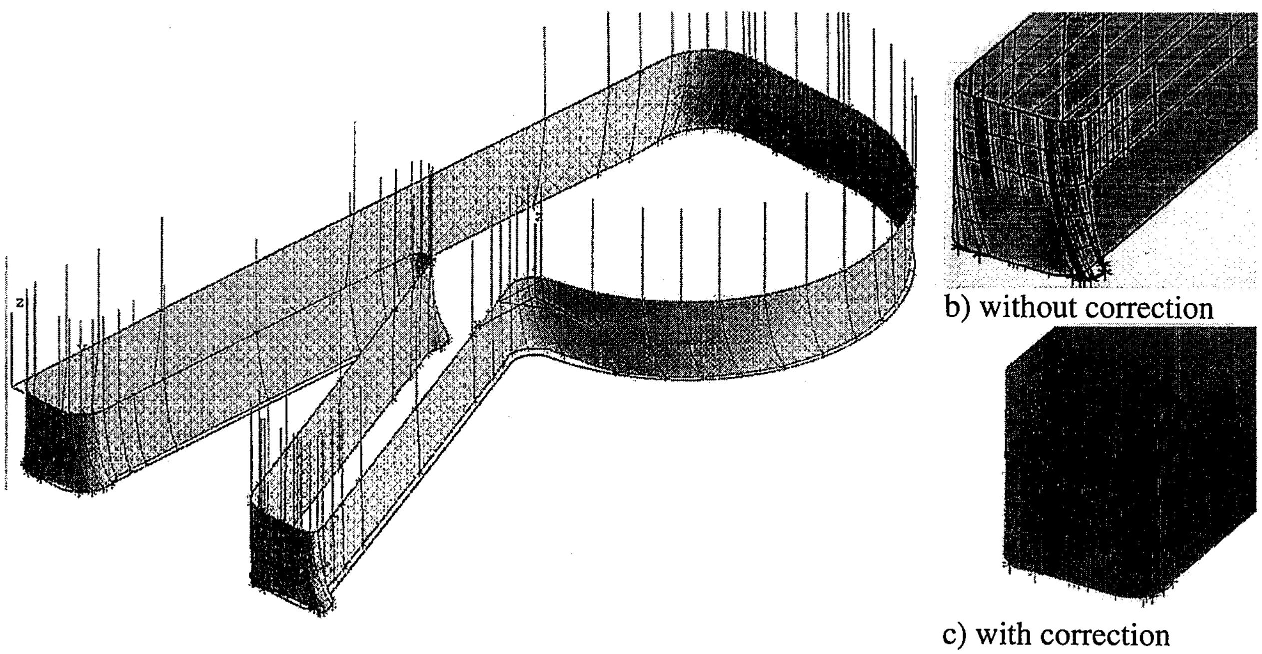


Figure 8: Simulation of the Water Jet Machining Process

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Paper 56

6-AXIS ARTICULATE ROBOT

WATERJET CONFIGURATIONS

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ABSTRACT

3-dimensional waterjets are a common processing tool for a variety of cutting and cleaning applications. This paper addresses automating 3-dimensional manipulations of UHP nozzle(s) through integration of engineered hardware, software and tooling into production work cells.

Modular design, cost effective component integration, and user friendly control systems pave the way for the proliferation of turnkey systems throughout the industry.

Organized and Sponsored by the Waterjet Technology Association.

1. INTRODUCTION

Flexible componentry bridging ultra-high pressure (UHP) pump systems and UHP nozzles have evolved from the stationary nozzle being dependant upon the workpiece addressing the cutting process, to a pre-programmed dynamic cutting tool capable of addressing the workpiece in many configurations.

The design configuration of an automated work cell is influenced by the process flow requirement and primary budget constraints, in most cases. The design should be simple, basic and lend itself to modular upgrades for more complex, efficient, value-added systems.

2. ROBOTS

The key core components of any articulate robot cell is the reliability and durability of the mechanical arm, and the computational power and flexibility of the controller. Payload specification of the arm is relevant to the application. In general, a majority of UHP cutting systems typically employ robots with a minimum payload capacity of 10 kg. The higher flow rates used in cleaning systems typically employ robots with a minimum of 60 kg., and in most cases a "foundry" specification robot is chosen because the cleaning environment is extremely wet. Payload capacity rating is due to a difference of the reactionary force (Hashish et al., 1985) relevant to the flow rate requirements of the nozzle (whether the application is cutting or cleaning). The design of the robot "end of arm tooling" must accommodate the thrust moment factor at full nozzle flow rate, and maintain stability with frequent on/off cycles. The total weight of the "end of arm tooling", UHP nozzle, plus any ancillary devices, such as "break-away" wrist clutch, probe sensors, etc. complete the payload weight calculation. Another factor influencing robot selection is the expected work envelope size. Many UHP cutting applications involve large capacity robots (< 100 kg.) only due to a requirement to cover a larger work envelope, utilizing a lightweight tool assembly (fig. 11).

A very important feature with the robotic manipulator is the ability to process dynamic positional data to enable very smooth and repeatable nozzle movement. Straight lines and concentric circles are a challenge for most robots. Internal control software for applications such as continuous welding or sealant dispensing are well suited for repeatable UHP cutting requirements. Software for spot welding applications for example, is focused only on specific programmed positional teach points, whereas cutting systems rely on continuous tracking between and through all programmed teach points.

Offline programming of all teach points is readily available with additional software capable of post processing active CAD files, and writing a program translation to the specific robot control. The offline programming system can enable many program changes or modifications to many work stations involving multiple robot arms without taking the robot offline.

3. MODULAR CONCEPTS

The single most basic system involves a "Floor Mounted Robot" (fig. 1) and a simple fixture tool with a cutting tank. A modular expansion of this work cell involves the addition of a second tank (fig. 2) or more to maximize the useable work envelope of the robot.

Optimizing the work envelope with rotary tables and rotary walls will increase the productive output (fig. 3). Elevating the base of the robot to a vertical position can maximize the horizontal work envelope plane. This situation is also modularly expandable from a "Single Robot Column Mount" (fig. 4) to a "Dual Robot Column Mount" (fig. 5). Employing multiple robots in a common work envelope is a cost effective solution when cutting cycle times must paramount molding or forming times for pliable goods (e.g. in a "just-in-time" manufacturing environment).

Modularly expanding on the "Column Mount" robot cell is accomplished by employing dynamic tooling (fixturing). This is also achieved by utilizing a "Two-Position Shuttle" (fig. 6) or "Rotary Table / Wall" (fig. 3).

"Gantry Walk-Thru" systems allow 4-sided access to the tool and provide mounting platform for all equipment off the floor (fig. 7), or "Ceiling Mounting" the robot (fig. 7.1).

"Over and Under Shuttle" systems (fig. 8) compliment the material handling or material transferring issue, which is the true benefit of automating the waterjet process. Maintaining control of the material throughout the complete process before and after waterjetting is the main focus of committing to automation.

4. ANCILLARY EQUIPMENT

In addition to the basic modular hardware components as described in Section 2 above, the following equipment is typically integrated for specific applications, as follows:

4.1 PLC (Programmable Logic Controller)

The typical robotic waterjet system is expected to endure high production cycle rate demands. The robot is a computer controlled unit employing the use of a very sophisticated network of multiple servo controls operated by a Central Processing Unit (CPU), using multiple sub-processors which are calculating positional data, monitoring outputs and input functions. Please keep in mind this description is simplifying the task load on the robot control, meanwhile the main control function is to calculate the Tool Center Point (TCP) from the base axis #1 thru 5 more axes to the final 6th axis to which a nozzle is attached further on out in space. All of this is happening while at full speed, handling a waterjet cutting tool.

Integration of the robot into a Waterjet Cutting Work cell will add more demands on the robot control. Peripheral accessories such as vacuum system on/off, vacuum pressure monitoring, time delay on the vacuum cycle, etc., adds to the robot workload. Shuttle systems, rotary wall/table(s), operator start/stop buttons and many other features added to the system will definitely contribute to the robot processor menu load resulting in SLOWER CYCLE TIME.

The robot must scan repeatedly all of the required monitor functions and the program being executed at all times. Light guards and safety mats and all safety devices connected on the cell must be monitored, a slow scan time of the "loaded" robot control may result in a missed signal, or a signal that is not "seen" in time. This is a SAFETY HAZARD. Any program selection, changes or cell functions must be signaled through the robot control, usually you do not want an operator pushing these buttons.

Integration of a Programmable Logic Control (PLC) will take the load OFF the robot system. This will free up the robot to "concentrate" on the fastest cycle time processing. Multiple user friendly controls can now be interfaced to the system, this would include a simple program selection via selector switch, push buttons, bar code scanners, etc. Also, all peripheral and safety devices are monitored at scan speeds faster than the robot controller multi-tasking could achieve, resulting in FASTER PRODUCTION.

Troubleshooting from a robot control displays an alarm code which must be referenced with a maintenance manual, whereas the PLC will enable quick recognition and a Message Display Panel (20 character alphanumeric, or touch screen monitor) will announce the problem and the solution in most cases resulting in ENHANCED UPTIME. A PLC will also allow system diagnostics and remote monitoring from a main frame office computer, if required.

The following points summarize the benefits of a PLC:

- Faster cycle times - higher productivity.
- Robot control is alleviated of all peripheral monitoring and multi tasking.
- A PLC unit functions as a master control.
- Allows user friendly, easy-to-read switches and push buttons to be used.
- Self-diagnostic capability.
- External mainframe network communications and modem capability.
- ISO 9000 data download capability.

Touch screens are a recommended addition to the PLC main control. A touch screen replaces the required labor and materials such as lights, pushbuttons, paddle switches, etc. used on a standard NEMA 12 enclosure panel.

The touch screen allows a single point program access location and allows a customized screen display specific to the customer's needs and specific to the operation. In the event of a failure mode, the self-diagnostics program will indicate to the maintenance personnel the cause and/or condition. Work cell status, production counts, and external interface communications are also part of this configuration.

This package is the state-of-the-art cell control which is aesthetically clean and not congested as in a pushbutton and signal light configuration. Custom panel arrangements are easily programmed on the screen and is an industrially proven component.

4.2 Vacuum / Effluent System

Vacuum assures consistent positioning and repeatability of most pliable parts to be cut. The vacuum/effluent system is offered as a stand-alone unit, or it can be fully integrated as in the Modular Column design (fig. 4), Over/Under design (fig. 8) and Gantry Walk-Thru design (fig. 7). The vacuum can be integrated into these designs to reduce floor space required for work cell.

The integrated vacuum system is designed to perform the effluent evacuation of the tool and maintaining the position for the part being cut. This is important to maintain the repeatable cut quality required for high accuracy trimming. The vacuum is typically drawn through drilled holes in the "splash" tooling (see section 4.3) around trim details as well as through the cut in the splash where the waterjet passes through. Large holes are supported by stand-offs which support the splash in those locations. By eliminating large openings and drawing all the water and effluent through the vacuum system, the noise of cutting is kept below 85 dBa.

This vacuum system may be used at various sea level elevations and can be sequenced between two (2) separate cutting fixtures. The vacuum utilizes a centrifugal blower with a muffler/silencer. This silencer will reduce the noise levels from the blower to below 85 dBa without the need to vent the discharge through the roof of the building. The blower draws through a cyclonic separator and pulls material from the fixture and through a basket screen (which would be dumped once per shift). The fine particles and water sludge are deposited into the sump tank which is then diaphragm pumped to drain or external filtration equipment.

4.3 Fixturing / Tooling

Custom fixturing is available for all types of part configurations. This tooling is very critical for repeatability and long term endurance. By using innovative techniques to reduce noise and dissipate the ultra-high pressure energy of the waterjet process. The result is a low noise and long lasting quality tool built with non-oxidizing components.

Fixtures are custom built to the skin (splash). The splash is a solid fiberglass form of the material to be cut. This form is typically a reverse mold of the tooling. Fiberglass thickness should be at least 13 mm and peripherally exceed in size at least 100 mm (4") past the outside trim line. This splash is then molded to a non-oxidizing 30 mm (1-1/4") aluminum tooling plate. The tooling plate is precision machined and tooled with hardened bushings. The tooling plate will rest on the stainless catcher tank, located with dowels. The splash is reinforced internally with stainless steel supports and replaceable jet deflectors to protect the fixture and offer noise abatement. Provision for forklift removal should be a design feature too (fig. 9).

4.4 Robot Plumbing

4.4.1 UHP Hose (fig. 10)

Simple, basic robot plumbing can be achieved by connecting a length of UHP hose directly to the UHP nozzle and maintaining the required orientation with a retractable, spring adjustable tensioner. Custom bracketry and containment rollers are used to maintain the pliable hose along the arm of the robot. Pressure restrictions up to approximately 3061 bar (45,000 psi) limit the hose applications in industry. Robot programming is generated "around" the hose, due to hose bend radius restrictions. A 3-axis UHP swivel joint is required at the nozzle for maximum flexibility.

4.4.2 UHP Coils (fig. 11 / 11.A)

Stainless steel tubing 6 mm O.D. (1/4") is used to convey the UHP water along the robot arm to the nozzle. The tubing is specially coiled into compliant type of torsion, axial and radial springs. Special clamps and bracketry along the robot arm support the tubing. Coil tubing must be "auto frettaged", and clamping devices must be softer than the tubing to prevent stress risers leading to premature cycle fatigue failure. Coils are capable of handling applications with maximum pressures up to 3740 bar (55,000 psi). Coils may add complexity to programming, inhibit accessibility to the robot arm and the component being programmed.

4.5 Work Cell Plumbing - UHP

Stainless steel high pressure tubing is available in O.D. sizes of 6 mm (1/4"), 9.5 mm (3/8") & 14.3 mm (9/16"). I.D. of the tubing is generally 1/3 of the O.D. Consideration of pressure losses are a factor in relation to the distance of the UHP pump source. Generally, 6 mm tubing is used up to 35 meters from the pump for low flow rate cutting applications. Larger tubing (14.3 mm) is typically installed for longer runs up to 120 meters maximum.

5. SAFETY

Machine compliance codes such as OSHA, ANSI, CSA, JIC, CE, etc., must be adhered to when designing and implementing robotic machinery. Operator protection involves physical hard guarding, light curtains, safety mats, optic scanners, etc., and most importantly - TRAINING.

Training courses familiarize personnel with the work cell function, mechanical limitations and safety issues imperative for understanding an automatic machine. All safety interlocks must be fail safe and tied into instant depressurization "Block & Bleed" valves to ensure safe operation.

6. CONCLUSION

Robot work cells thrive in environments subject to constant changes of the parts being processed. Parts with multiple programs (or options) can be simultaneously processed for "just-in-time" production schedules.

Manual cutting applications lend themselves well to robotics due to increased costs of human fatigue and realizing the benefits of higher productivity, repeatability and flexibility with robotic work cells. However, consideration must be given to the level of technical expertise required to maintain the equipment and the costs associated with new and unfamiliar technology. Initiating a robot work cell should include a pre-planned equipment specification defining the expected objective, performance, hardware, operation and acceptance criteria.

System componentry used in and around all areas in contact with any water must always be non-oxidizing. Fixtures and tools must be zero datumed and connected to the robot base structure.

Ensure your existing parts are processed with the same cutting/cleaning parameters during the machine acceptance, as the initial test samples at the beginning of the project. Involving the maintenance and production people with the project early on will ensure secure employee confidence. Continuous communication with regular updates between the builder and user will ensure a concurring relationship during the system build lead time, and most importantly, after the installation.

7. REFERENCES

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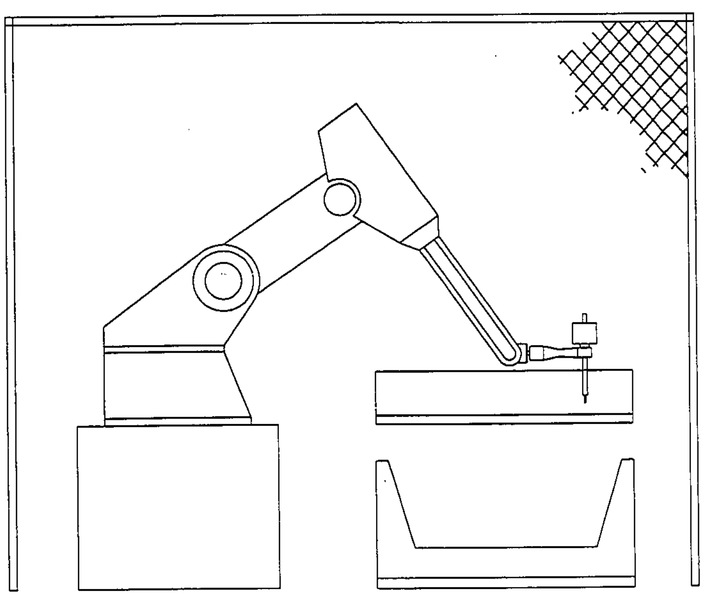


FIG. 1 – FLOOR MOUNTED ROBOT

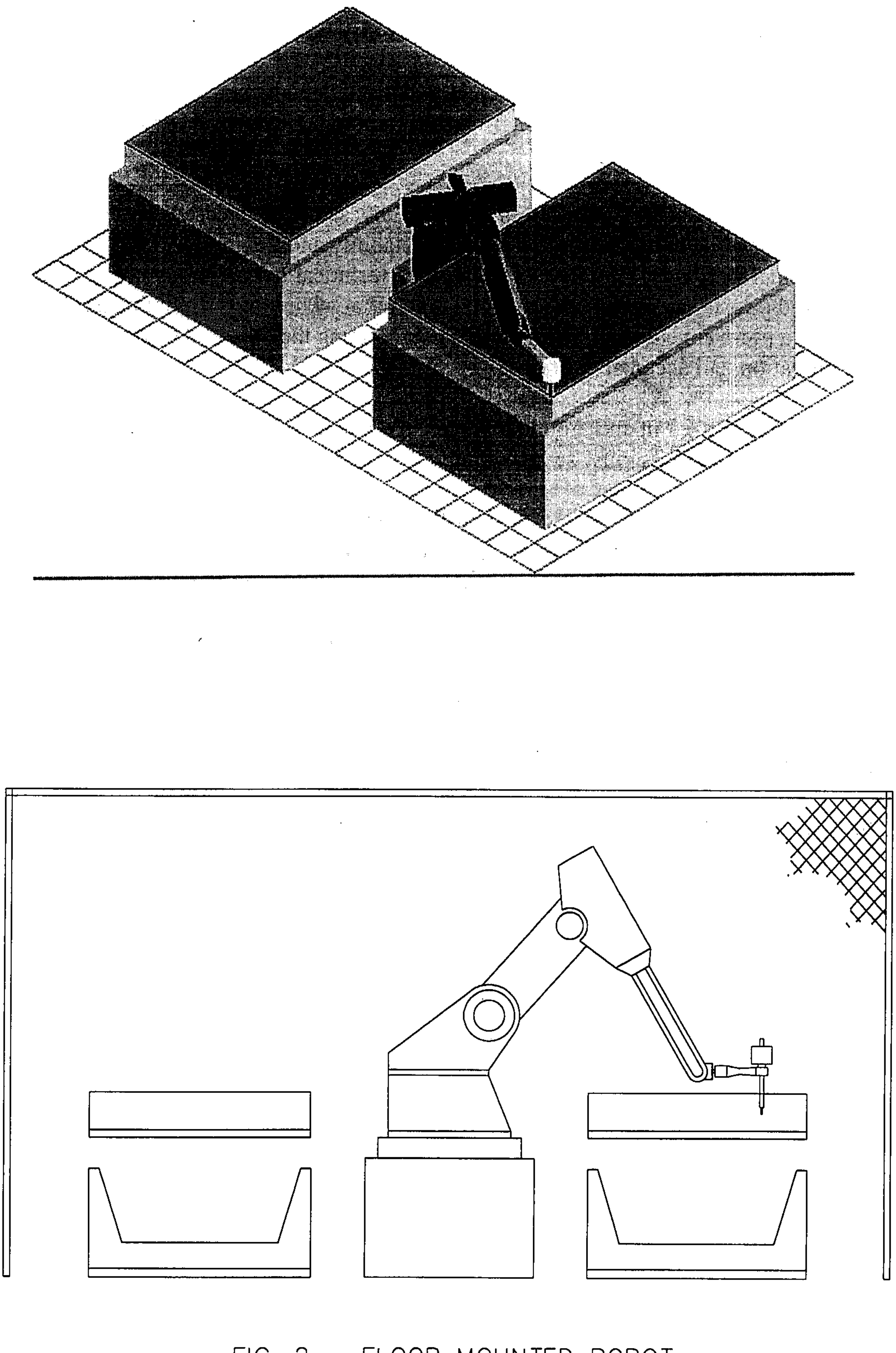


FIG. 2 — FLOOR MOUNTED ROBOT
MULTIPLE FIXTURES

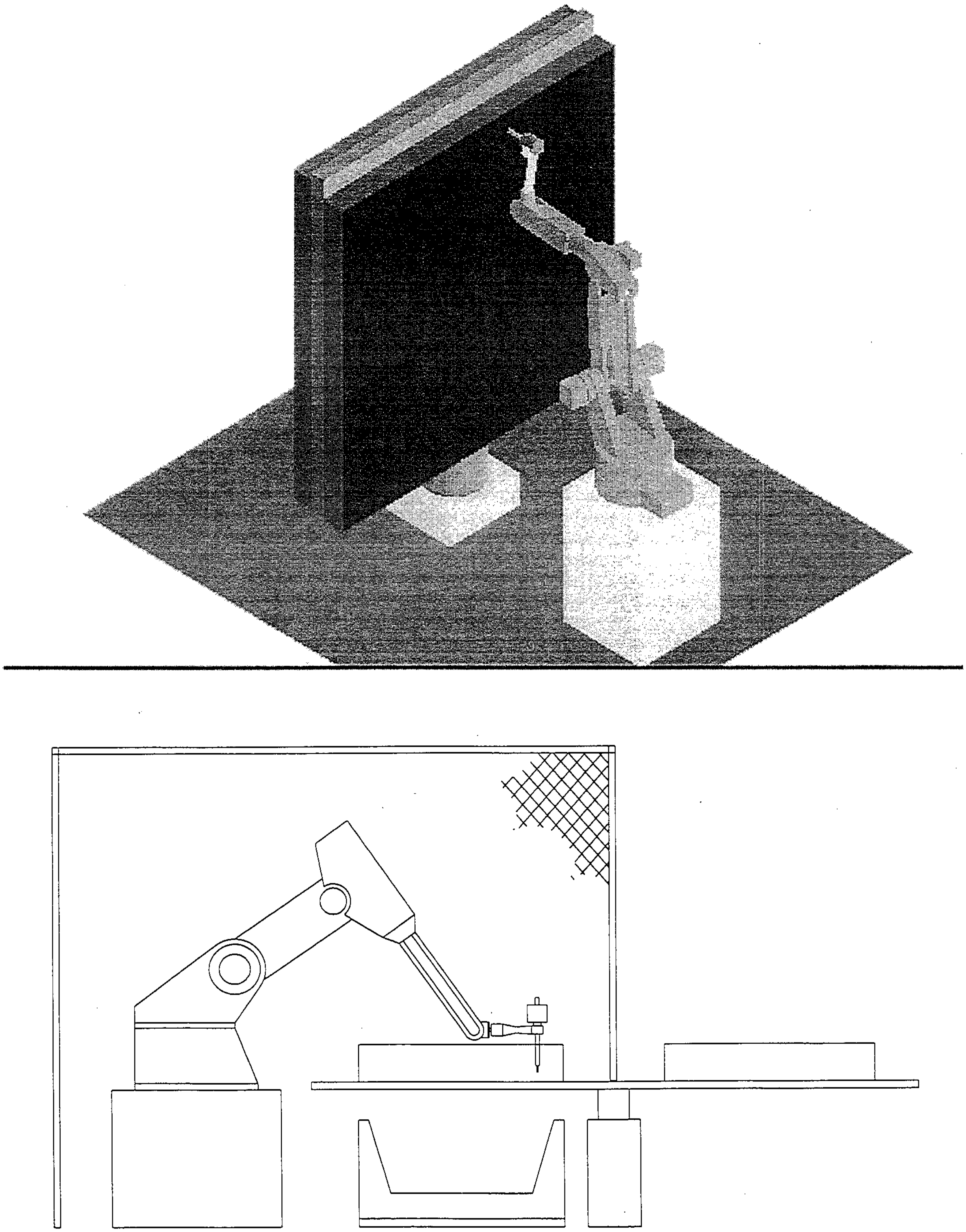


FIG. 3 – FLOOR MOUNTED ROBOT
ROTARY TABLE

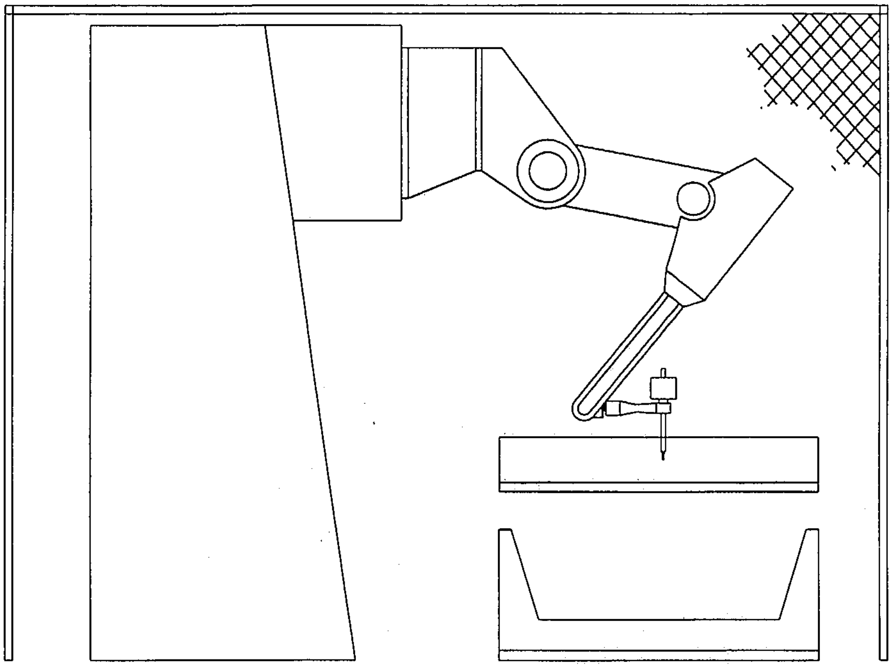


FIG. 4 – COLUMN MOUNT ROBOT

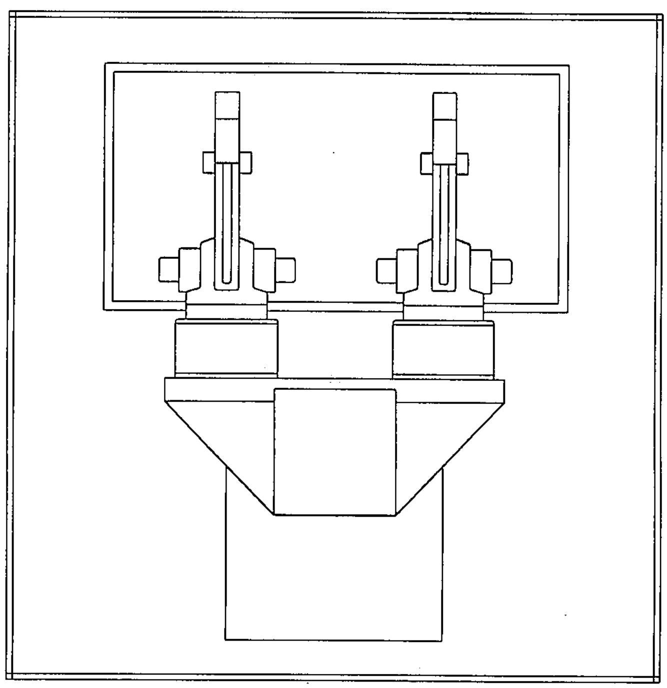


FIG. 5 – DUAL ROBOT COLUMN MOUNT

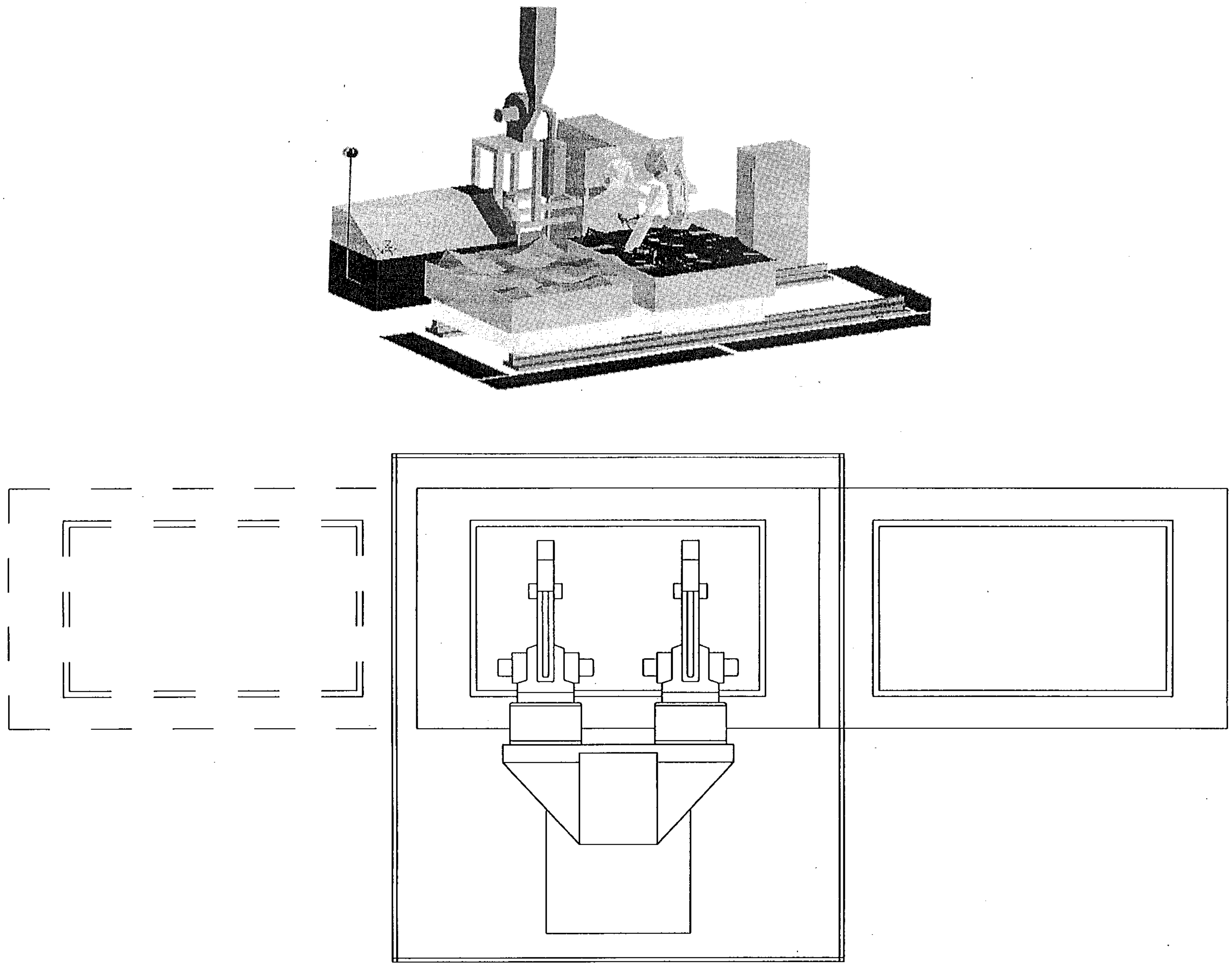


FIG. 6 – TWO POSITION SHUTTLE

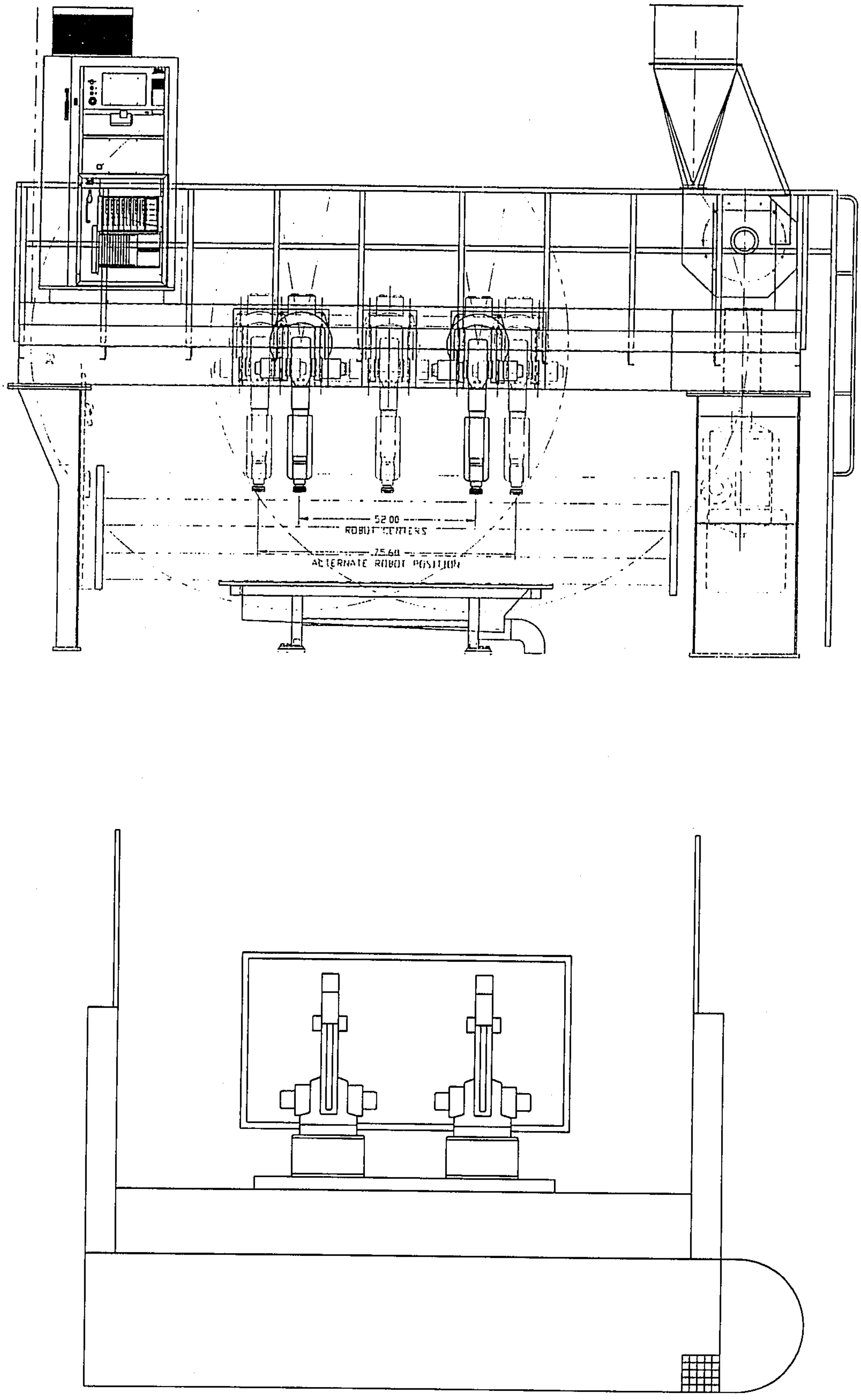


FIG. 7 – GANTRY "WALK-THROUGH"

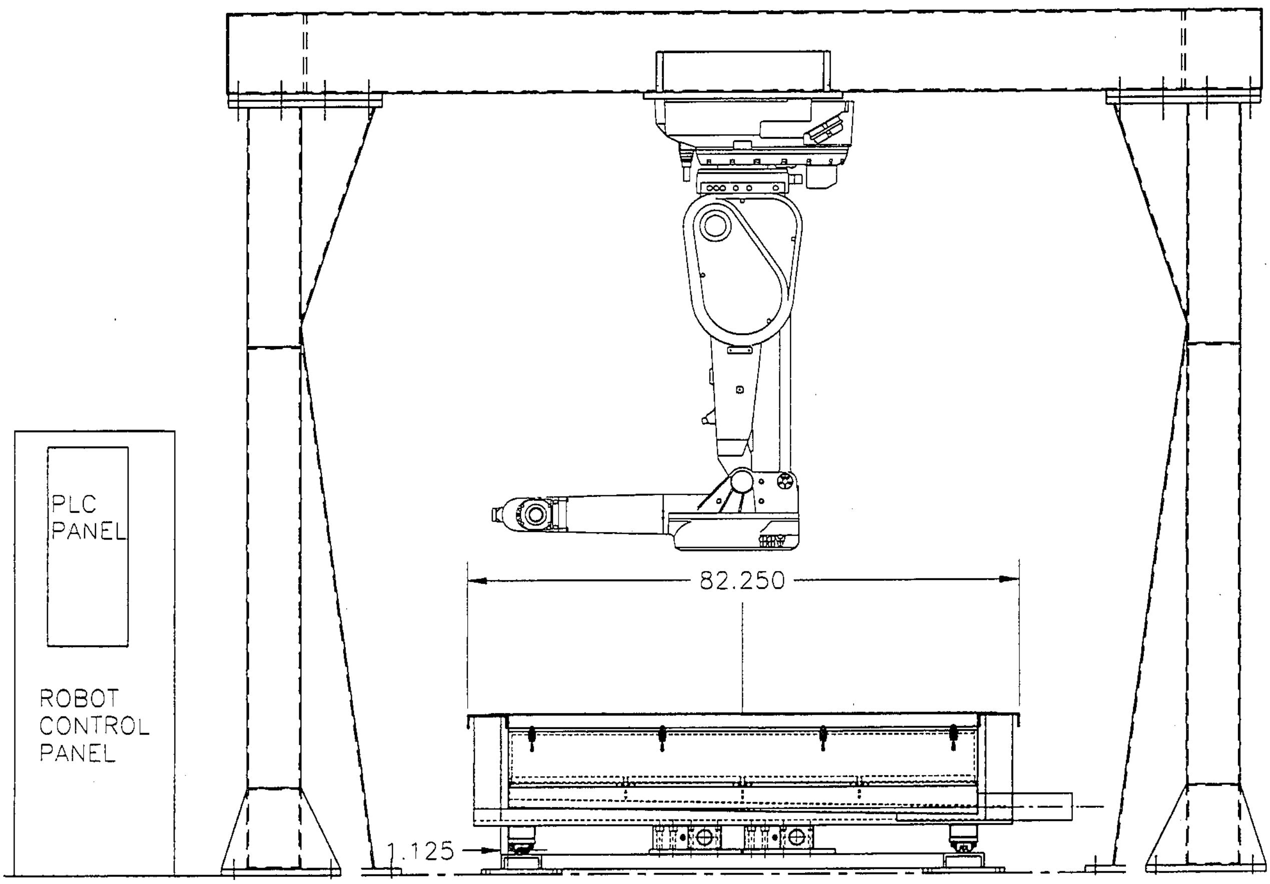
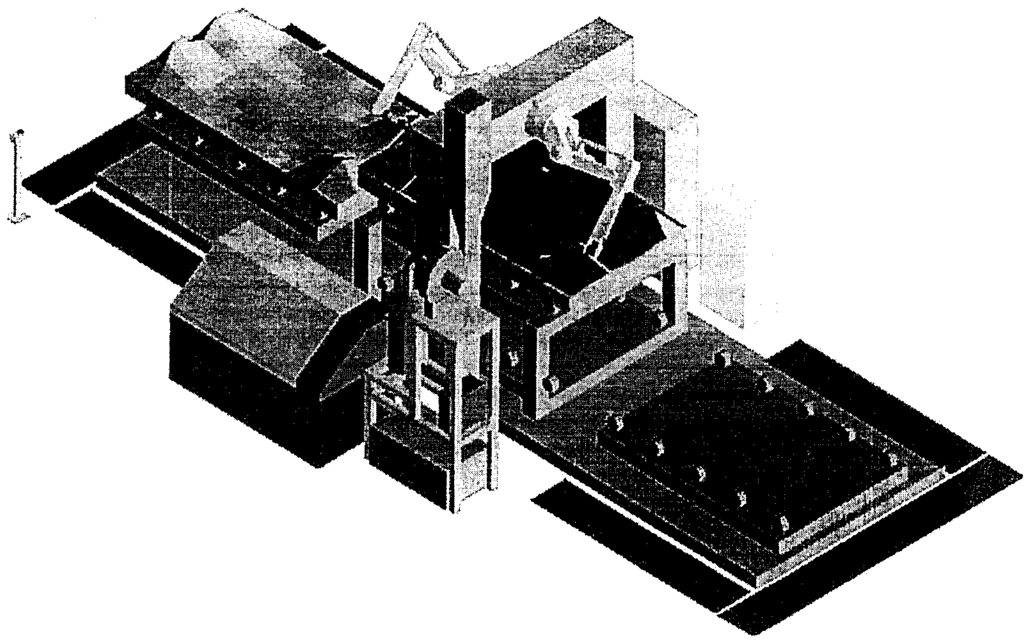


FIG. 7.1 CEILING MOUNT ROBOT



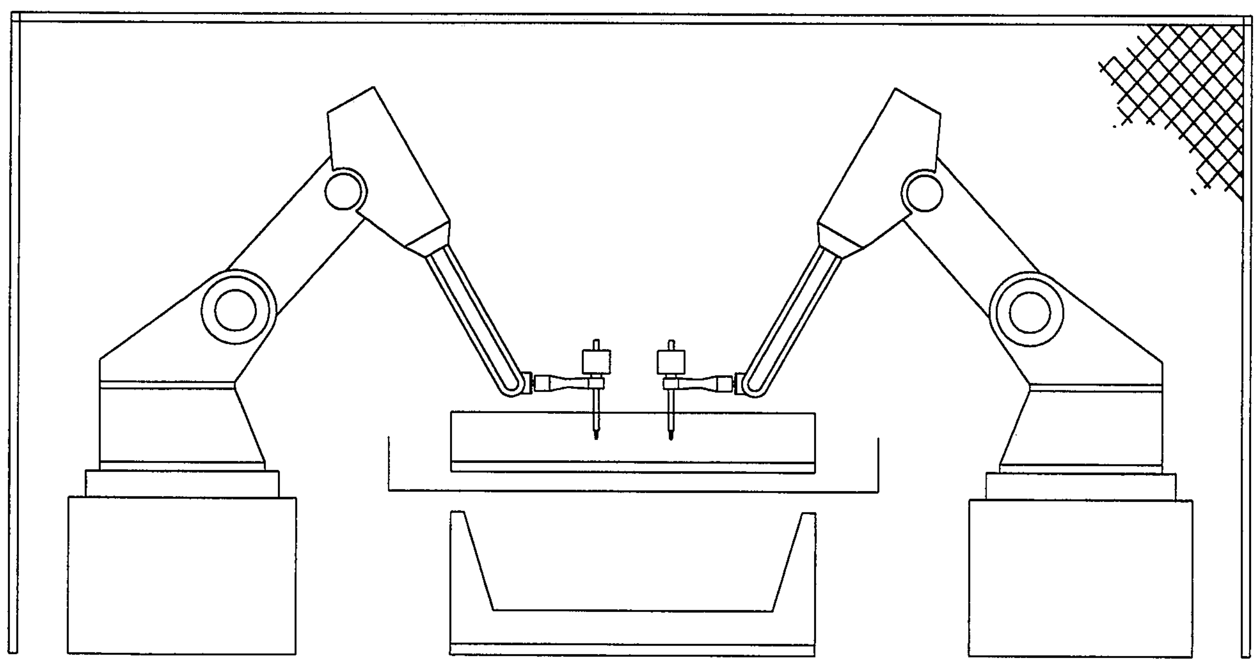
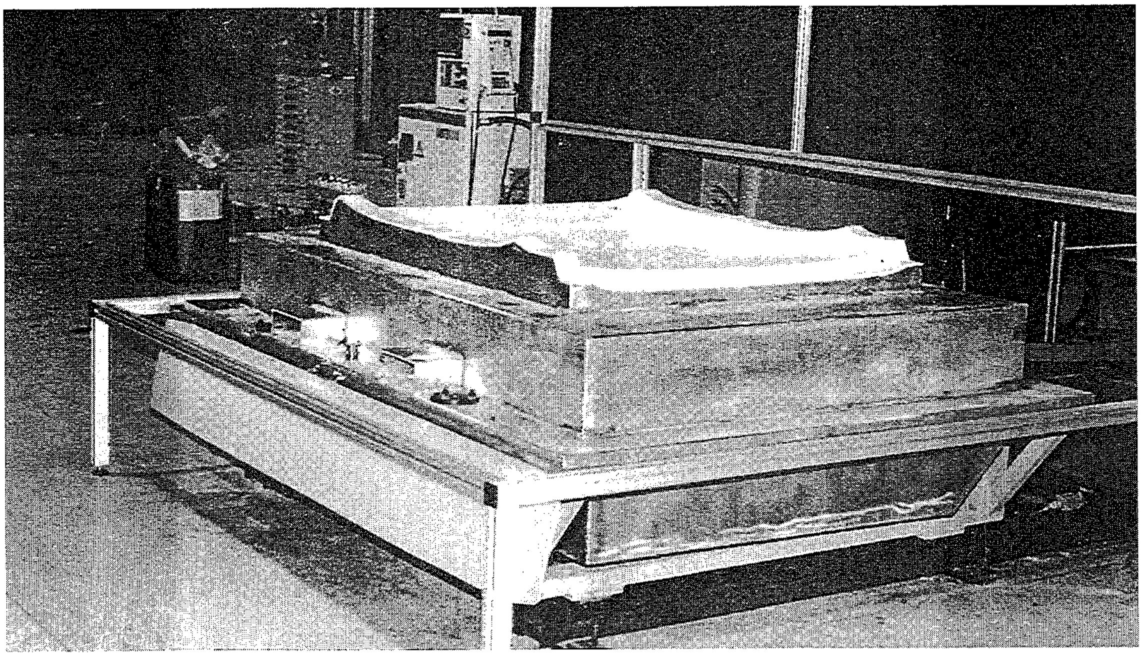


FIG. 8 – OVER/UNDER SHUTTLE



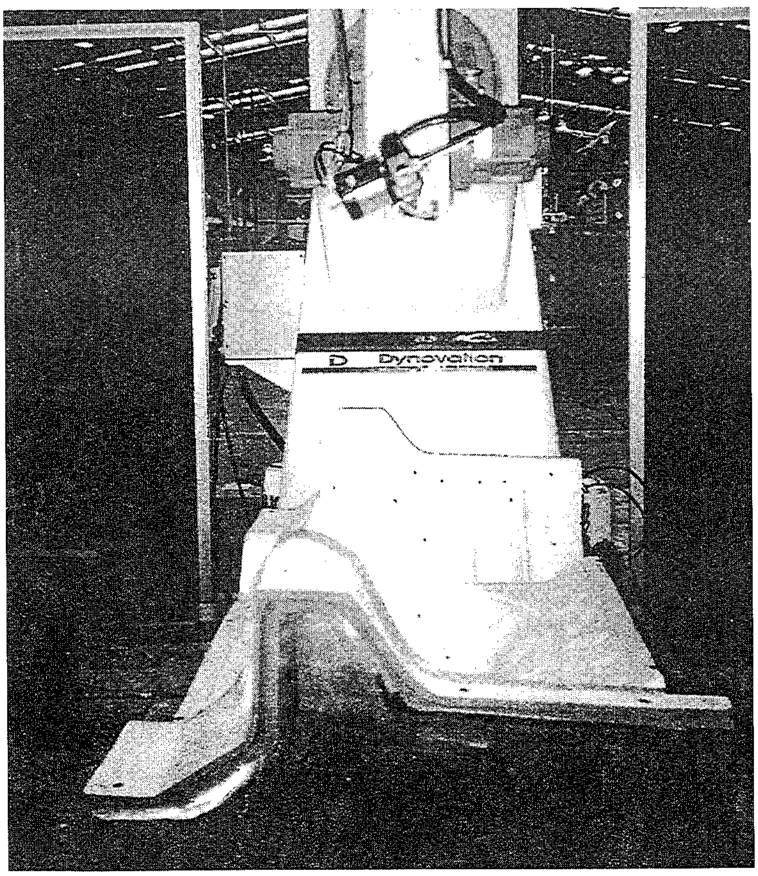


FIG. 9 FIXTURING / TOOLING

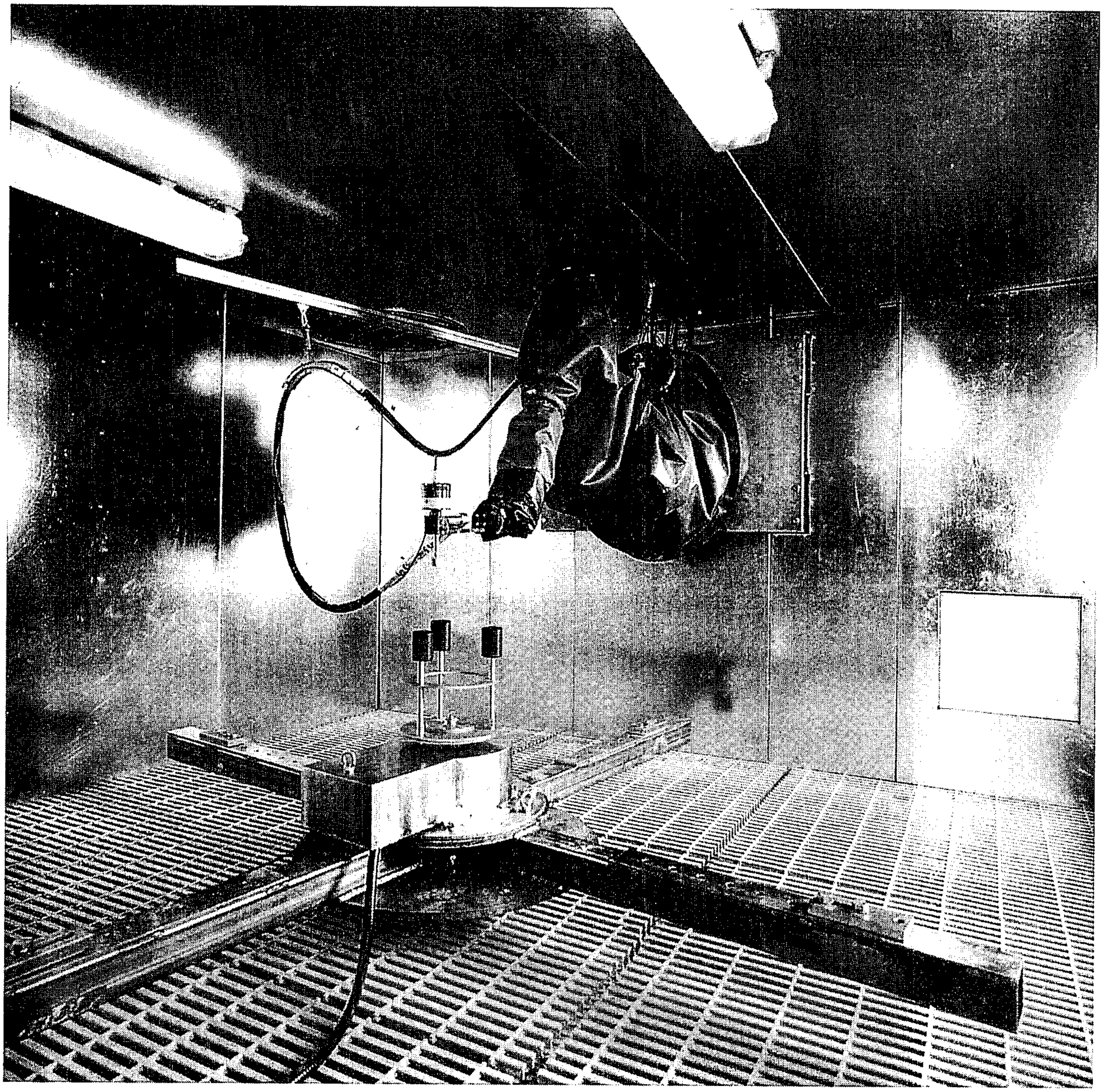


FIG. 10 ULTRA HIGH PRESSURE HOSE PLUMBING KIT

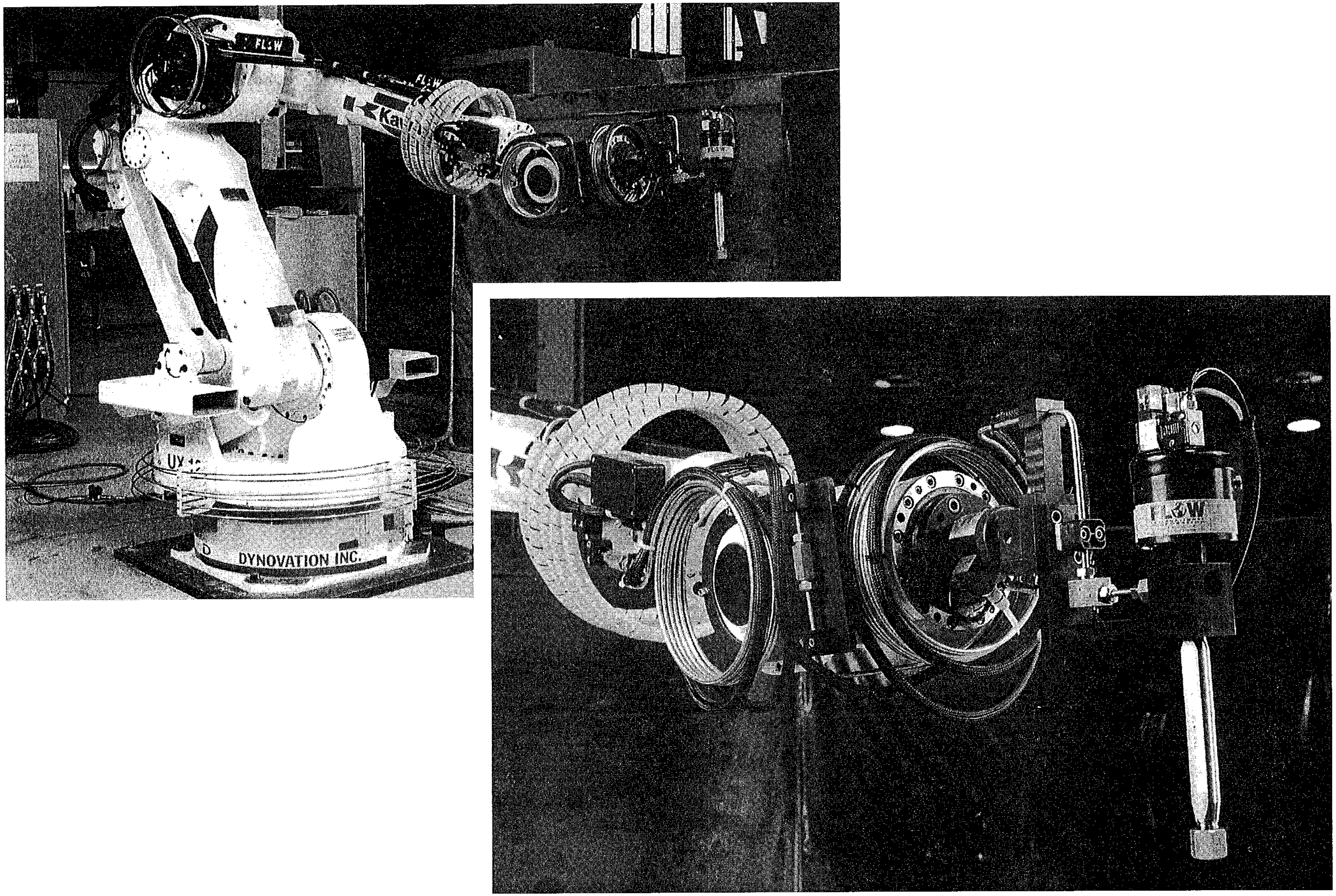


FIG.11 ULTRA HIGH PRESSURE COIL PLUMBING

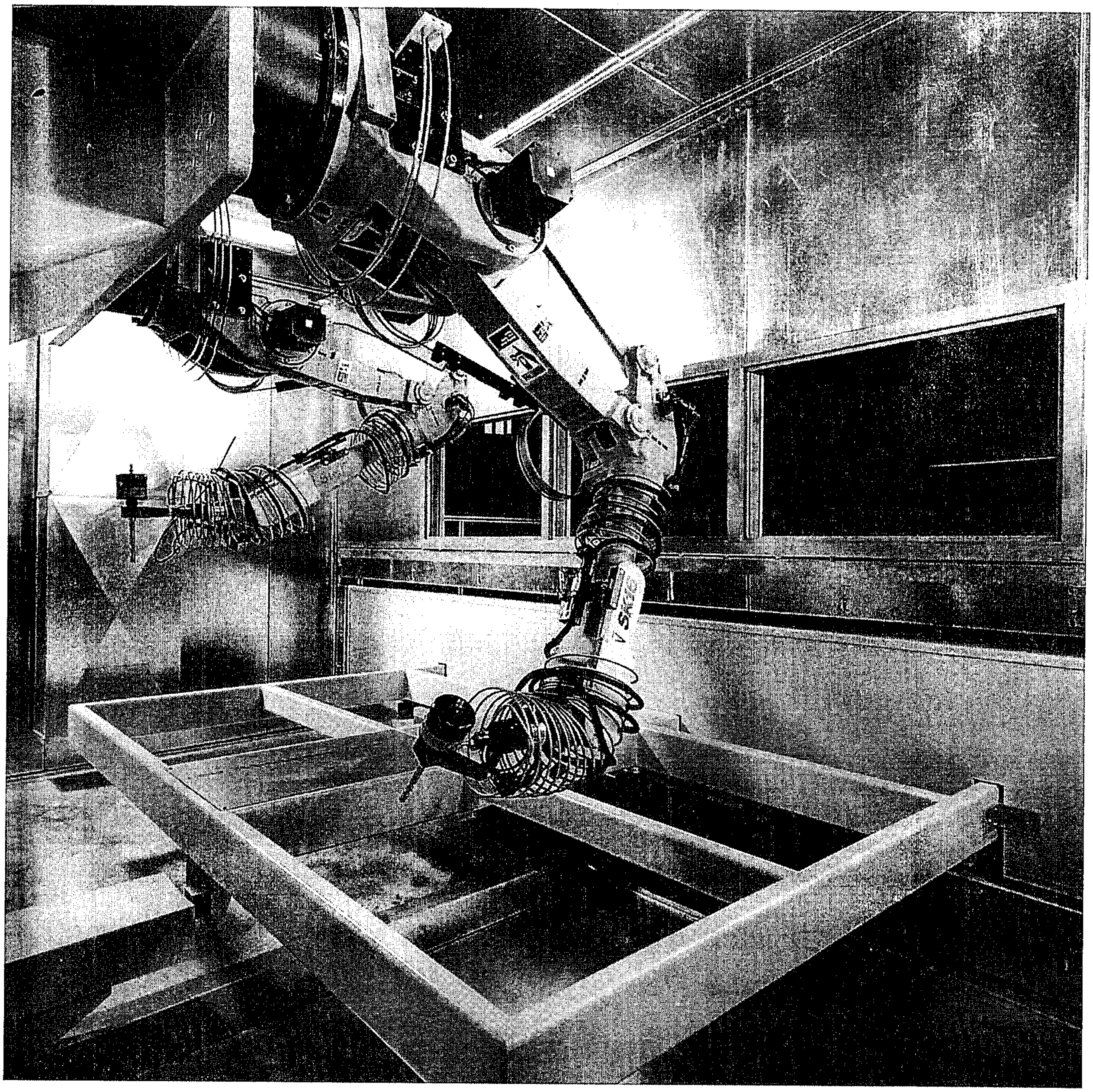


FIG. 11A ULTRA HIGH PRESSURE COIL PLUMBING KIT

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HIGH PRECISION WATERJET CUTTING OF 3D-CONTURES IN THE INDUSTRIAL PRODUCTION

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ABSTRACT

With the adaption of the tool high-pressure waterjet to industrial robot systems, for the waterjet cutting technology many possibilities were initiated. The meaning of waterjet cutting for industrial production of three-dimensional pieces is known, therefore you can find many installed systems. The demand of high precision is not very high, therefore robot systems are able to produce these parts with satisfaction.

However waterjets three dimensionally led, are able to solve difficult duties in industrial production with a corresponding machine system. For example, in automotive industry complex bowls are used for rather different functions and therefore corresponding duties for precision, quality and production or installation units are demanding cutting tasks, which have to be done just in time with a high number of pieces and high precision. The industry sets great store on the productivity, the precision and reliability of the production technology.

This paper discusses recent developments to improve the flexibility of 3D waterjet cutting systems by easy programming, to improve the productivity of 3D waterjet cutting systems by the use of quick change preadjusted cutting heads and ultra-quick high-pressure valves, to improve the use of 3D-waterjet cutting systems by optimizing the size of the cutting heads and special catching systems.

Organized and Sponsored by the Waterjet Technology Association.

1. INTRODUCTION

The stronger competition grows the more important it is what your machines can provide to meet this competition and can contribute to your profit., e.g. with more flexibility or better material exploitation. Installing 2D water jet cutting machines, equipped with an alternating table, five cutting heads or more, with a separate height adjustment, a suction device for the water mist and integrated drying unit, as well as with a waste disposal unit, were the answer to the gasket industries to modernize and to keep the German production in town. Equipped with a high feed speed, today, such machines do the work of several manual punching machines. An optimal material exploitation, high flexibility, low costs for tools and preparation time, no stock keeping for tools, programming with a CAD-system, and the good feeling, to always be able to fulfill customers' requirements within no time.

The same requirements are in the interest of the automotive supply industry, which cuts non-metal parts in 2 or 3 dimensions with punching systems or water jet cutting robot systems. Punching systems are not flexible and cutting robots are not precise enough.

In team with automotive suppliers FORACON in winter 1995 designed a new 5 axes cutting table which supports all the advantages of the water jet technology, as multi head and flexible working distances, combined with FORACON table qualities, precision and speed.

2. THE CONCEPT

Base of this cutting machine is a high precision 5 axes CNC-table. Especially for this application FORACON designed a new compact cutting head. This cutting head is installed at the very solid bridge, the X-axes of the CNC-table, with a turning and swivel axis. The repeatability of every single axis is better than 2/100 mm. In total, all inaccuracies of driving amount at the top of the tool is less than 1/10 mm/m. Based on linear conducting units and ball screw drives the linear axes are designed with high dynamics. For supervision of collisions the motors of the cutting machine are controlled against overload (Fig. 1).

The **programming** of this cutting machine is computer supported with an effective **CAD-CAM**-system. Therefore complicated robot-kinematical programming systems or time expensive teaching of cutting contours is not necessary.

Because the workpieces are mostly designed with a CAD-system, the user is able to transform the contour very quickly into a nc-program through data processing of the confined areas. The programmed cutting movement is shown offline at the monitor with position vectors of the cutting head, or online with a cutting head movement simulation tool (Trace-module).

Equipped with the angle functions **sinus** and **cosinus**, every user is able to move without any problem in the cartesian system of coordinates of the cutting machine and manually change the nc-programs for himself (Fig. 2). The cutting table is controlled by a powerful unit of SIEMENS (SIEMENS 840 C). The concept of machinery is able to react with high flexibility to every product change. The POWER-bundle: precision, velocity and cartesian programming renders this cutting machine a superior to the common cutting robots.

2.1 Master and Slave - Cutting head

This cutting table is already designed several times as a single or double head machine. Minimizing the production time was the idea for designing a double head cutting table. One table with one bridge and two separately drivable cutting heads means only small additional costs but doubled cutting power (Fig 3). This way, two identic or two symmetrical work pieces can be worked at the same time. At the treatment of symmetrical workpieces the task is easily reflected by the control unit.

Therefore it's enough to program the track of the master head, and the track of the slave is reflected, the movement dragged (Fig 4). With a double head cutting table it is also possible to work with a single head, that means master oder slave is able to cut unsymmetrical parts on their own. In comparison to a single head cutting table long ways for positioning are economized and this means a lot more cutting productivity.

2.2 A la Carte - The workpiece transport system

Depending on the user, the cutting table is designed with a special workpiece transporting system. Equipped with two motorized Y-Axes (gantry design) a workpiece transporting system easily brings the pieces into or through the cutting area. Starting with a simple alternating table or a comfortable workpiece transporting system all varieties are possible. Adapted to customers needs and given production time a special solution will be selected (Fig 5.)

For example, for the total cutting of an assembly system for the automotive industry four cutting tables were combined to one transfer line. The workpieces have symmetrical and unsymmetrical parts. For treating the workpiece in a very short time, two double heads and two single heads are integrated in this transfer line. Every single table is fully equipped, that means that any time the tables can be used as a standalone machine. Connected with a central control unit the single tables will be synchronized, supervised and the selection of cutting programs can be chosen centrally. The workpiece transporting system can be loaded and unloaded manually or with a special handling system. As a protection against malfunctions and emissions, the cutting line is equipped with a machine housing.

2.3 Waterpower - control of jet position and jet quality

The cutting table uses a high-pressure water jet as cutting tool. The cutting tool is able to cut also through double wall workpiece areas. Distances between 30 and 40 mm between front and back can be cut without any problem. Distances up to 100 mm from nozzle exit to workpiece surface are possible for single wall workpieces. These are great technological advantages, when direct access is not possible.

The cutting tool, a high speed water jet, is focused by a special cutting head at the FORACON table. By three dimensional guidance of the cutting tool, it is of great interest to know the three dimensional position of the jet, respectively, to bring the position in congruence with the machine reference. At the FORACON cutting table it is possible to control on demand the jet quality and position between cutting cycles in a jet test unit. The jet test unit obtains a drill whole target, which must be hit in the center from a testing jet. Only jets with a good quality and the right position are able to switch a control sensor. The accuracy of the jet controlling unit is very high. Only ± 0.1 mm out of the target or to bad in jet quality causes a report.

2.4 Pitstop - quick cutting head maintenance

Based on economical ideas, it is useful, that 3D cutting machines are working with preinstalled tools. As shown in every case, profit and loss are mainly controlled by the necessary time of setup work. Therefore the 5-axes cutting heads of FORACON are especially designed for quick adjustment and installation. The collimation tube and cutting nozzle can easily and with high precision be removed out of the cutting valve. Based on the high-precision quick-change connection the collimation tube with cutting nozzle is adjusted in a separated extern jet control unit. With three jet tuning screws the user can correct the jet position in x and y direction (Fig 2). The precise quick-change connection offers the most shortest installing times. In combination with the control unit in the cutting machine all conditions for restart the cutting process within 5 minutes are given with a new jet and a proofed jet position. With a production tact of 50 s and three working shifts these are more than 1,200 pieces a year, in comparison to the conventional installation time of 15 minutes, (nozzle system: saphir, lifetime app. 50 h).

2.5 Water Go - the high pressure valve

The high-pressure water is brought with swivels and metallic tubes to the movable cutting head. The jet stream is controlled by an ultra quick high pressure valve. In comparison to normal standard valves, the switching time of the FORACON valve is more than 60% shorter. With only 0.1 s opening and closing time the contours can be cut without any start and stop distances. Only with this powerful valve an increase of productivity is possible for pieces with many contours (Fig. 5).

2.6 Workpiece Support

The workpiece (wp) is positioned by a special tool. The positioning tool has a multifunction. Apart from positioning the work piece tool system protects relief-cut parts, catches the cutoff and destroys the remaining water jet. It is possible to suck off the cutting mist with a vacuum system at the work piece tool.

Positioning and transporting of the tools is made by a special system. By means of suitable clamps the workpiece receive its cutting position, day by day and night by night.

After loading the workpiece support, the support enters the cutting area. The position of the workpiece support is indexed. After the cutting process the support is automatically cleaned from cut-offs by turning the support and dropping the cut-offs onto the conveyor belt.

3. CONCLUSION

More and more high precision cutting 3 dimensions is now requested. Flexibility, precision and productivity are the most urgent challenges. The FORACON 5 axes cutting table is high dynamic, equipped with a especially designed cutting head. The opening and closing time of the high pressure valve needs only 60% of standard time. High productivity is the result. The user is able to exchange preadjusted water jets after the lost of jet quality or jet position. Short setup times means more productivity.

Jet quality and jet position might be measured on demand in the cutting table between two cutting cycles. High quality and production reliability are the results.

The workpieces are positioned with special tools in the cutting area. The tool transporting system can be led into or through the cutting area. The waterjet system design depends on the users need.

One or two turning and swivelling heads can be installed on the two dimensional cnc-table. The cutting heads can act as single or as a reflection system. Higher productivity is the result.

The programming of these cutting machines is very easily made by CAD-CAM. Flexibility and short preparation times are the result.

4. FIGURES

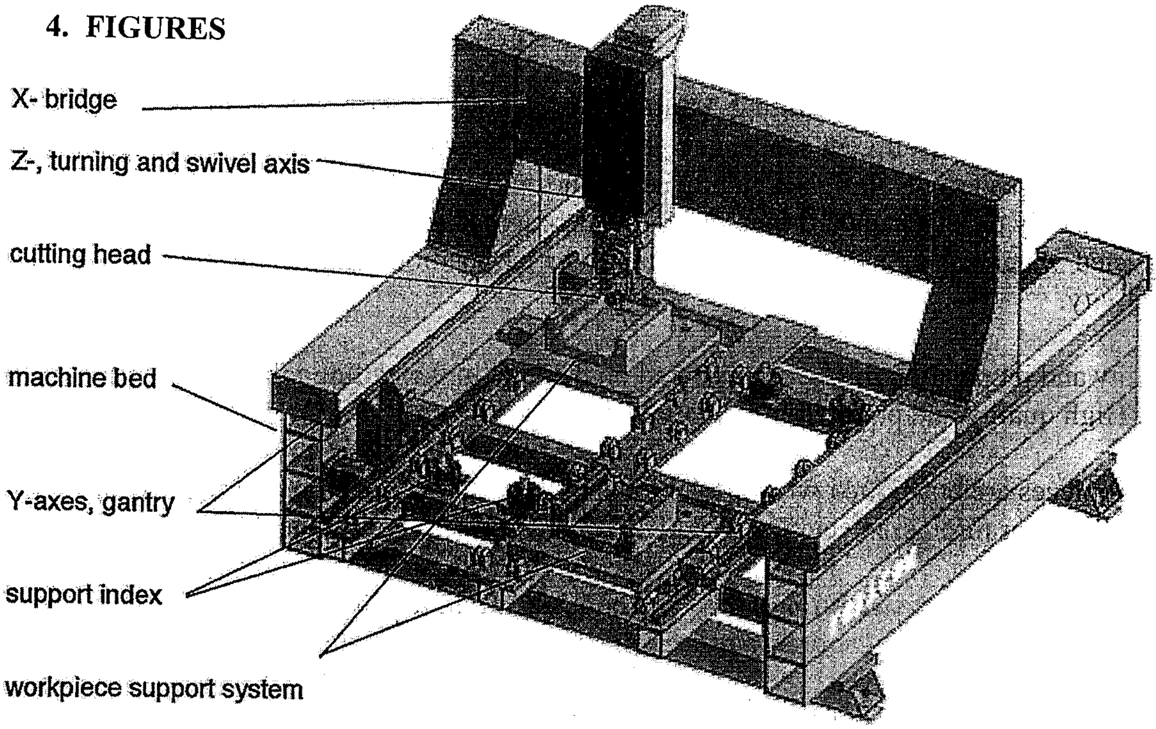

Figure 1: 5-axes Water Jet Machine with a single cutting head

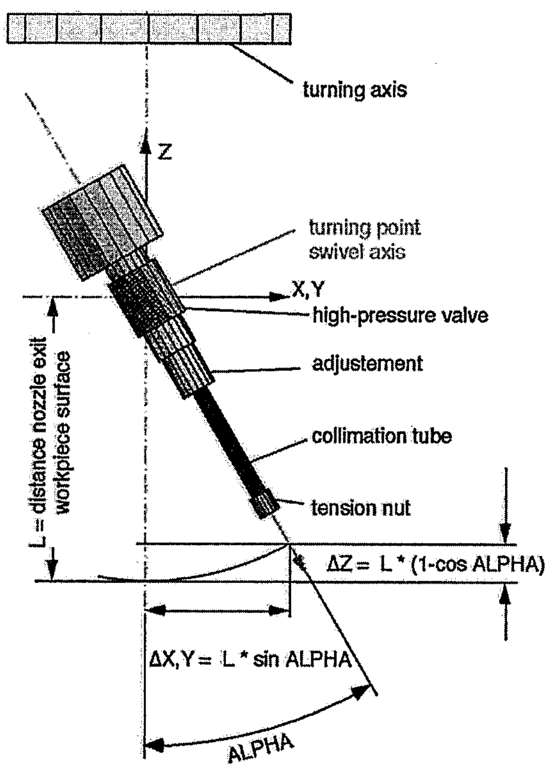

Figure 2: Cutting head programming with the angle functions sinus and cosinus

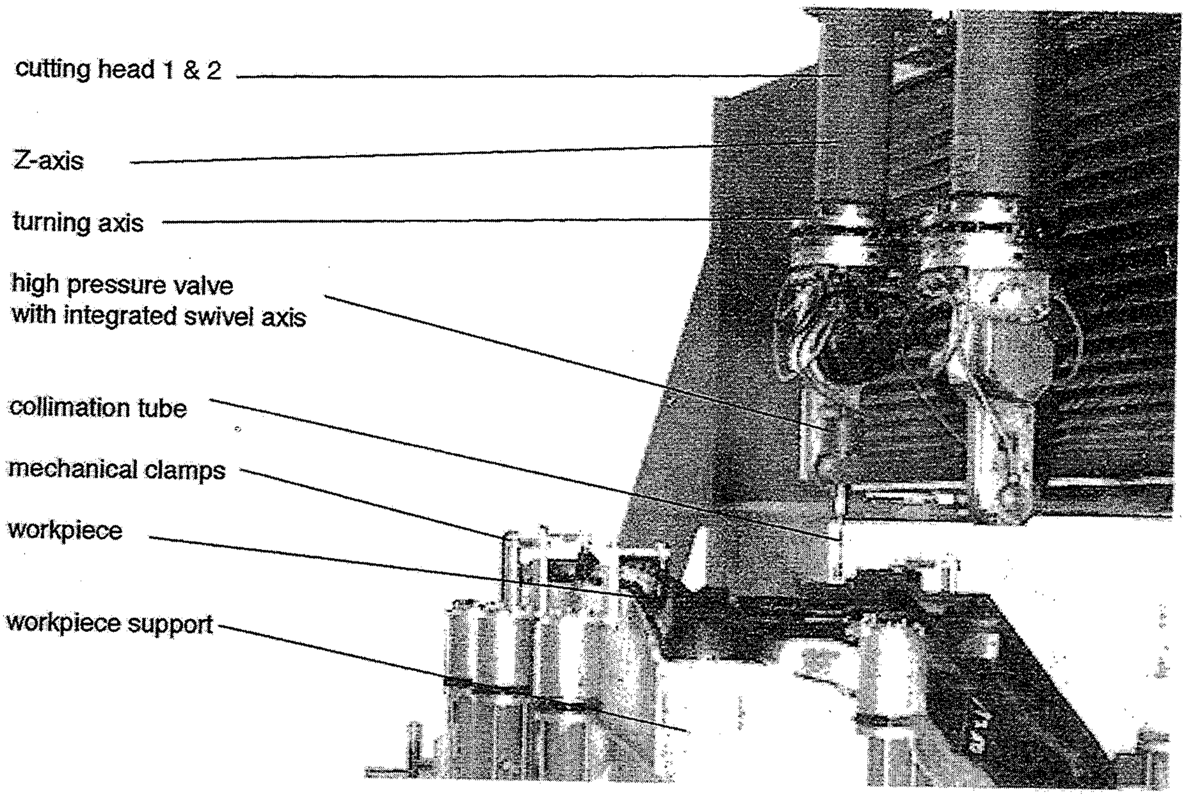

Figure 3: 5-axes Water Jet Machine with a double cutting head

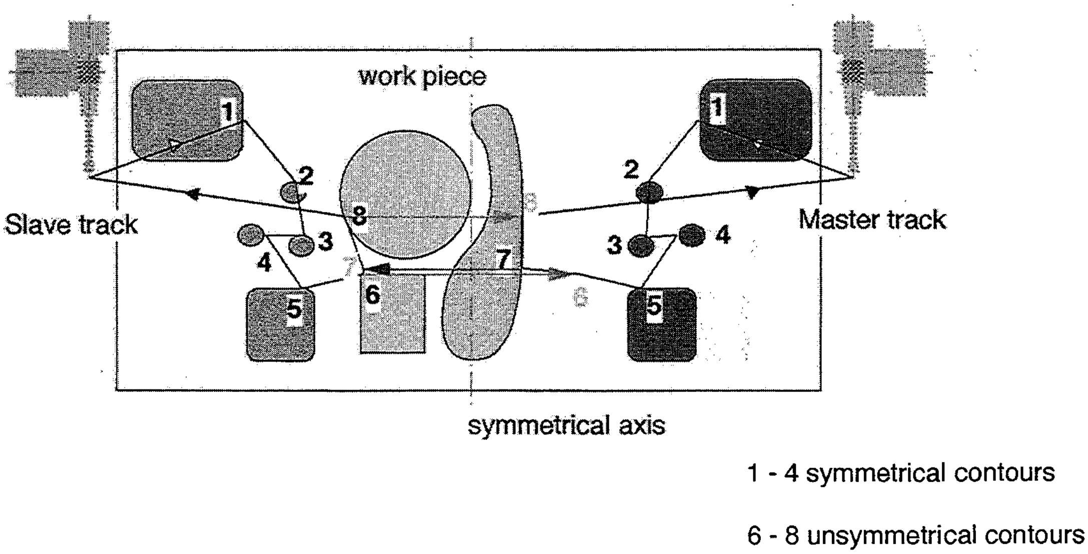

Figure 4: NC-Programming of symmetric and unsymmetric workpieces

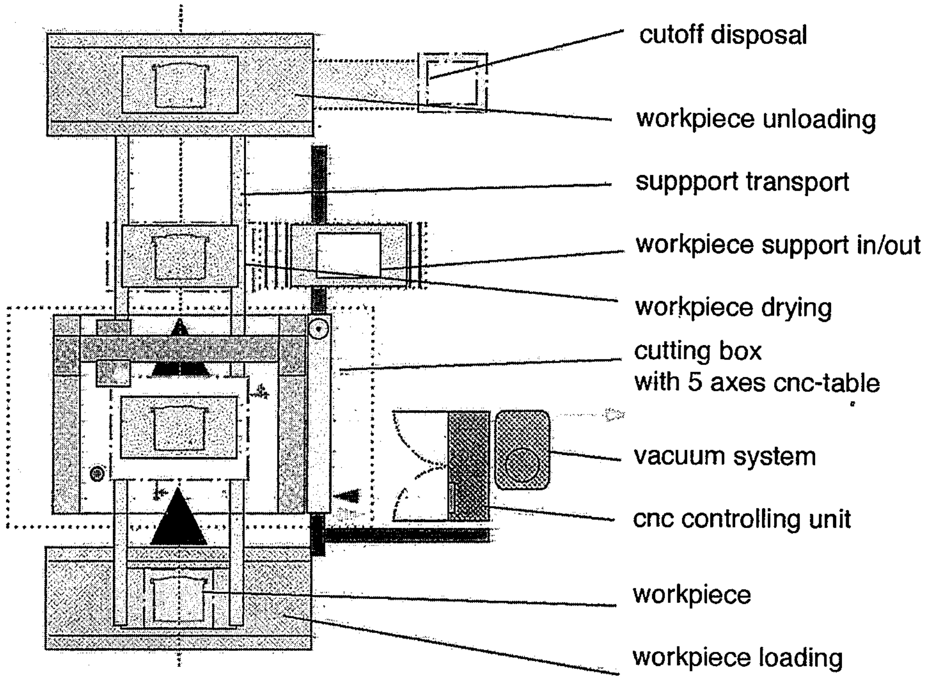

Figure 5: Layout of a high precision 5 axes water jet cutting system with workpiece transport, cleaning and drying station cutting mist vacuum system

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Paper 58

WATERJET MACHINE TOOL OF THE FUTURE

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ABSTRACT

This paper presents a vision for the waterjet machine tool(s) of the future. Significant advances have been made in the 1990s towards the goal of developing waterjet machine tools. New processes have been developed, refined, and implemented. New manipulators have been introduced. PC-based controls and software are emerging in the marketplace. However, existing systems are far from being "machine tools" by implication of being robust, deterministic, and precise. It is envisioned that, by implementing the state of the art in waterjet technology, a waterjet "machine" can perform as a "machine tool."

Organized and Sponsored by the Waterjet Technology Association.

1. INTRODUCTION

Waterjet (WJ) beams have unique capabilities as new machining tools. With a single waterjet-based system, several machining operations can be performed on a wide range of materials and geometries. For example, an abrasive-waterjet (AWJ) can cut, drill, turn, and pocket mill difficult-to-machine materials such as composites and high-strength alloys. Figure 1 shows an automatic sequence of complex shape machining. Current machining capabilities are listed in Table 1.

In addition to the capabilities listed in Table 1, WJs have great potential for other operations. For example, WJs can be used in the factory for surface preparation, stripping, surface peening, and cleaning.

To capitalize on the wide range of capabilities and high flexibility of waterjet-based systems, several existing advances need to be incorporated into a "marketable" standard WJ machine tool.

In the next section, the generic criteria for a WJ machine tool will first be listed. This will be followed by listing the elements of the waterjet machine tool. Meeting the generic criteria by the different elements will then be addressed for some selected components.

2. GENERIC CRITERIA

The generic criteria for a waterjet machine tool with single or multiple capabilities are:

1. Process robustness
2. Operational robustness
3. Accuracy and precision
4. Automation
5. Environmental control
6. Modularity
7. Maintenance
8. Cost effectiveness
9. Ease of use
10. Safety

Many of the above criteria are inherent advantages of the WJ process. For example, WJs/AWJs lend themselves to automation, and they are environmentally sound. The degree to which they meet the above criteria is application dependent and is, by proof of technology success, beyond the industry acceptable threshold. However, as the WJ/AWJ technology continues to mature, more demands will be placed on strict conformance to the above criteria.

The approach of this paper is to address conformance to the generic criteria through a matrix that links the above requirements to the elements of the machine tool.

3. ELEMENTS OF A WATERJET MACHINE TOOL

The waterjet machine tool consists of several subsystems that can be categorized in several ways. The following categorization is most common. Some selected components are listed in parentheses for each subsystem.

1. Ultrahigh-pressure (UHP) system (pumps, tubes, hoses, swivels)
2. Abrasive feed system (abrasives, metering device, vacuum assist, transfer system)
3. Tools/nozzles system (orifice, mixing tube)
4. End effector (nozzle body, Z-axis, wrist)
5. Manipulator system (motion system, tool changer)
6. Control system (motion, process)
7. Process sensor system (pressure, abrasive flow, jet health, nozzle diameter)
8. Machining sensor system (piercing time, kerf width, hole size)
9. Software (geometry, process software, inspection)
10. Water filtration system (for fresh and recycled water)
11. Abrasive recycling system
12. Fixturing system (part fixturing, jet referencing, residual handling)
13. Catcher and disposal system
14. Inspection system

In the above classification, observe that the end effector was listed separately from the manipulator. Observe also that it includes the nozzle housing. It is envisioned here that the WJ machine tool of the future will be highly modular and will incorporate only those items that satisfy the purpose of the machine tool and its cost range. With each class of machines, there will be a number of options for extended capabilities. For example, recycling of water and abrasives, inspection, pump capacity upgrade, turning upgrade, milling upgrade, drilling upgrade, and so on.

The challenges facing the machine tool of the future are satisfying a wide range of requirements and upgrading using standard components that can interface together properly. This is analogous to the personal computer's (PC) open architecture and will be a main feature of the future WJ machine tool. Starting from a basic manipulator configuration, the machine tool can be built up and upgraded. Obviously, there will be a number of "starting" geometries from which to choose. The following sections discuss the control strategy for the future WJ machine tool and list manipulator geometries and sizes that may form the starting platforms.

3.1 Controller

PC-based Open Architecture Control (OAC) strategy will be the standard control strategy for the WJ machine tool of the future. Extensive efforts have been spent to shift from the current "closed" CNC proprietary, incompatible architecture to a single "open" industry-standard, cross-platform compatible architecture. The open system architecture and modular design techniques do not exist today in the manufacturing control system industry. Current work on Manufacturing Operating System (MOS) designs uses standard PC platforms with off-the-shelf hardware. Existing PC-based, two-dimensional, WJ machining centers have demonstrated that PC control is viable. Figure 2 shows an example of such machines. The strategies used for control and communications are, however, different from one vendor to another. As the PC-based controller industry grows, a standard MOS for WJ and other machine tool processes will be used. This common platform will significantly enhance the acceptance of the WJ as a machine tool.

3.2 Manipulator Configuration

The following manipulator configurations are envisioned for the standard waterjet machine tool. Many of these configurations are already in the marketplace. However, these units will share common components, control platforms, and software. As in the machine tool industry, special systems will always be built to address specific and uncommon applications.

Single axis

- Stationary part (moving nozzle)
- Moving part (stationary nozzle)

Two axis

- Small size (0.5 m × 1 m [2 ft × 4 ft])
- Medium size (1 m × 1 m [4 ft × 4 ft])
- Large size (1 m × 2 m [4 ft × 8 ft])

Three axis

- The third axis on these machines will be an option for two-axis machines. Also, adaptive control (for terrain following) will be incorporated.

Four axis

The fourth axis will be a rotary axis for

- Angular positioning
- Turning and shaping
- Flat milling and stripping

Five axis

- A Z-axis adapted with a gimbal-type wrist (including internally plumbed nozzle housing) willbe an optional item for two-axis machines.
- A new class of axes with limited tilt angles within 15 degrees for taper and trailback control will be common for precision two-dimensional and three-dimensional cutting applications.

Six axis

- This will be of gantry and articulated arm types.
- The sixth axis for gantry machines will be an optional rotary axis as with four-axis machines.
- Articulated arm manipulators.

4. HYBRID MACHINE TOOLS

The use of WJ processing and mechanical drilling on the same machine is already in industrial use. In the future, a class of standard hybrid machine tools will be available. A modular mechanical end effector may be added or interchanged with the WJ end effector. Also, waterjet/laser hybrid machines will be developed for special processes. For example, a hybrid drilling machine where a laser is used for fast drilling and an AWJ is used for hole finishing may find wide use in the aerospace industry.

5. PROCESS ROBUSTNESS

The AWJ process encompasses several parameters, which can be divided into three groups:

1. Dynamic variables
   - Pressure
   - Abrasive flow rate
   - Traverse rate
   - Jet angle(s)
   - Stand-off distance
2. Quasi-static variables
   - Mixing tube diameter
   - Waterjet orifice
3. Static variables
   - Mixing tube length
   - Abrasive

For robust operation of an abrasive-waterjet system, we must be able to *optimally select* the above parameters to meet the machining criteria. Process sensitivity to influencing parameters must be minimized by operating at a wide plateau of optimal parameters. Databases and prediction models have been developed for a wide range of materials. Both can be used to select a robust set of parameters using proper software and expert systems. However, the accuracy of these predictions needs to be improved and extended to incorporate more parameters. For example, the operator must be able to input the required surface finish in common units.

A wider range of nozzle sizes and combinations will be needed to increase the flexibility of machining. For example, longer nozzles will be needed for robust cutting of thick materials. Also, predictable jet angulation routines for taper and trailback control will be used for precision five-axis machining. Process robustness will significantly improve with enabling hardware components.

6. OPERATIONAL ROBUSTNESS

Operational robustness is related to the implementation of robust parameters and thus is affected by several elements of the machine tool. Table 2 lists the needs for improved performance for relevant subsystems.

Significant advances have been made to improve the operational robustness of AWJ machines. However, many of these advances have not yet been incorporated in machining systems. The following is a list of these advances and their implementation status:

- The waterjet/mixing tube alignment problem has been resolved by precision manufacturing or by using an alignment system. Future nozzles will be aligned to quantifiable standards.
- A method for precise and quick changing of the orifice/mixing tube assembly has been developed and used in selected industries. This method has substantially improved tool tip locating accuracy.
- Vacuum assist for abrasive feed and flushing water for cleaning the mixing chamber have been developed for reliable and precise hole drilling operations.

- Process sensors for fail-safe AWJ machining have been demonstrated in the machining of fragile materials.
- PC-based, robust, two-dimensional control systems have been incorporated in AWJ machining systems.
- Cutting process software has been developed and integrated with PC-based control systems for AWJ two-dimensional cutting.

As process and operational robustness improve, the need for process sensors and monitors will be reduced. A feature of the WJ machine tool of the future will be the use of minimal amounts of process fail-safe sensors. Sensors will only be used for automation and status monitoring or for highly critical applications. Today, however, the use of sensors is a means of robustness improvement.

7. ACCURACY AND PRECISION

The AWJ has been demonstrated for machining to tight tolerances, as can be seen in Table 1. The demand for more precise (0.025 mm) WJ machine tools will increase as the technology continues to mature and as the number of highly trained WJ machinists increases. For example, most job shops that have been using the AWJ for rough cutting are now becoming familiar with the AWJ process and need more accurate and precise AWJ systems with additional capabilities (Ulrich, 1997, and Woleman, 1997). A most important driver to the need for accuracy is the engineering awareness of the WJ process and its advantages. It will be common that the WJ process is specified on engineering drawings with tighter tolerances.

Waterjet machine tool builders will face the challenge of improving the machine precision through both hardware and software improvement while maintaining competitive prices to other techniques.

Three classes of precision are proposed here for waterjet machine tools. These are:

- Class A: High precision (0.025 mm)
- Class B: Medium precision (0.13 mm-0.38 mm)
- Class C: Low precision (>0.38 mm)

The errors that affect the accuracy of WJ machine tools can be divided as follows:

Manipulator errors

- Position
- Orientation

Jet location errors

- Jet diameter (affected by wear)
- Jet vector position (affected by nozzle mounting/changing)

Process control errors

- Traverse rate
- Pressure
- Abrasive flow rate

The error budget is not linearly distributed among the above factors, and careful analysis must be made to account for the overall error budget. Strategies for accuracy control, such as precision system manufacturing and error compensation, must be optimally combined for practical implementation. For example, grid-mapping techniques will be a common option. Tilt wrists for jet vector compensation are another example. Cut taper and straightness will be easily controlled with tilt wrists.

For thin kerf cutting and accurate small feature machining, the ASJ process will be incorporated into WJ machine tools.

8. AUTOMATION

Automation requires enabling hardware, sensors, and robust control. In this section, we will focus on the nozzle/tool change as the critical enabling hardware for automation. Sensors may be needed for process sequencing or control. For example, the use of a piercing sensor (e.g., acoustic sensor) is important for controlling the dwell time during hole drilling. Mixing tube exit diameter sensing for tool compensation and replacement is another example. The use of machine vision assistance to develop the tool path or to inspect results in-process has been demonstrated. Standard sets for automation sensors will be available for the WJ machine tool of the future. *Plug-and-Automate* will be enabled by the openness of the control system.

The following sections describe selected components suitable for automation.

8.1 Nozzle Change

A precise automated quick-change nozzle system for both WJ and AWJ operations has been developed. This nozzle system consists of nozzle housing and WJ/AWJ tool assemblies (cartridges).

The nozzle housing body (Figure 3) will be an integral part of the end effector, which will contain a mounting recess for the WJ/AWJ tool and provisions for all of the process connections such as the UHP water, abrasive feed, flushing water, vacuum assist lines, and tool sensors. The UHP water flows through a port on the top of the nozzle. Seals for each port are integrated in the nozzle body to allow flow to the WJ/AWJ tool assembly. In the WJ machine tool of the future, the nozzle body will be an integral part of the end effector.

The WJ/AWJ tool assembly is a modular unit that plugs into the nozzle body. There will be several tool geometries and sizes to satisfy different machining requirements. Among these tools are:

- AWJ tools with different combinations of d_n/d_m (waterjet size/mixing tube length)
- WJ tools with different orifice and mixing tube sizes and geometries (round and fan)
- Side-firing and angle-firing tools

The WJ/AWJ tools will have locating features and matching ports to mate properly with the nozzle body. Tool tip position accuracy of 0.025 mm or better will be routinely achieved.

The WJ alignment station is a device that will be used to ensure that the WJ vector is in the correct direction before loading the tool on the machine. The need for this WJ alignment can be eliminated with precision manufacturing of components, especially orifices. An AWJ alignment station will be used during the fabrication/assembly of AWJ tools and in the quality control (QC) area to ensure correct tool alignment.

Automated WJ machine tools of the future will incorporate a tool changer for periodic nozzle change due to wear or for performing different programmed machining operations.

The tool change station clamps the WJ/AWJ tool in a rigid frame/turret. The manipulator provides enough force to push the WJ/AWJ tool into the nozzle body during pickup. Once the tool is seated, tool lock is activated in the nozzle body. The pneumatic clamp is then released, and the manipulator lifts the WJ/AWJ tool out of the station. The sequence is reversed during tool replacement.

8.2 Automated Abrasive Metering

Automated abrasive feed devices will be linked to the controller PC. The required abrasive flow rate will be programmed and can either be selected by the operator or the expert system software. Closed-loop control of the abrasive flow will not be needed for standard machines using robust process and operation procedures.

8.3 Abrasive Flow Rate Sensor/Detector

Abrasive flow rate sensing can be used for automatic closed-loop control of abrasive flow for special applications. However, common WJ machine tools will not need this level of control. Instead, an abrasive flow sensor/detector can be used for system shutdown when clogging or abrasive interruption occurs.

8.4 Orifice Health Monitor

Chipped or worn orifice edges result in poor waterjets and, consequently, deteriorated cutting performance. To detect orifice edge changes and wear, vacuum pressure monitoring at the plane of the WJ exit has been found reliable (Hashish et al., 1993). To incorporate an orifice health sensor, the machine controller would include a calibration utility to record a pressure-based sensor calibration reading. Alarm trigger points are set above and below the average calibration reading. This arrangement has proven to be an effective monitoring system.

8.5 Vision-Assisted Machining

Machine vision can be used to assist AWJ precision machining. For example, edge cut detection can be used to offset tool path. A standard vision module will be optional for future WJ machine tools.

9. ENVIRONMENTAL CONTROL

A significant advantage of the WJ/AWJ process is its environmental friendliness. However, two environmental issues need to be addressed for the future machine tool. These are noise and waste handling/recycling.

Noise can be reduced with shrouding or by cutting under slightly submerged conditions. The latter is in current practice and is most suitable for two-axis cutting, while the former is more suitable for multi-axis work. The noise levels for drilling and milling operations are within acceptable levels (<80 dB).

The recycling of abrasives is greatly advantageous for minimizing waste. If abrasives are recycled twice, then significant waste reduction can be obtained. It is believed that abrasives can be economically separated for re-use. However, their performance will be degraded. The use of recycled abrasives on an

AWJ machine tool will be for rough cutting and machining of less critical requirements. Also, recycled abrasives can be used for sandblasting applications. The WJ machine tool of the future will incorporate an optional abrasive recycling system with software capabilities for supporting the use of recycled abrasives.

10. MODULARITY

Configuration modularity is a key feature and an advantage of the WJ machine tool. Unlike conventional machine tools, WJ machine tools can be built in modular configurations. Examples of configuration modularity are given below.

10.1 UHP Pumps

Intensifier pumps lend themselves to modularity. A framing design where intensifier units plug in will simplify upgrading and maintenance. Direct drive pumps can also be modularized on the wet-end side. The pump modularization, however, will be limited due to power needs.

10.2 Manipulator

A few basic manipulator frames will be used for system configurations with a wide range of add-on features. For example, modules for turning, drilling, and milling can be added.

10.3 Software

Process software for WJ machining operations such as drilling and milling will be easily installed and continually upgraded. Geometry software will be extended to three-dimensional operations.

11. EASE OF USE

Both the software and hardware affect ease of use. Simplified software and part programming will be critical for PC-based machine tool acceptance. Hardware components such as quick tool/nozzle changing, simplified fixturing, self-cleaning catchers, and bulk abrasive handling are important for ease of use. In the following sections, we briefly address some ease-of-use issues.

11.1 Tool/Nozzle Changing

Quick and precise nozzle changing will provide a significant improvement to the ease of use of WJ/AWJ machine tools. This change can be made manually or automatically.

11.2 Software

Software programs have been developed to select cutting parameters based on process models. Existing software has demonstrated that AWJ operations could be made very easy and with very limited training. This trend will continue in the future with simpler and extended modules. Software that will further simplify WJ/AWJ operations is discussed below.

1. Process software—new software features will include:
   - More emphasis on quantitative results such as surface finish and wall taper
   - Modules for different machining operations such as drilling and milling
   - Software for tilt wrists for cutting around corners and straightness control
   - Virtual cutting for geometry and surface feature inspection
2. Nesting and inlay software
3. Direct cut software with input via scanner or modem

11.3 Abrasive Handling

For large WJ machine tool installations, abrasives can be handled automatically. A large hopper is used for storage and as a master feeder, while small hoppers are used for local feed. For small machine tools, abrasives are delivered in 100-lb bags. A special bag/container handling cart will ease the operators from having to lift the abrasives.

11.4 Self-Cleaning Catchers

In future WJ machine tools, no one will have to shovel abrasives out of the catcher. Abrasives will be either recycled or stored in disposal drums. Effective means will be implemented to keep the catchers clean.

12. CONCLUSIONS

Waterjet machine tools will be common in machine shops when they meet 10 basic generic criteria. In this paper, machine tool components have been divided into 14 items to discuss their effect on the generic criteria. Table 3 shows a matrix of generic criteria dependency on system components. Most important to WJ machine tools of the future will be their robustness, determinism, and ease of use. Waterjet machine tools should not be built to look like conventional machine tools, rather they should be built as WJ machine tools.

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Hake J., and Hashish, M., "The Next Generation of Waterjet and Abrasive-Waterjet Processing Technologies, Volume 2 - Manipulator Requirements," National Center for Manufacturing Sciences report under contract number NCMS-89-MPM-2, 1992.

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Table 1. Examples of Current AWJ Machining Capabilities

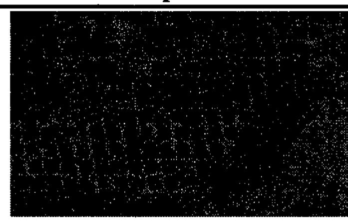
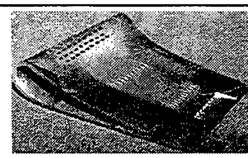
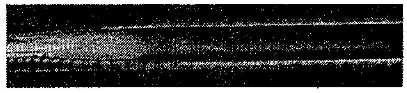
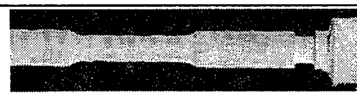
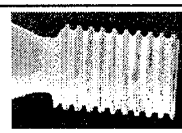
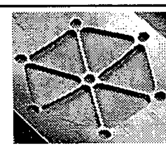
Process	Current Capabilities	Examples
Cutting	- Thin Sheet (5 mm) Straightness: 0.025 mm Surface Finish: 2.3 μm - Thick Materials (300 mm) Straightness: 0.5 mm Cutting Speed 0.2 mm/s	25 mm  Shaped hole cutting in titanium
Drilling (Piercing)	Small holes (0.4 mm in diameter) can be drilled at angles (25°) in thin (4 mm) materials.	25 mm  Holes drilled in jet engine vane
Deep Hole Boring	Holes can be drilled hundreds of millimeters deep in metals.	 Steel rod with 20-mm hole drilled with AWJ tool
Turning	Materials can be turned to accurate (0.025 mm) diameters.	25 mm  Turned Kevlar rod
Threading	Not sensitive to initial shape.	25 mm  Threads in glass
Wafering	Thin (0.15 mm) wafers can be sliced from 25-mm-diameter rods.	 Wafers sliced in carbon
Milling	Controlled depth to 0.025-mm accuracy can be obtained in metals and fragile materials.	100 mm  Milled shape in aluminum
Polishing	Surface finish of hard materials can be quickly improved to about 1 micron.	25 mm  Polished diamond film

Table 2. Operational Robustness Needs

Subsystem	Problem	Needs
UHP system	Hose failure. On/off valve response time.	UHP hoses with extended and predictable life. UHP on/off valves that respond in milliseconds. Pressure ramping for drilling systems.
Abrasive feed system	Abrasive line clogging.	Moisture control for fine abrasives. Vacuum assist, especially with pressure ramping. AWJ abrasive standards need to be established.
Tools (nozzles) system	Irregular wear. Nozzle change. Tool tip location.	Need longer life mixing tube for hard abrasives. Implement quantitative jet-tube alignment. Precise and quick change WJ/AWJ nozzle.
End effector	Not originally designed for WJ.	Includes all services to nozzle for no handling by operator during nozzle change. Height control means for large sheet cutting.
Fixturing		Need improved methods for handling cut outs. Eliminate part backside erosion due to jet sprayback.
Control system	CNC is not suited for AWJ.	PC-based Robust controller.
Process sensory system	Not implemented.	Implement process sensors (e.g., jet health sensor) System diagnostic. Responsive abrasive flow sensing.

Table 3. Generic WJ Criteria Dependent on WJ System Components

System / Criteria	1	2	3	4	5	6	7	8	9	10
UHP system		■			■	■	■			■
Abrasive feed		■								
Tools/nozzles	■	■	■	■		■			■	
End effector			■	■		■			■	
Manipulator			■	■	■	■	■	■		■
Controller		■	■	■		■				
Process sensors		■		■				■		
Machining sensors		■		■						
Software				■		■			■	
Water filtration					■					
Abrasive recycling					■			■		
Fixturing system		■	■			■			■	
Catcher and disposal					■		■			
Inspection system			■					■		

Key for Criteria

1. Process robustness
2. Operational robustness
3. Accuracy and precision
4. Automation
5. Environment control
6. Modularity
7. Maintenance
8. Cost effectiveness
9. Ease of use
10. Safety

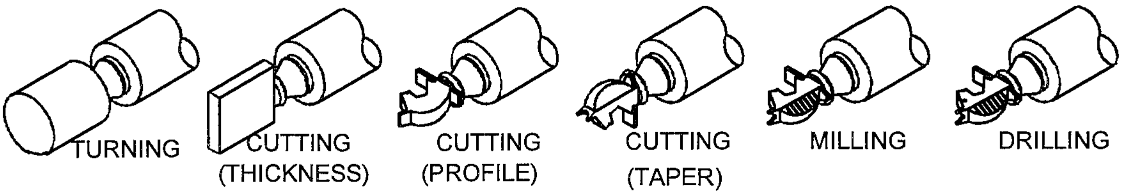


Figure 1. Complex Shape Machining Sequence

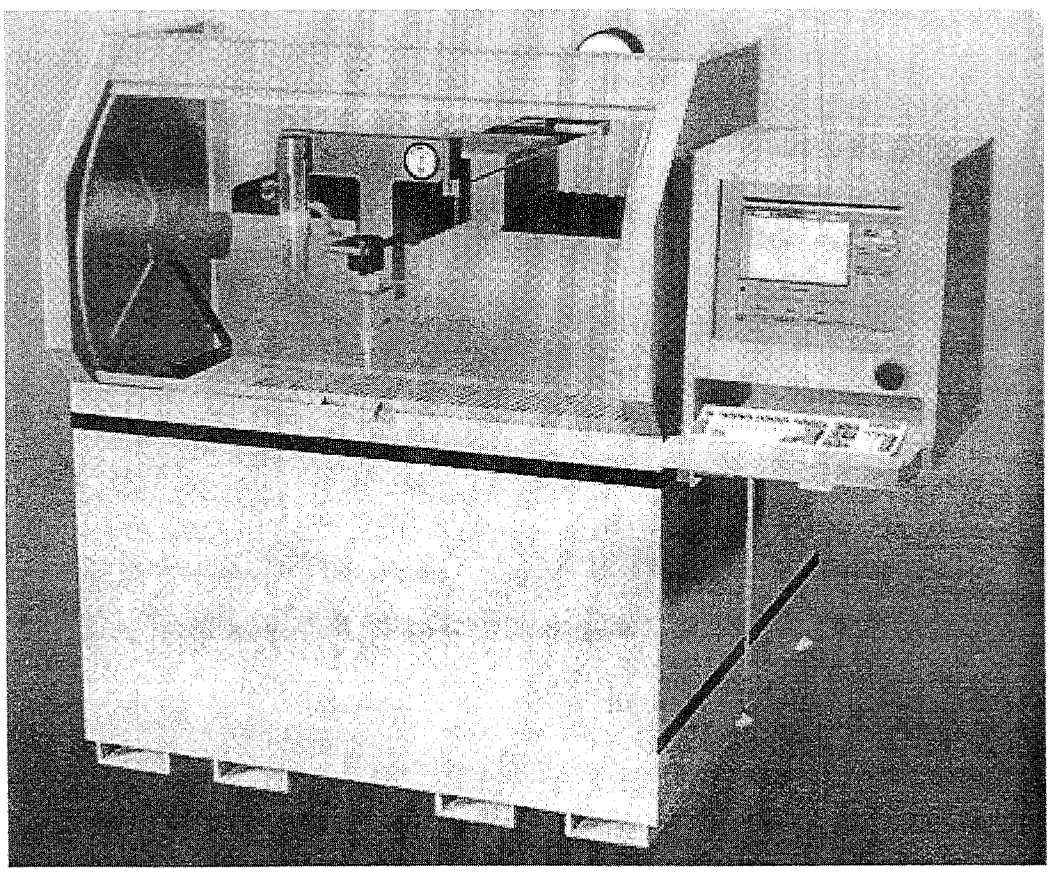


Figure 2. Example PC-Based WJ Machine Tool

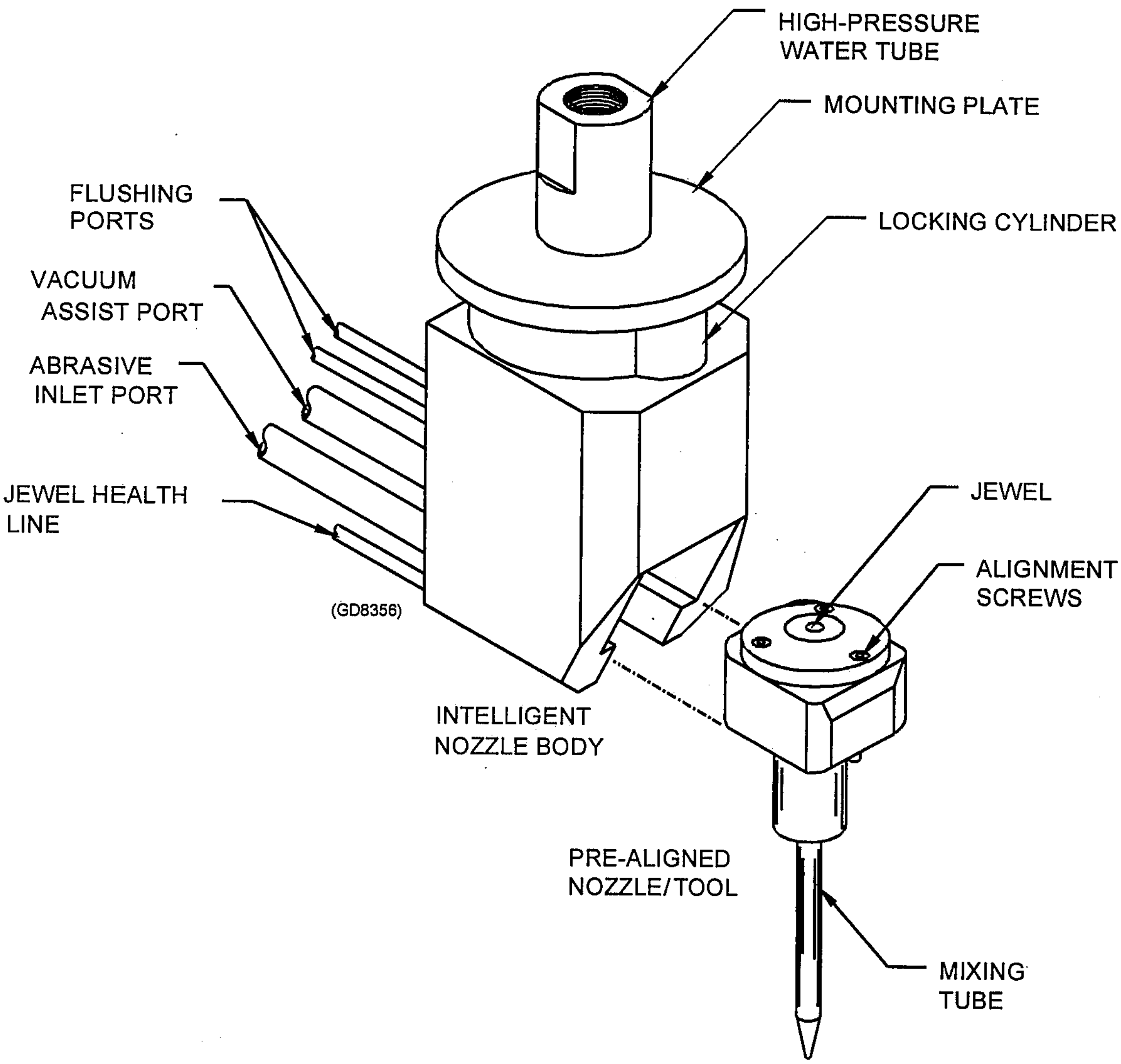


Figure 3. Quick Change Nozzle Assembly for Automation

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WATERJET-RELATED NOISE AND ITS COUNTERMEASURES

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ABSTRACT

During the water jetting operation, considerable noise is sometimes generated, though the noise level is usually lower compared with the other corresponding operations. In this report, "How hazardous is the noise radiated from the water jet and the water jetting equipment?" is assessed from the comparison between some measured results obtained in this research and the bibliographical data, and then some countermeasures of the noise are recommended.

At first, the otological and psychological influences of noise on man have been researched bibliographically. Next, the measurements about the noise generated during the water jetting operation were obtained from experimental research. Finally, some countermeasures to reduce the dangerous effects of the noise are recommended in this report.

For example, it has been confirmed in this research that the operator of the water jet can be exposed to a noise level which exceeds the otological upper limit of man even when the delivery pressure of a pump unit is not very high.

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1. INTRODUCTION

Man chiefly senses sound by his ears. The sound with low level seldom causes any problems. However, when it increases to high level, it causes mental pain and sometimes causes physical trouble such as hearing loss. Such sound which causes the mental pain or the physical trouble as mentioned above is "noise," which is defined as "Unwanted sound" in the book referenced in 7.

In some machines or some works where the water jet is used, considerable serious noise is generated. Though a lot of safety codes or recommended standards such as the references of 4, 6, 9, 15 are in the various countries, there are only a little quantitative information relating the noise generated during the water jetting operation.

In this report, "How hazardous to man is the noise generated during water jetting operation?" is assessed, and some recommendations to reduce the risks of the noise are shown with some measured results of the noise.

2. STANDARDS OF NOISE ASSESSMENT

2.1 Noise-induced Hearing Loss

In the working place where noise exceeds L_{pA} = 100dB, a cruel tinnitus is caused by the noise even when the staying is for a short period of time, and the temporary hearing loss occurs. Even when the noise level does not exceed such a high level as above, the decrease in hearing ability occurs and is related largely with the noise level and the staying time in the place, especially with the amount of high pitch sound around f = 4kHz. The periodical exposure to such noise for many years causes permanent hearing loss. (3)

The temporary hearing loss caused by the big noise of the short period is called "Noise-induced temporary threshold shift, NITTS or TTS simply." The periodical exposure to such big noise for many years causes unrecoverable hearing loss, which is called "Noise-induced permanent threshold shift, NIPTS or PTS simply." It is said that NIPTS never recovers forever. (1)

ISO 1999:1990 "Acoustics -- Determination of occupational noise exposure and estimation of noise-induced hearing impairment," shows that the pure tones of noise the noise exposure level normalized to a nominal 8h working day $L_{EX,8h}$ of which are less than the following values do not cause NIPTS on man of 50% in average. f is the frequency of the pure tone.

$L_{EX,8h}$ = 93dB at f = 500Hz
$L_{EX,8h}$ = 89dB at f = 1kHz
$L_{EX,8h}$ = 80dB at f = 2kHz
$L_{EX,8h}$ = 77dB at f = 3kHz
$L_{EX,8h}$ = 75dB at f = 4kHz
$L_{EX,8h}$ = 77dB at f = 6kHz

According to these values, the otological upper limit of noise under which the hearing impairment does not appear is thought to be roughly 80dB in continuous A-weighted sound pressure level. In most countries, L_{pA} = (85~90)dB is the legal upper limit.(8) Therefore it is recommended that workers are never exposed to the noise the level of which is more than L_{pA} = 90dB for a long period of time periodically.

2.2 Effects of Noise on Aural Communication

Hearing loss caused by the noise is not the only hazardous effect on man. In general, the more noisy the working site becomes, the less effective the aural communication between workers becomes. Based on the standard of 95%, which is used as the lower limit of satisfactory intelligibility in ISO/TR 3352-1974, it is thought from the data of the reference 9 that the A-weighted sound pressure level L_{pA} = 65dB is the upper limit of noise for the satisfactory aural communication. The noise of more than this level causes that the workers need to speak together in contact very closely with each other for the aural communication. The noise of more than L_{pA} = 90dB causes the serious slow-down of work because workers need to speak each other quite loudly near the ear.(2) So that, from the safety aspect, such high noise at the work site is a serious hazard that causes delay of coping with an accident or an emergency.

It is said that the percentage of correct hearing in a large classroom decreases to 80% when the noise there increases to more than L_{pA} = 50dB, and that the noise in a small room needs to be less than L_{pA} = 60dB for the aural communication. [10] So that, it is thought that when the noise level in the room for a preparatory meeting for example exceeds L_{pA} = 60dB largely, the hearing failure of some important subjects happens in the meeting and an accident based on it is possible to be caused.

3. NOISE RADIATED FROM WATER JETTING EQUIPMENT

Though various equipment is used during the water jetting operation, almost all the noise is radiated from a pump unit and the water jet including its surroundings such as nozzles and work objects. The pump unit, which generates high-pressure water, is assembled of a pump, an electric-motor, a diesel engine and/or a lot of various attachments. Nowadays, an electric-motor is so quiet compared with the other equipment, but the pump and the diesel engine sometimes radiate big noise as before.

The book of JSME (12) has reported that a diesel engine, which is widely used in a construction site, with 6 tandem cylinders radiates a noise of L_{pA} = 97dB at the distance of 1 m. So that, an operator of the pump unit which includes a diesel engine can be exposed to the noise badly exceeding the otological upper limit of noise, if any appropriate countermeasures are not applied.

In the unit to generate high-pressure water for water jetting operation, a reciprocating-type displacement pump with plungers or pistons is used usually. Noise from the reciprocating-type pump is mainly caused of intermittent flow induced by the cyclic motion of the mechanism. Though the authors could not obtained the data on the noise from the displacement-type pump for high-pressure water, usual oil-hydraulic piston pumps of 60kW has been reported to radiate the noise of roughly L_{pA} = (50~70)dB. (11)

It is thought from these data that the noise from the diesel engine is much higher than that from a pump itself in general.

4. NOISE RADIATED FROM WATER JET

The noise generated from the water jet during the water jetting operation is thought to be mainly composed of

1. Noise originated by the breakdown of the work object.
2. Noise originated by the hitting of the drops of water to the solid surface of the work object.
3. Noise originated by the flow turbulence induced by the collision of the jet and the work object.
4. Cavitation noise.
5. Jet noise.

The noise of 1~3 is mainly generated on the surface of work object or in its neighborhood, but the noise of 5 is generated near the nozzle. The noise of 4 is thought to be generated in both of these two spaces.

In this research, the noise radiated from the water jet discharging from a cylindrical nozzle and hitting a work object normally during the water jetting operation was measured. The nozzle did not move during each experiment.

4.1 Experimental Apparatus

As the experimental apparatuses, two systems named A and B as shown below were used in this research. The nozzles were set for the jet to be discharged horizontally in the air and to hit the surfaces of work objects perpendicularly.

System A Pump unit: 5 MPa in delivery pressure.
Nozzle: Cylindrical nozzle of 1 mm in diameter.
Work object: Cement block.
Standoff distance l = 5 cm ~ 30 cm.
A sound level meter microphone was set at a distance of about 90 cm from noise sources.

System B Pump unit: 200 MPa in delivery pressure.
Nozzle: Cylindrical nozzle of 0.25 mm in diameter.
Work object: Aluminum block.
Standoff distance l = 2.5 cm ~ 28 cm.
A sound level meter microphone was set at a distance of 2 cm from noise sources.

Noise were measured by a sound level meter which complies with IEC 651 Type 2 from one of the following 12 measuring directions shown by the vectors in Fig. 1, excepting the case that it is indicated as the other type meter was used.

$\boldsymbol{A}_1$	:	Spatial vector on x-axis facing to the origin O.
$\boldsymbol{B}_1$	:	Spatial vector on xz-plane facing to the origin O. Both the angles between the vector $-\boldsymbol{B}_1$ and x-axis and between the vector $-\boldsymbol{B}_1$ and z-axis are $\pi/4$.
$\boldsymbol{C}_1$	:	Spatial vector on z-axis facing to the origin O.
$\boldsymbol{A}_2$	:	Spatial vector on xy-plane facing to the origin O. Both the angles between the vector $-\boldsymbol{A}_2$ and x-axis and between the vector $\boldsymbol{A}_2$ and y-axis are p/4.
$\boldsymbol{B}_2$	:	Spatial vector on the plane including the vector $\boldsymbol{B}_1$ and y-axis facing to the origin O. Both the angles between the vectors $\boldsymbol{B}_1$ and $\boldsymbol{B}_2$ and between the vector $\boldsymbol{B}_2$ and y-axis are $\pi/4$.
$\boldsymbol{C}_2$	:	Spatial vector on yz-plane facing to the origin O. Both the angles between the vector $-\boldsymbol{C}_2$ and z-axis and between the vector $\boldsymbol{C}_2$ and y-axis are $\pi/4$.
$\boldsymbol{A}_3$	:	Spatial vector which is parallel to the vector $\boldsymbol{A}_1$ facing to the point O_w.
$\boldsymbol{B}_3$	:	Spatial vector which is parallel to the vector $\boldsymbol{B}_1$ facing to the point O_w.
$\boldsymbol{C}_3$	:	Spatial vector which is parallel to the vector $\boldsymbol{C}_1$ facing to the point O_w.
$\boldsymbol{A}_4$	:	Spatial vector which is parallel to the vector $\boldsymbol{A}_2$ facing to the point O_w.
$\boldsymbol{B}_4$	:	Spatial vector which is parallel to the vector $\boldsymbol{B}_2$ facing to the point O_w.
$\boldsymbol{C}_4$	:	Spatial vector which is parallel to the vector $\boldsymbol{C}_2$ facing to the point O_w.

The point O is the origin of xyz-axes Cartesian coordinates of right-hand system and set at the pointed end of nozzle, where the jet discharges. The y-axis corresponds both to the center line of the jet and to the discharging direction of the jet. The point O_w is the point on y-axis where the jet hits the surface of work object. The x- and the y- axes are horizontal and the z-axis is vertical. The distance l between the points O and O_w is the stand-off distance. The noise radiated to the measuring directions shown in the vector $-\boldsymbol{B}_2$ and $-\boldsymbol{B}_4$ is so important because this noise comes directly to a nozzle operator.

In order to separate the noise radiated from a certain point from the others, a circular straight tube of 83 cm in length and 7.5 cm in outer diameter was applied in some experiments. The internal surface of the tube was covered with fiberglass wool of about 1 cm in thickness to absorb the noise different from the selected. The internal diameter of the circular opening that noise passes through was about 4 cm. This tube is called "Focusing tube" in this report.

4.2 Experimental Results and Discussions

The level L_{pA} of the noise radiated from the pointed end of the nozzle and its surroundings in the system A was 55.7dB ~ 57.5dB in the average values of 50 measurements of each measuring directions. The focusing tube was set between the nozzle and the sound level meter. The one end of the tube was set near the pointed end of the nozzle, where the jet discharged, and the sound level meter was set in the other end of the tube. All the differences among the measuring directions shown by the 6 vectors $\boldsymbol{A}_1$, $\boldsymbol{B}_1$, $\boldsymbol{C}_1$, $\boldsymbol{A}_2$, $\boldsymbol{B}_2$ and $\boldsymbol{C}_2$ were negligible compared with their uncertainties of measurements.

Figure 2 shows the experimental results on the relation among the noise level L_{pA}, the stand-off distances l and the measuring directions. The system A was used as the experimental apparatus for these measurements. The focusing tube was set between the point O_w and the sound level meter. The pointed end of the tube was set near the point O_w and the sound level meter was set in the other end of the tube. All the points in the figure show the average values of 50 measurements.

The level L_{pA} of the noise radiated from the hitting point of the jet on the surface of the work object, O_w, and its surroundings to the directions shown by the 3 vectors $-\boldsymbol{A}_4$, $-\boldsymbol{B}_4$ and $-\boldsymbol{C}_4$ were much higher than the level of the noise radiated from the nozzle and its surroundings shown above. Almost all the noise radiated from the point O_w and its surroundings is thought to be generated by the hitting of a water jet and the excavation of a work object. The noise radiated from the nozzle and its surroundings is thought to include the jet noise of water jet. Therefore the noise originated by the hitting and the excavation including the break-down of a work object may be much higher than the jet noise during the water jetting operation, though the characteristics of the focusing tube on sound is not very clear.

In the case of $l \approx 20$ cm for the system A the level of the noise radiated from the point O_w and its surroundings to all the directions shown by the 6 vectors were higher compared with the cases of the other stand-off distances in each directions.

Figure 3 shows the change in the level L_{pA} during the first 20 minutes just after the time when the water jetting started ($T = 0$ min ~ 20 min). All the plotted points on the figure show the average value of 5 measurements. The system A was used. The focusing tube was set between the sound level meter and the noise source.

The case of $y = 0$ cm shows the change in the noise which was radiated from the nozzle and its surroundings and measured by the sound level meter set at the measuring direction shown in the vector $\boldsymbol{B}_2$. The 5 cases of $l = 10$ cm ~ $l = 30$ cm shows the noise which was radiated from hitting point O_w on the work object and its surroundings and measured by the sound level meter set at the measuring direction shown in the vector $\boldsymbol{B}_4$.

This figure shows that the level L_{pA} of the noise radiated from the hitting point O_w and its surroundings was higher at the time just after the jetting started and reduced a little and then kept nearly constant. In this research, this reduction of noise was $L_{pA} = (10\sim15)$dB. It is confirmed from this figure that the level L_{pA} of the noise from the nozzle and its surroundings rarely changed during all the above period of time.

In the case that $l = 20$ cm and the focusing tube was not used, the level L_{pA} of the noise which was measured by the sound level meter set at the measuring direction shown in the vector $\boldsymbol{B}_4$ was $L_{pA} = (90\sim94)$dB. The noise level $L_{pA} = 94$dB was measured at the time the jetting started, and the noise level $L_{pA} = 90$dB round was measured at the time 1 minute after the jetting started and later. Therefore even when the delivery pressure of a pump unit is 5 MPa or lower the operator of the water jet is possible to be exposed by the noise the level of which exceeds the otological upper limit of man.

Figure 4 is the change in the octave-band sound pressure level L_p of the noise in this case during the first 20 minutes after the jetting started. A sound level meter with octave-band band-pass filters was set at the measuring direction shown by the vector $\boldsymbol{B}_4$. The focusing tube was not used. This figure shows that level L_p of higher-frequency noise was higher than those of the lower frequency noise. This frequency dependence of the octave-band sound pressure level L_p of noise are very similar to the earlier experimental results obtained by C. R. Barker et al. (5) in the frequency range of f = 63Hz ~ 8kHz. Therefore, the noise radiated from the waterjet has a lot of high pitch sound, which causes the hearing loss seriously as mentioned before.

Figure 5 shows the results obtained by the system B. The changes in the level L_{pA} of the noise during the first 5 minutes just after the jetting started are shown in this figure. The noise was measured by a microphone which was 20 mm distant from the hitting point O_w and set at the measuring direction shown in the vector $\boldsymbol{C}_3$. Though the noise of this experiment, where the pressure of water jet is much higher than that of previous cases, is much higher than the noise measured by means of the system A, the time-dependence of the change of noise level during the excavation of a crater is very similar to each other. The noise radiated from the hitting point O_w and its surroundings during the excavation by water jet changes in such the manner as the noise level is higher at first and becomes lower to a certain level and then keeps almost constant.

In order to clarify the relation between the above change in noise and the process of excavation by water jet, the change in the depth D_e of the crater excavated by water jet was measured. Figure 6 shows the results. From the comparison between the figures 3 and 6, it is confirmed that during the first a few minutes just after the jetting started, when the noise level was higher, the excavation speed $\partial D_e/\partial T$ was higher, in general.

4.3 Field Work

The authors did field work on the noise generated during water jetting operations in conjunction with the above laboratory work and have obtained the following results.

For the preparation of internal surface of a long steel pipe the internal diameter of which was about 5 m for painting, the water jet of the pressure of 180 MPa and the flow rate of 800 cm^3/s was used. The water jet nozzle was not a hand-held type but set in a machine which was remotely controlled. The noise in the pipe measured during the jetting was L_{pA} = 112dB at about 3 m distant from the nozzle. It is understood that the noise level in the pipe exceeded seriously the otological upper limit of noise and reached the state where appropriate countermeasures were necessary for the protection against the hearing loss.

5. RECOMMENDED COUNTERMEASURES OF NOISE

From the above research, it has been confirmed that countermeasures of the high-level noise generated during the water jetting operation are necessary.

Countermeasures of the noise are separated into the following 4 categories.

1. At noise sources.
2. In noise-propagating paths.
3. Around or on workers.
4. By means of management.

5.1 Countermeasures at Noise Sources

The most important way to reduce the hazardous effects of noise is that the power level of noise radiated from each noise source becomes lower. Sometimes not only water jetting equipment but also the equipment which is not used in the water jetting operations become the noise source, because the vibration generated by the water jetting equipment propagates to the equipment through solid materials such as floor, pipe, etc. and changes to noise.

The following are important for the countermeasures of the noise generated during the water jetting operation.

1. The pump unit should be chosen as its noise level is as low as possible.
2. The pump unit should be operated as its delivery pressure is as low as possible.
3. The pump unit should be supported by the material which isolates vibration such as rubber, to stop the propagation of vibration generated there to the other equipment.
4. The work object should be fixed tightly not to generate vibration.

5.2 Countermeasures in Noise-Propagating Paths

Noise radiated from noise sources propagates as air-borne noise and/or structure-borne noise and finally reaches the ears of man as the former. Hence, in the case that noise cannot be reduced effectively at the noise sources, it can be reduced in the propagating paths of noise as the second choice of countermeasures.

In general, sound pressure level L_p drops at a rate of 6dB for each doubling of distance away from the sound source, when a point sound source, which is small enough compared with sound propagating distance, radiates sound in all direction homogeneously in a free sound field, which is a field in a homogeneous, isotropic medium free from boundaries. This is called as "Inverse square law."

When sound wave transmits through a panel, the energy of sound dissipates or reflects and the sound-transmission loss T.L. occurs. T.L. is equal to the number of decibels by which sound incident on the panel is reduced in transmission through it. T.L. shows the degree of the sound insulation of the panel. For a single panel of uniformly distributed mass, with no air leaks through it, and with negligible stiffness, the transmission loss at a given frequency and angle of incidence is determined only by the mass. This ideal case is expressed by the theoretical "Mass law", which predicts an increase in the sound-transmission loss T.L. at a rate of 6dB for each doubling of frequency or mass per unit area.(15) When a small window is opened in the panel, T.L. becomes much smaller, because the T.L. of the open window is so small.

Therefore the following two ways based on the inverse square law and the mass law are effective as the countermeasures in noise-propagating paths. All the noise sources should be set in the places as distant from workers as possible. All the noise sources should be full-covered by the panels the mass per area of which is as heavy as possible. The covering panels should not have any unnecessary openings. It is very important that the noise is insulated at the position as close to the noise sources as possible.

5.3 Countermeasures around or on Workers

In the case that the above two countermeasures are not effective, workers must be protected against the noise by such means as follows.

1. Workers are in places which are distant from noise sources.
2. Human bodies are covered by the materials which noise does not pass through.
3. Ears are covered by the materials which noise does not pass through.
4. Ear canals are closed by the materials which noise does not pass through.

In the case that all the equipment used in the water jetting operation are controlled remotely and/or automatically, workers should be in the places which are distant from the noise sources or in quiet rooms insulated from noise. These are the countermeasures based on 1 or 2. But in the cases that these countermeasures can not be applied, the ways based on 3 or 4 should be used. In these cases protective equipment for personnel has to be used. Typical protective equipment for personnel against noise is earplugs and earmuffs.

In the *Recommended Practices* by WJTA, "All operators and all visitors shall be issued and shall wear hearing protection while in the working area." is stated. (15) In Japan, for example, the Ministry of Labor regulates legally as workers must use the protective equipment against noise such as the earplugs in the working sites the noise level L_{pA} of which is 90dB or more. There are similar legal regulations in many other countries, too.

There are various types of earplugs. At least, the earplugs fitting individually to the ears should be chosen, otherwise noise passes through the opening. The training by the experts or professionals is quite effective. Earmuffs are also effective for the hearing protection, especially to insulate the higher-pitch noise. As the noise radiated from water jet has a lot of higher pitch noise as mentioned before, earmuffs are much more effective than earplugs. But some workers feel them as obstacles, and the earmuffs interrupt communication among the workers.

Which type of hearing protections should be worn during the jetting operation? The answer should be derived case by case within the range where the noise coming into the ears is less than the otological upper limit of noise. In the case where the noise level in working site is much higher than L_{pA} = 90dB it is effective that the earplugs and the earmuffs are worn together. To keep communication between operators, the earmuffs with telecommunications devices should be taken into consideration, too.

5.4 Countermeasures by Means of Management

It is said that the effect of noise on a worker depends on his working condition. The total amount of noise which a worker receives is one of the important factors of noise-induced hearing loss as mentioned above. The countermeasures of noise by means of the management are thought to be effective. The appropriate alternation of a worker is sometimes one of the applicable countermeasures. The alternation may stop the accumulation of the total amount of noise and stop the change in the noise-induced hearing loss from the temporally threshold shift to the permanent threshold shift.

The countermeasures mentioned in this paper are effective only when workers and managers apply them correctly in their working sites. Education and training in advance are necessary to be done correctly. Through the education and training of the operators, supervisors and managers, the appropriate actions on the noise protection should be taken in accordance with the situation of noise in the site.

6. CONCLUSIONS

Some experimental and bibliographical researches on the noise generated during the water jetting operation and its countermeasures have been done. Some of the results shown in this paper are summarized as follows.

1. Even when the delivery pressure of a pump unit is 5 MPa the operator of the water jet may be exposed by the noise to a level which exceeds the otological upper limit of man.
2. The noise radiated from the point hit by a water jet and its surroundings on a work object is much higher than the noise radiated from the nozzle and its surroundings during the excavation by the water jet.
3. The noise radiated from the point hit by a water jet and its surroundings during the excavation by the water jet is higher at the time when the water jetting starts and then reduced gradually to a certain level.
4. The noise radiated from a water jet has a lot of high pitch sound, which causes the hearing loss seriously, during the excavation by the water jet.

7. ACKNOWLEDGMENTS

Finally the authors heartily express their thanks to Mr. Kunitoshi Akatsuka of Nihon Setsubi Kogyo Co., LTD. for his assistance in many experiments and to Mr. Hisayoshi Tomae of Toho Kogyo Co., LTD. for his kind offer of the chance to measure the noise in his working site.

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9. NOMENCLATURE

$L_{EX,8h}$: Noise exposure level normalized to a nominal 8h working day defined in ISO 1999:1990.
L_p : Sound pressure level.
L_{pA} : A-weighted sound pressure level.
l : Stand-off distance, SD.
T : Time which has passed after water jetting started.

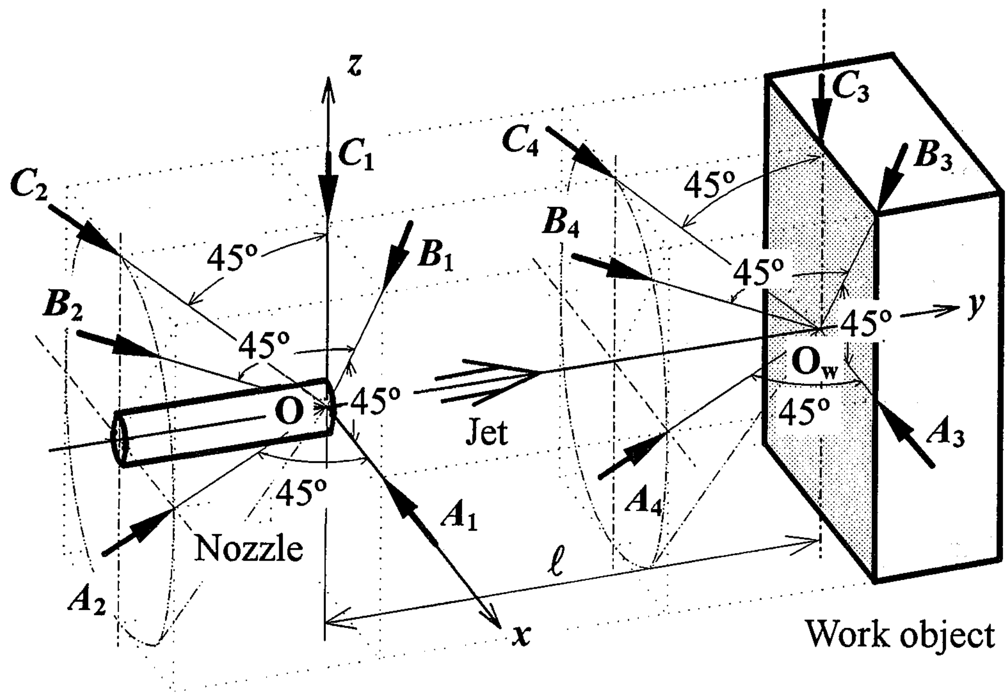

Fig. 1 The Definitions of the *xyz*-axes Cartesian Coordinates and the Vectors Showing the Measuring Directions.

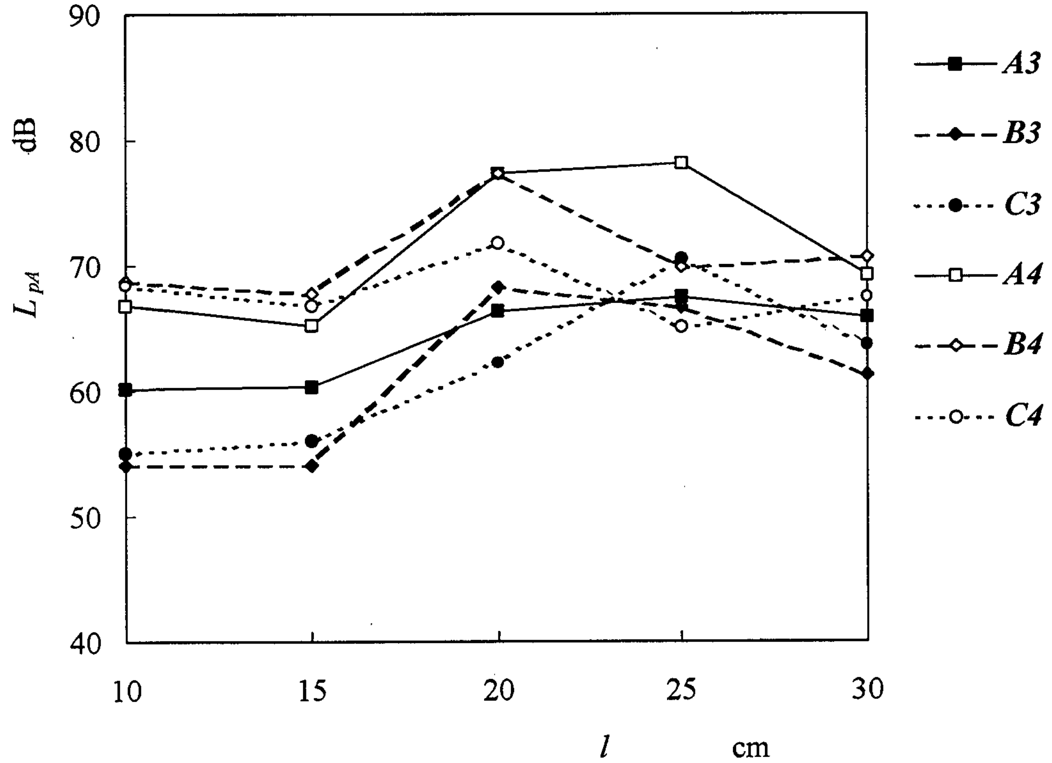

Fig. 2. The Level L_{pA} of the Noise Radiated from the Hitting Point O_w on the Work Object and its Surroundings in Relation to the Stand-off Distance l. The Focusing Tube and the System A were Used.

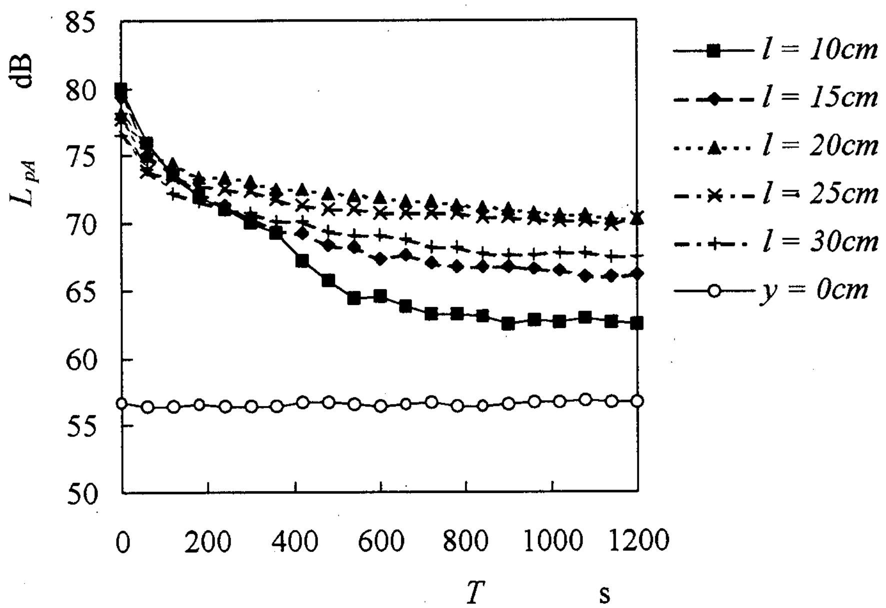

Fig. 3 The Change in the Level L_{pA} during the First 20 Minutes just after the Time when the Jetting Started. The Focusing Tube and the System A were Used.

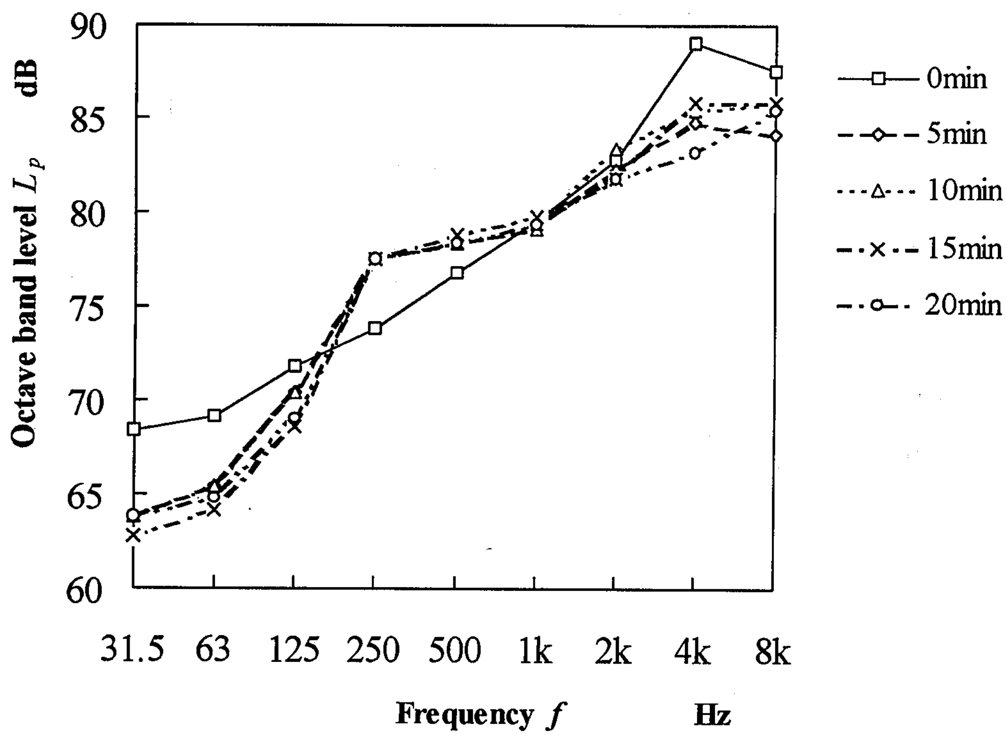

Fig. 4 The Change in the Octave-band Sound Pressure Level L_p of the Noise during the First 20 Minutes just after the Jetting Started. The Focusing Tube was Not Used. The System A was Used. The Stand-off Distance l = 20cm.

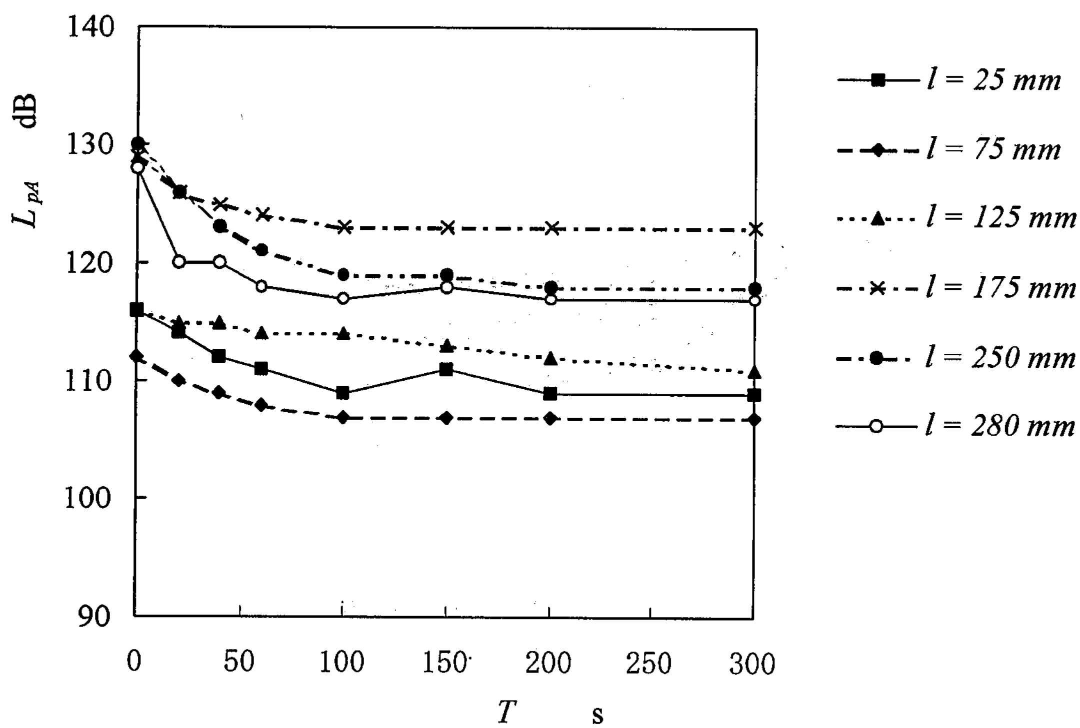

Fig. 5 The Changes in the Level L_{pA} of the Noise during the First 5 Minutes just after the Jetting Started. The Focusing Tube was Not Used. The System B was Used.

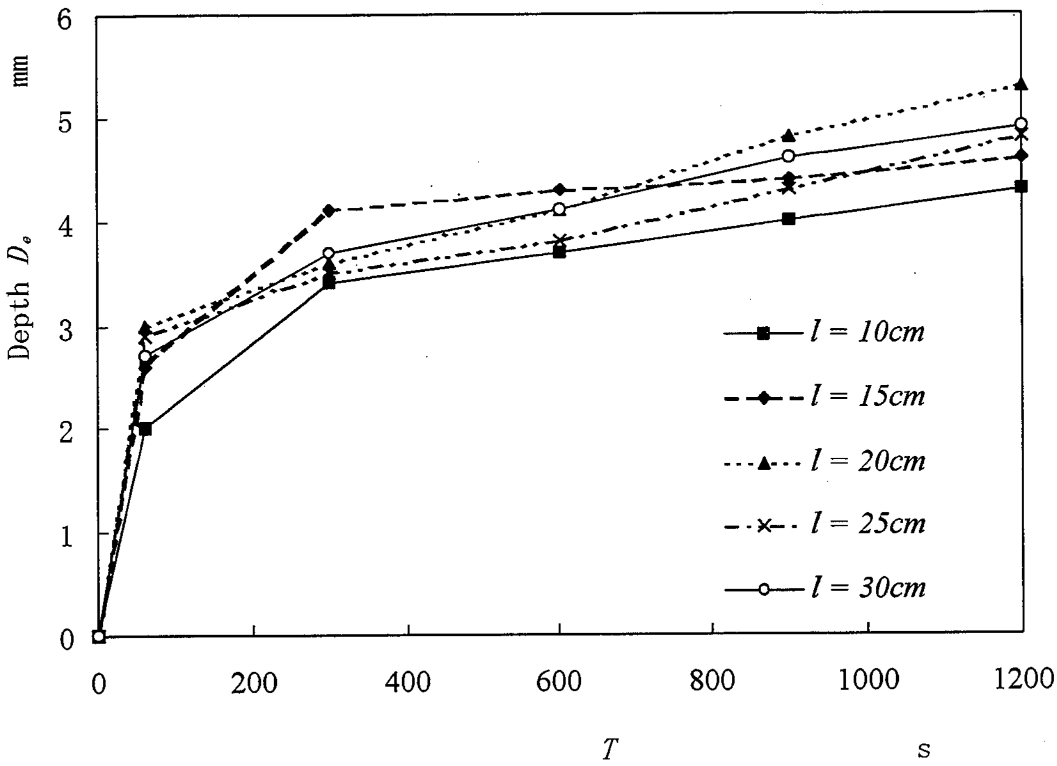

Fig. 6 The Change in the Depth D_e of the Crater Excavated by Water Jet during the Jetting. The System A was Used.

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Paper 60

THE HYDROBLADE™ KERATOME; PRINCIPLES AND MICROSCOPIC CONFIRMATION OF SURFACE QUALITY

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ABSTRACT

The operating principles of a new microkeratome are described. In the new device, the conventional surgical blade is replaced by a small diameter (33 μm), high speed, homogeneous waterjet (actually sterile, saline solution). The operating principles, the various methods or modes in which it can be used, and the experimental method will be described. The results of scanning electron microscope studies and light microscope studies will be described for the new microkeratome and compared to conventional devices.

The new HydroBlade™ Keratome is intended to be used for corneal surgery, particularly "damage free" removal of shaped or parallel discs such as for therapeutic surgery, corneal lamellar transplants, producing parallel hinged flaps, refractive surgery, and rapid precise removal of epithelium (the anterior surface of the cornea) without damage to the underlying Bowman's layer.

Epithelial removal by a HydroBlade™ Keratome is shown to be at least as good as alcohol removal without the concerns associated with using alcohol and quicker and far better than scraping with a conventional blade. By any standard, the HydroBlade™ Keratome is shown to be virtually an ideal lamellar surgery device and probably far better than current scalpel devices.

Organized and Sponsored by the Waterjet Technology Association.

1. INTRODUCTION

Deficiencies in mechanical or laser surgical devices for lamellar surgery motivated the work on this new approach to corneal surgery based on the use of a waterjet. Conventional microkeratomes, using oscillating metal, diamond or sapphire blades, have some serious theoretical and actual deficiencies. Among these are the necessity for establishing a high intraocular pressure (IOP), typically above 65 mm Hg, a microsaw cutting action which tears and shreds rather than cleaves the lamellar structure, loss of keratocytes at the surface, mechanical distortion of the tissue during the cut with the potential for wedge shaped or irregular flaps, inability to precisely control the thickness, and a residue of blade chips. All of these limit the usefulness and safety of microkeratomes for keratomileusis in situ.

The accuracy of current refractive surgery techniques is also in question. Neither photo refractive keratoplasty (PRK) nor keratomileusis in situ produce a postoperative change in refraction that is acceptable when compared to spectacles or contacts. Nominal correction errors for PRK or LASIK are reported to be as large as ± 1 diopter while keratomileusis in situ, albeit with larger attempted corrections, may have errors as large as ± 3 diopters (Seiler, 1996).

The desirability of having a microkeratome that is safer and more effective led to the work described herein. The HydroBlade™ Keratome, based on the use of a high speed waterjet, was invented by the first author of this paper and initially reported by Medjet Inc. in 1994 (Dillman, 1994). The initial experimental work for demonstrating corneal surgery was done at Medjet Inc. and refinements, including the concept of the shaping template, led to the HydroBlade™ Keratome.

Another motivation was the belief that conventional epithelial removal as a necessary precursor to PRK contributes to the variability in the achieved refractive results. Blade scraping disrupts the surface of Bowman's layer and establishes local differential hydration changes based on the timing of the removal. This would have an effect on the local ablation rate.

In what follows the reader will find a description of the various tissue cutting mechanisms of the waterjet which were used to produce hinged or unhinged flaps, excise shaped or parallel discs of a chosen thickness and cleanly and rapidly remove epithelium in defined areas. Finally, results on cadaver eyes and a brief description of animal experiments will be presented.

2. METHODS

2.1 How The Waterjet Works As A Tissue Separation Mechanisms For Surgery

The classic text by Eisner is fundamental to much of what is described here (Eisner, 1990). Eisner describes cutting, cleaving and erosion as the fundamental tissue separation options. The sectility of the tissue is essential to the choice. In the case of low sectility material, cutting is optimal since moving blades enhance the tissue separation. However, cutting with metal and sapphire blade is necessarily damaging since there is a tearing and shredding component associated with blade friction. As will be seen later, the damage associated with cutting is exceptionally high in the cornea. Erosion produces enormous tissue damage and should be avoided for lamellar surgery.

The cornea is highly sectile in a direction roughly parallel to the lamellar interface. Tissue that is highly sectile favors cleaving as the separation mechanism and cleaving limits tissue damage. Hence, it follows that lamellar surgery is best done in a cleaving mode. Since we demonstrated that the waterjet could operate in a cleaving mode, we thought that it might be an ideal tool for lamellar surgery. In particular, we have shown that a waterjet that is scanned in an approximately lamellar direction perpendicular to the direction of the water flow operates in a cleaving mode only if the tissue is not under compression. When the tissue is under compression then it separates tissue by erosion. Hence, whenever the corneal tissue is to be cleaved by a waterjet, it must be under slight tension in a direction perpendicular to the anterior surface. In contrast, when tissue is to be removed, such as in epithelial removal, erosion is appropriate and the tissue should be under compression.

Another characteristic of the waterjet is its ability to cut, cleave or erode certain tissue when the water speed is above a threshold value, but not when it is below. The threshold value depends on the tissue and it is typically different for each tissue in a heterogeneous structure. The water speed may be set above the threshold value for cutting the tissue of interest but below the threshold value for damage to adjacent material. Hence, the waterjet is capable of anisotropic tissue separation or removal when the beam speed is chosen properly. Therefore, we considered that it would be possible to totally erode away the epithelium in a prescribed area without loss or damage to a single cell of the Bowman's layer.

2.2 Microkeratome Design

The results described here were obtained on a laboratory microkeratome utilizing computer controlled, X-Y linear position drives for scanning and positioning with 1 μm placement accuracy, a filtering system for the sterilized water with 0.1 μm pores, and water pressure capability up to 20,000 psi. The beam forming orifice is a ruby jewel with a specially shaped aperture (36 μm diameter) and a shaped nozzle. The resulting beam diameter is typically 0.9 times the orifice diameter.

2.3 Beam Characteristics

The waterjet microkeratome is implemented by using a circular, parallel beam of sterile, highly filtered water moving at supersonic speed. Beam diameters ranging from 10 μm to 100 μm are used depending on the application. The achieved fish line lengths are typically more than adequate for the applications described here.

For lamellar surgery the beam parameters are not especially critical. Typical settings are as follows: The stagnation pressure is 20,000 psi or 1360 atmospheres and the beam diameter is 33 microns. This produces a fish line length of about 10 cm. The measured water flow rate in the beam is about 0.367 ml/s. We approximately calculate the maximum beam speed at the beam center from the stagnation pressure using Bernoulli's Equation. This gives 460 m/s. The speed at the surface of the beam is lower. The average beam speed is established by two experimental methods, (1) the total beam momentum and (2) the flow rate: (1) When incident on a force transducer, the entire beam essentially comes to rest, i.e., has zero momentum. It exerts a force of about 15 gram wt. on the transducer which by calculation gives the incident beam momentum flow; i.e., the momentum change per unit time. Using the measured water flow rate and the momentum change per unit time, the average speed can be calculated to be about 400 m/s. (2) From the beam diameter and the flow rate we calculate the average speed. This gives about 430 m/s. The beam area is not known to at least the degree of difference between the two. We take 400 m/s as the proper value.

From the flow rate and the average speed, we calculate that the beam carries a continuous kinetic power of about 29.4 watts (80 joules per milliliter). The measured temperature rise of the spent beam in a non calorimeter arrangement is of order 10°C, is probably consistent with this calculation.

The globe is kept at normal IOP which increases by no more than 15% during the cut (as measured by a needle tonometer). The beam is mechanically scanned in a direction perpendicular to its length, defining a cutting plane. The emerging beam beyond the cutting region is only slightly changed in appearance since only the surface of the beam is in contact with the tissue and there is some scattering. During a cleave, the exiting beam force as measured on the force transducer is reduced by only 1.5 gram wt. for the longest cleave dimension, 8 mm. Some of the water is scattered, and not stopped, and simply does not fall on the transducer. If this factor is ignored, the 1.5 gram wt. reduction can be equated with the maximum force on the cornea. However, the force on the cornea is most likely substantially less.

The cleave, within the plane across 8 mm of cornea at a scan speed of 10 mm per second, takes 0.8 second (compared to 2 seconds for a scalpel cut), and requires no more than 294 microliters of sterile water. By measurement of the flap thickness and the residual corneal thickness, it cannot be said that absolutely no tissue is lost since the measurement error is a few microns. However, by electron microscope observation of the cleaved surfaces it can be said with certainty that no tissue is lost during the cleave; rather the cleave is demonstrably a perfect blunt dissection. The short time for the cleave and the negligible force on the cornea during the process (a maximum of 1 - 2 gram wt. compared to tens of gram wt. for a conventional scalpel cut) insures the precision of the cut. Even an unsupported cornea at normal IOP does not visibly move or compress when it is cut by a HydroBlade. In this case, the HydroBlade can shave off layers as thin as a few microns.

Beam contact with the tissue along its path is for only about 20 microseconds and the water moves only parallel to the surface of the cut tissue, and not into the tissue, hence there should be no hydration. Absence of hydration is verified by the complete absence of aeration in the tissue which would be expected if there were hydration since the water in the beam contains air in a concentration well above the normal concentration at atmospheric pressure. When hydration is produced intentionally, as by directing the beam into the tissue, there is substantial aeration. This is further confirmed by transmission electron microscope observation of the cross section after a blunt dissection.

We expect that there is minimal heating of the tissue. For reference, note that at room temperature it takes about 4.2 joules to raise by 1 °C the temperature of 1 milliliter of water. Since the beam carries 80 joules of kinetic energy per milliliter, the maximum temperature rise the spent beam water can experience, assuming no heat loss to the surrounding, is 18 °C. During the time the beam is cleaving the tissue, at most only a tenth of its kinetic energy is converted to heat in the tissue or spent water, since a maximum of 0.1 of the beam is stopped by the tissue, if it is stopped, based on the force measurements. The rest of the kinetic energy remains in the transmitted, unscattered, beam water. Hence, worst case a maximum of 2.4 joules of energy could be dissipated in the cleaved area of the cornea.

The spent water with a volume of 0.029 milliliters coming in contact with the cornea would have a maximum temperature rise above ambient of 18 °C if no heat were transferred to the cornea. However, if part of this energy actually goes into the cornea, which has a similar specific heat, we would need to know the volume of the cornea that is heated to estimate the temperature rise. We expect that this heated corneal volume could be at least 0.025 milliliters, producing a total heated volume, spent water plus cornea, of at least 0.052 milliliters, twice that of the water. The associated equilibrium temperature rise would be not more than 9 °C and probably much less since it would take time for the heat in the spent water to transfer to the cornea and the spent water moves away before that can happen efficiently. Recall that there is no hydration; the water is not really in contact. Under no circumstances could the temperature of corneal tissue rise by as much as 18 °C, even in a thin layer. If there is a significant temperature rise it would be for at most a brief instant measured in microseconds. However, it should be kept in mind that the water is probably not stopped, but scattered, and gives up little of its kinetic energy. As a sanity check it should be noted that when a cut is made and the cornea is immediately touched with a finger there is no evidence of a temperature rise. In general, this is a topic worthy of more study even though the heating is too small to be of significance It really bears on the precise mechanism of cleaving.

There are no shock waves, although a low background acoustic spectrum might be generated based on waterjet studies on hard materials (Geskin et al., 1993). In fact, there are no known physical or chemical mechanisms other than the mechanical force at the level of 1 gram that might impact the safety of the procedure or the condition of the tissue. As noted, the magnitude of the mechanical force is substantially lower than that associated with scalpel cuts.

2.4 Cleaving and Shaping

The physical explanation for how the HydroBlade cleaves is fairly complex but a simple way to understand the physics is to consider that water molecules or micron sized droplets at the boundary of the beam collide with tissue as the beam begins to come into contact with the tissue. The boundary water mass is deflected and changes its transverse momentum component from virtually zero to some finite value directed inward into the beam. This is equivalent to providing an outward reactive force on the tissue from the beam. The beam behaves much like a circular wedge of enormous rigidity not available from normal materials. It cleaves along the easiest path, sacrificing beam energy as it goes. The stagnation pressure is made large enough that the cleave is completely through the tissue for the chosen scan speed, which is typically about 10 - 20 mm per second. The emerging beam shows little degradation.

In contrast, cutting across a lamella and breaking all the fibrils takes substantially more energy than an interlamellar cleave in which only a few fibrils need to be cut. Thus, the scan rate is chosen to be lower for a shaped lenticule in which lamellae must be cut.

The nature and shape of the incised tissue is defined by the shape of the anterior surface of the cornea during the planar HydroBlade™ cut. The anterior shape during the cut is established by a suction template, since incision by a waterjet requires that the tissue not be under significant compression. A suction template deforms the tissue by pulling it toward and into the template rather than by applanating the tissue. A flat template spaced a predetermined distance away from the plane of the cut produces a parallel, lamellar flap of thickness equal to the distance. A hinge of predetermined width may be produced by blocking the jet during the scan so that it does not cut all the way from side to side. A slightly concave template allows removal of a plano convex lenticule of predetermined refraction. Lenticules with positive, negative or astigmatic refraction may be removed.

The design features of the actual template are complex and include a micro-roughened surface that grips the anterior corneal surface and insures the stability of the cornea during the cleave. This minimizes corneal oscillations, thereby ensuring achievement of the desired thickness of the lenticule and the accuracy of position of the cleaved boundary region. In producing a flap, the template design consists of a circular cylindrical trephine as the boundary within which is the circular template. A small circular gap between the template and the inner wall of the trephine provides a vacuum suction ring which converts the template surface into a vacuum chuck. The trephine is used to create a well defined, shallow gutter region surrounding a central corneal plateau. The jet therefore enters the lamellar structure without the need to cut through lamellar layers.

3. EXPERIMENTAL METHODOLOGY

3.1 Lamellar Resections

Pairs of eyebank (cadaver) eyes from the same donor, no more than two days old were mounted in holders. A flap was created in one eye by Robin Beran, MD, using a Chiron ACS Keratome. The Medjet waterjet microkeratome was used to produce an 8 mm diameter, 150 μm thick flap in the other eye. The corneas were fixed and prepared for electron microscope study using standard fixing techniques.

3.2 Epithelial Removal

The same methodology was utilized except that the microkeratome was used in the erosion mode, i.e., the template was used as an applanator and the cornea was compressed. The stagnation pressure was set at 3000 psi and a 100 μm orifice was used. About 4 ml of water was used for the removal.

An approximate 8 mm diameter circle was cleared. The second matched eye was scraped with a #15 Bard Parker blade for about 1 minute in an 8 mm circle by a laboratory technician who is highly experienced in epithelial removal.

For purposes of our understanding, an experimental template in the form of a transparent glass slide was used in order to ease alignment and to observe the process. The round beam was aligned to be incident at an angle of about 15° on the flat template and the water would sheet across the template surface. The water flowed between the template surface and the Bowman's layer. The force of the waterjet impinging on the epithelium eroded and washed it away. In this experiment the HydroBlade removal took about 1 second using about 10 milliliters of water. The shape of the removed area was determined by the perimeter shape of the applanated area. The shape of a non planar template and a non spherical cornea also influences the perimeter shape of the cleared area.. (The dynamics of the sheet waterjet beam are complex and what we learned will be the subject of a future publication.)

4. EXPERIMENTAL RESULTS

4.1 Lamellar Resections (Cleaving)

Parallel cleaving with a waterjet to generate a corneal flap produces a new stromal (lamellar) surface such as would be expected with an ideal blunt dissection. The removed cap is without wedge. The cadaver eye cap is 8 mm in diameter and about 150 microns thick. The top untouched surface and the underside cleaved surface are essentially indistinguishable. The associated surface of the stromal bed is not smooth on a microscopic level since the ideal lamellar surface is not smooth. A visibly smooth surface would be a damaged surface.

In scanning electron microscope (SEM) comparisons of the HydroBlade cleave and the conventional mechanical microkeratome it can be seen that the mechanical microkeratome pulls and rips tissue while the HydroBlade cuts only the few collagen fibrils linking vertically adjacent. Keratocytes are not removed in the process of HydroBlade cleaving. They are removed in microkeratome blade cuts. In transmission electron microscope (TEM) and scanning electron microscope (SEM) studies of the cornea cross section after resection, there is absolutely no evidence of subsurface change.

Resection of non parallel lenticules (cutting through the lamellae) takes more energy from the beam. The trajectory of the cut is along the interlamellar boundary and then quickly across the lamella and then along the boundary again. The transit across the lamellae requires cutting many more fibrils than in an interlamellar cleave. The locus of the across-the-lamella transit is generally a narrow circular ring and it was anticipated that this would be the site of haze in the post surgical live cornea. In contrast, no haze was expected in the interlamellar region. It was, in fact, observed experimentally in rabbits that low level haze occurs only where the cut is across the lamella. It does not occur along the cleaved interlamellar boundary. Thus, the haze in Dutch Belted rabbits was observed in the form of a bull's-eye pattern and it was generally low level and gone in less than 15 weeks.

4.2 Epithelial Removal

It is observed that the HydroBlade™ removal of the epithelium is right down to the surface of the Bowman's layer with no alteration of Bowman's tissue whatsoever. Blades used for scraping the epithelium actually remove surface Bowman's layer material and the resulting surface may be locally smoother in appearance under SEM than what is produced by the HydroBlade™. In contrast to blade scrapings, no epithelial cells remain on the Bowman's layer nor is there damage to the fibrils of the Bowman's layer. Indeed, to the best of our ability to determine by SEM and transmission light microscope (TLM), the removal is identical to the removal produced by alcohol without the potentially deleterious effects of alcohol (Cintron et al., 1979).

5. DISCUSSION AND SUMMARY

New approaches to epithelial removal and lamellar surgery based on the use of a waterjet as an alternative to a blade have been described. It is explained and demonstrated that the HydroBlade™ is much less damaging to the cornea than oscillating blades in common use and potentially much safer. The new HydroBlade™ Keratome is intended to be used for lamellar surgery, particularly "damage free" removal of shaped or parallel discs such as for therapeutic surgery, partial corneal transplants, for producing parallel hinged flaps; for refractive surgery, etc.; and for rapid, precise, complete removal of epithelium without damage to the Bowman's layer.

It is shown that the mechanism of lamellar cleaving with a HydroBlade™ is that of an ideal blunt dissection. Confirmation is provided by high magnification SEM comparisons between conventional scalpel microkeratomes and the HydroBlade Keratome using cadaver eyes from the same donor. It can be expected also that the surface shapes of removed or cut sections can be defined within microns to produce accurate refractive changes. We anticipate no irregular astigmatism or wedge. We anticipate that the keratocytes that remain on the surface with HydroBlade cuts and the lack of damage to the fibrils and lamellae should result in less trauma and more stable and quicker healing especially for hinged flaps such as used in LASIK. We anticipate that less epithelial ingrowth will occur. The beam does not come into contact with epithelium during the cleave.

It is expected that the HydroBlade™ Keratome will be easier to use and safer than conventional microkeratomes. The relative simplicity and low cost of the equipment may lead to much lower cost for the associated procedures bringing the technique within reach of many more individuals.

Epithelial removal is quick, immaculate and damage free. The superior ability to clear the epithelium is expected to result in more accurate PRK surgery. The cornea hydrates quickly when the epithelium is removed with either a blade or a HydroBlade. The hydration changes the rate of photoablation. Thus, a quick, clean procedure can improve the accuracy of PRK.

The virtually damage-free and accurate lamellar keratoplasty and quick, immaculate epitheliumectomy auger well for a new era of corneal surgery.

6. ACKNOWLEDGMENT

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8. NOMENCLATURE

Hg	≡ mercury
HydroBlade™	≡ registered trademark of Medjet
IOP	≡intraocular pressure
LASIK	≡ laser assisted keratomileusis in situ
ml/s	≡ milliliters per second
mm	≡ millimeters
m/s	≡ meters per second
μm	≡ microns
psi	≡ pounds per square inch
PRK	≡ photo refractive keratoplasty

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NORMALLY CLOSED VALVE OPTIMIZATION WITH APPLICATION TO POLYNOMIAL MODELS

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ABSTRACT

Most high pressure waterjet cutting systems use normally closed pneumatic valves (NCV). These valves are designed and used only as nozzle valves to control and operate flow. While the characteristics and performance of a simple NCV are well known, the influence of these parameters on the time response is not so clear. This paper presents an experimental approach for the solution of this problem.

An experimental approach (investigation) was conducted to investigate the influence of NCV parameters on the time response in abrasive waterjet cutting. High water pressure, air pressure and orifice diameter were the principal variables that were investigated. Using the multifactor method of experiment, four polynomial equations for geometrical and mechanical parameters of the normally closed valve were created. Closure speed function of actual pressure and orifice size were used. Comparison of two different polynomial models such as linear and mixed for NCV were made. The experimental data was compared with the results of a polynomial model and good correlation was found. The result of these equations also suggests a potential for optimizing the design of the NCV and orifice tube composition.

Organized and Sponsored by the Waterjet Technology Association.

1. INTRODUCTION

The Normally Closed Valve (NCV)is being designed and used only as a nozzle valve [5]. It is a very sophisticated device, which works in a wide range of pneumatic and high water pressures. The NCV is used mostly for waterjet abrasive cutting systems and is intended for controlling high pressure water flow. Fast response for this type of control device is extremely important -stop/start operation has strong impact on quality of cutting. Instantaneous opening/closing should be possible at all pressures. The existing NCV is a very safe, fast responding and reliable valve. However, the main goal of this investigation is to overlook the existing design of the NCV and show ways to improve its characteristics.

The most important characteristic of the valve is its reaction speed [4]. This is especially important in numerous piercing operations. In turn, the speed of reaction is determined by the forces applied to the movable parts of the valve. Theoretical calculations of the closing time for the NCV as a hydromechanical system are possible, but several unknown parameters, mostly internal friction, make results unstable or even unpredictable. An experimental approach is preferable for a case like this. The multifactor method of experiment, suits this investigation better. Results of the analytic investigation would be compared with polynomial models such as linear and mixed.

2. DESCRIPTION

The standard NCV [3] is a pneumatically actuated, normally closed, on/off valve with an integral nozzle. The NCV is designed to accept a wide variety of orifice mount assemblies and nozzle nuts to accommodate specific cutting or trimming applications. For safety reasons it should be closed by spring force without any certain air pressure for the entire range of high water pressure. Although serving the purpose, these valves have seat in high-cycling applications due to the constant pounding between the two components. NCV is called the normally closed valve because the valve port is closed by the valve stem through spring force exerting on the actuator piston. To open the outlet port of such valves, compressed air is introduced into the actuator chamber below the piston to lift the piston against the spring, thus releasing the downward force acting on the valve stem. Venting the compressed air will again close the outlet port. Since the spring force is directly transmitted to the valve seat through the valve stem, a striking force of significant magnitude is produced during the time that the outlet port is opened and closed. The exact magnitude of this force is a function of the spring involved and the fluid-induced force on the valve stem.

The design of the NCV are shown in **Fig.1**, where Body (1), Cylinder (2), Nut (3), Seat (4), Stem (5), Back-up (6), Ring-b/u (7), Seal (8), O-ring (9), Cap (10), Piston (11), Springs (12), O-ring (13), O-ring (14), Seal (15), Plastic cap (16) are parts of the valve. The NCV principles of operation are depicted in the figure shown. As the stem (5) moves through seals (6), (7), (8), (9) and finally departs from the seat (4) surface, the high-pressure water flows through channel (19), seat (4) channel (20) and the orifice (not shown) in the form of a dense high-energy jet. In the static state, the stem is seated against the nozzle due to the spring (12) force which exceeds the force generated by water pressure at the inlet port (19). When the shop air is applied and fills the chambers (17), (18), the air pressure acting on the piston (11) will result in an opposing force to the spring force.

3. THEORETICAL FORCE ANALYSIS

The Normally Closed Valve is a hydro-pneumo-mechanical system which works under the balance of mechanical (spring), hydraulic (high water pressure) and pneumatic (air pressure) forces. The fourth component of force is friction, because several parts in the NCV move during the open/close procedure. In turn, the high pressure water force contains two components. The first is a static pressure force which is applied to the cross section of the stem against the spring force. The second is a dynamic component, which is developed by a flow of liquid (drag force) and is also applied to the stem in the nose area in the opposite direction. The air pressure force is a force developed by the static air pressure and applied to the piston. The spring force is a force which is developed by springs and is also applied to the piston but in a direction opposite of the air pressure force.

There are a five forces (components of the total force which is applied to the stem and piston inside NCV) responsible for the movement and closing/opening time of the NCV.

1. The high water pressure force is calculated by using a formula: $$F_{hwp}=S_t \cdot P_w \qquad (1)$$
2. The air pressure force is calculated by using a formula: $$F_{air}=S_p \cdot P_{air} \qquad (2)$$
3. The spring force is calculated by using a formula: $$F_{spring}=k \cdot x \qquad (3)$$
4. The drag force is calculated by using a formula: $$F_{drag}=0.5 \cdot C_D \cdot \rho_0 \cdot S_{tn} \cdot V^2 \qquad (4)$$
5. The friction force is calculated by using a formula: $$F_{friction}=\sum f_k \cdot F_{nk} \qquad (5)$$

Where: $\mathbf{C_D}$ - the coefficient of drag for the nose of the stem, approximately equal to 1, if the Re number stays in the range of 10 to 500,000;

V - the speed of water flow (m/sec). The speed which is calculated by fluid flow finite element analysis will not exceed 40 m/sec in the minimum cross section of the flow (around nose of the stem).

$\mathbf{F_{nk}}$ - the radial component of forces such as weight or other forces (N).

Finally, the total force which is applied to the stem and piston is:

$$F_{total}=F_{hwp}+F_{air}+F_{drag}+F_{spring}+F_{friction} \qquad (6)$$

For the first calculation let's assume that the total force is a constant during the closing/opening of the valve. This assumption will give us the minimum possible value for the closing time. By using Newton's equation, in this case of constant forces, we can define closing time by the formula:

$$T_{const}=\sqrt{2 \cdot \frac{W}{g} \cdot \sqrt{\frac{S}{F_{total}}}} \qquad (7)$$

Note that the closing time is calculated from the moment of time when the stem/piston system began movement until the moment when the stem contacted the seat. For the practical range of changes in these parameters of the real NCV the value for the closing time is represented in **Fig.2**.

According to this calculations and **Fig.2** notes:

1. The distance of travel is approximately less then 0.005 m (0.2 inch) for the existing design of the NCV.
2. The total internal force of the NCV does not exceed 3000 N for investigated design, the maximum water and air pressure, and for the highest friction coefficient.
3. According to the result of this calculation, the closing time for the total force of 1500 N is less than 1.25 msec for a full 0.005 m stroke.
4. Definitely more accurate results for the closing time could be obtained if all of the forces influencing the movement of the piston /stem system were accounted.

Actually, the internal forces are changed in time and the real dependence on these forces has a very complicated character. The diagram for the real water, air, spring, drag and friction forces, measured inside the NCV, is shown in **Fig.3**.

From the diagram in **Fig.3**, we can see that the total force during opening/closing is changed by linear law. That means the total force is a time proportional. Consider a more accurate calculation of the closing time with an assumption that the closing force is changed in time by known law. Assume that in general that force is a proportional to time (8) and for a different "**n**" overview of three different models for the $\mathbf{F_{total}}$, which is dependent on the time by linear, by quadratic or by square:

$$F(t)=k\cdot t^{n} \qquad (8)$$

Model#1 $$F_{lin}(t)=k\cdot t^{1}$$

Model#2 $$F_{lin}(t)=k\cdot t^{2}$$

Model#3 $$F_{squar}(t)=k\cdot\sqrt{t}$$

The **Fig.4** represents the difference between those models, showing the behavior of the total force for both nonlinear models. Practically it is very unlikely that the friction force is very significant in initial study of movement, as model #3 shown. The linear model seems to be more realistic. Newton's equation was used to computing the closing time for these models:

$$m\cdot\frac{d^2s}{dt^2}=F_{total}=k\cdot t^{n} \qquad (9)$$

After some transformation, the expression for closing time is given by:

$$t=\left[(n+1)\cdot(n+2)\cdot\frac{m}{k}\cdot s\right]^{\frac{1}{n+2}}$$

Considering the equations (8), (9) a result for variable closing time, T, is obtained:

$$T=T_{const}\cdot\sqrt{\frac{(n+1)\cdot(n+2)}{2}} \qquad (10)$$

Substituting in equation (10) all "n" for the different models, resulted:

Model#1 $$T_{lin}(s)=T_{const}\cdot\sqrt{3}$$

Model#2 $$T_{quad}(s)=T_{const}\cdot\sqrt{6}$$

Model#3 $$T_{squar}(s)=T_{const}\cdot\sqrt{1}.875$$

Fig.5 represents the result of the calculation of closing time by these equations, which more or less considers the real characters of the internal forces of the NCV. Note that this analysis was done without the calculation of deformations of the walls and seals, without the calculation of the friction forces.

A couple of words about the friction forces. There are at least two wear couples where friction has a place and has a substantial level. These are a piston/cylinder pair and a stem/seal pair. Behavior of the forces is practically unpredictable, because the friction force depends on the condition of the O-ring, temperature, oilability, the relative speed of wear parts, geometrical parameters (concentricity, misalignment, clearance etc.) and materials, i.e. from the coefficient of friction. The magnitude of these friction forces has a very strong dependence on the performance of each valve individually, but for all tested NCV's never exceed 250 N. As a result of friction force action, the moment of time when the valve should be closed was changed significantly and the closing times were substantially increased. We can prove this by result of experiment.

4. DESIGN OF EXPERIMENT

Theoretical calculations of closing time for the NCV as a hydromechanical system are possible, but several unknown parameters, mostly the internal frictions, could bring the different results. Because it is a very complicated problem, and the behavior of some parameters is unpredictable, an experimental approach is preferable for this particular case. The multifactor method of experiment (design of experiment), is better for this investigation. The result of this experimental investigation could be polynomial models (for closing time, for example) such as linear or mixed. During the multifactor method of experiment (design of experiment) the next procedure is followed:

1. Select the most important factors and the range of their variation.
2. Select the effects or responses, which is most important for an understanding of the process.
3. Select the plan (matrix) of the experiment (full, part, type-latin square, star, etc.).
4. Make the right selection of the type of the model (linear, nonlinear, etc.).
5. Make a statistical analysis of the results of the experiment and receiving polynomial equations.
6. Check the model for the F-criterion and check coefficients for the t-criterion.
7. Analyze the final system of equation with coefficients above the significance level and look over the model.

Select the most important factors and select the range of their variation. Three factors were chosen for the process variables, in the factorial experiment plan, which influent the closing time:

X_1 - is High Water Pressure (HWP) and represents the water force;
X_2 - is Diameter of the Water Orifice (DWO) and represents the flow and indirectly the drag force;
X_3 - s Air Pressure (AP) and represents the air force and indirectly the friction forces. The spring force is not included because it is a constant.

All the other variable parameters, such as orifice tube size and length, jet inclination angle, fluid type, orifice material, crystal structure and shape were maintained constant during the experiments. Let's select all effects or responses, which are most important for understanding of this process. Because we are looking for a dependence between time of response (closing time - CT) and our variables, which are described above, it is better to select the following responses:

Y_1 - Closing Time (CT),
Y_2 - Air pressure after Closing (AC),
Y_3 - Air pressure after Opening (AO),
Y_4 - Friction air Pressure (FP).

These variables (factors) in original units and in coded units are represented in the Table #1. We have selected the friction air pressure, because the opening or closing speed and closing time is a function of actual air pressure, water pressure, orifice size and internal friction. In turn, the internal friction is defined by excessive air pressure necessary to overcome the friction force. Coded units are connected with the original by these equations (11):

$$\mathbf{X_1=(P_w-284.1)/71}$$
$$\mathbf{X_2=(D_o-0.254)/0.1016} \qquad (11)$$
$$\mathbf{X_3=(P_a-0.5327)/0.0355}$$

Selection of the plan of the experiment.

For this investigation, the Box-Benken plan of experiment [1] with 3 factors and 2 level for variation of their parameters was selected. The factors HWP, DWO, AP had two level of value: +1 and -1 are represented in the Table #2. Two levels were selected for these variables and each point was replicated three times. In order to reduce the influence of a possible uncontrolled systematic error in the experiment, the cuts were performed in a random sequence with the only constraint that two replicated cuts could not be performed on the same specimens. This Box-Benken plan is full, including a combination of 8 experiments, symmetrical relatively to the center of experimental field and allows us to obtain a model with liner and interactive effects. It provides a readily generalized method for direct and exact calculation.

Selection of the type of model.

We are looking for a dependence between Response Time (RT), Air Pressure after closing (AC), Air Pressure after Opening (AO) and Friction Air Pressure (FP) and our variables, which are described above. First of all, let's assume that function has a normal distribution Then we can assume that this dependence is a polynomial function of the kind:

1. Linear model: $Y=b_0+\sum b_i \cdot X_i$
(simple linear model of the factors)
2. Mixed non-quadratic model: $Y=b_0+\sum b_i \cdot X_i+\sum\sum b_{ij} \cdot X_i \cdot X_j$
(linear model with effect of interaction)

Where: $b_i=1/N \cdot \sum X_{ji} \cdot Y_i$ $\quad b_{ji}=1/N \cdot \sum X_{ji} \cdot X_{ui} \cdot Y_i$

i,j,u=1,2, ... ,k - numbers of the factors,

Experimental apparatus.

The normally closed valve used for experiments was a conventional valve, after 50000 opening/closing cycles under a certain amount of pressure. High water pressure came from a high pressure pump made by Ingersoll-Rand Inc. Air pressure used by conventional air supply line. High water pressure and air pressure was measured by pressure sensors made by Autoclave Inc. Response time was calculated as the difference between relay signal and jet impact time. Impact time was registered by a strain gage lever with stand off distance of about 0.0125 m. Friction force was registered by a load cell with a special stem end. All sensors were connected by Keithley Metrabyte DAS K-500 data acquisition system and recorded with a frequency of 100 Hz. Result of the experiments are represented in the Table #3.

1. Linear model.

For statistical analysis of the result of the experiment were calculated coefficients of the polynomial equations, of linear model, using formula (12) and the results of these calculations are shown in the Table #4.

$$B=(X^T \cdot X)^{-1} \cdot X^T \cdot Y \qquad (12)$$

In order to check the model adequation, the experiment #2-2 was repeated 3 times and standard deviation was found. Results of experiment #2-2 and calculations of the deviation are shown in the Table #5. After that, the model was checked using the F-criterion (Fisher Criteria) and a value of coefficients for the t-criterion was found.

$$F=\frac{(s_{ad})^2}{(s_y)^2}$$

In our case, F=0.5 and from [2] we have F(2;4)=6.9. This means that the calculated F is significantly smaller than the F-criterion from the table, and it means that the model is adequate. After the confidence interval was built and, using the t-criterion (from Student's distribution), all coefficients were checked for a significance, a final system of equations of four linear polynomial equations for responses (linear model, all factors coded, dimensionless is given as (13):

For Closing Time (CT) $\quad Y_1=54.125-9.125 \cdot X_1-6.625 \cdot X_2-7.875 \cdot X_3$ msec
For Air pressure after Closing (AC) $\quad Y_2=0.238-0.078 \cdot X_1+0.011 \cdot X_2+0.007 \cdot X_3$ MPa
For Air pressure after Opening (AO) $\quad Y_3=0.371-0.039 \cdot X_1-0.002 \cdot X_2-0.007 \cdot X_3$ MPa
For Friction Pressure (FP) $\quad Y_4=0.014+0.004 \cdot X_1-0.001 \cdot X_2-0.008 \cdot X_3$ MPa

2. Linear with effect of interaction model.

The results of the experiment were used and same procedure was repeated for the other model- linear with effect of interaction. Results of these calculations are represented in the Table #6. This model also was checked for the F-criterion (Fisher Criteria) and a value of coefficients for the t-criterion was found. In this case F=0.5 and from [1] we have F(2;4)=6.9. This means that model 2 is adequate. fter the confidential interval was built and all coefficients were checked for a significance, a final system of equations of four linear polynomial equations for responses (linear model with effect of interaction, all factors coded) is given as (14):

$$
\begin{array}{ll}
\text{CT ,msec} & Y_1=54.125-9.125\cdot X_1-6.625\cdot X_2-7.875\cdot X_3+4.125\cdot X_1\cdot X_2+2.875\cdot X_1\cdot X_3+0.375\cdot X_2\cdot X_3 \\
\text{AC ,MPa} & Y_2=0.238-0.078\cdot X_1+0.011\cdot X_2+0.007\cdot X_3+0.014\cdot X_1\cdot X_2+0.011\cdot X_1\cdot X_3+0.004\cdot X_2\cdot X_3 \\
\text{AO ,MPa} & Y_3=0.371-0.039\cdot X_1-0.002\cdot X_2-0.007\cdot X_3-0.007\cdot X_1\cdot X_2-0.005\cdot X_1\cdot X_3+0.004\cdot X_2\cdot X_3 \\
\text{FP ,MPa} & Y_4=0.014+0.004\cdot X_1-0.001\cdot X_2-0.008\cdot X_3+0.002\cdot X_1\cdot X_2-0.002\cdot X_1\cdot X_3+0.00093\cdot X_2\cdot X_3
\end{array} \quad (14)
$$

5. ANALYSIS OF RESULTS

Now consider the results and influence of each factor on the effects starting with the linear model. First of all, the system of equations (13) or (14) is 3-dimensional and difficult to reflect on 2-dimensional pages. This means we will try to keep one (or two) factors constant in order to investigate the influence others on effects. Let's start with the internal friction force and recalculate last equation for system (13) for worse friction conditions when $X_1=1$, $X_2=1$ ($P_w=355$ MPa, $D_0=0.3556$ mm) and air pressure variance from 0.4972 to 0.5682 MPa.

After some transformations of the system (13) we obtain:

Friction Pressure, kPa	$FrPr(AirP)=137-225.35\cdot AirP$
Equivalent Static Friction Force, N	$Fric(AirP)=3.832\cdot FrPr(AirP)$

We can see **(Fig.6)** a linear dependence between friction air pressure, or static friction force, and air pressure, with a full range of about 125 N. We selected friction air pressure, because the opening or closing speed and closing time is a function of actual air pressure, water pressure, orifice size and internal friction. In turn, the internal friction is defined by excessive air pressure is necessary to overcome the friction force. Notice, that force decrease with increasing of the air pressure.

Now, look over the other responses. Since, we can look over the influence of just 2 parameters, we can assume that $X_3=0$ ($P_a=0.5327$ MPa) and recalculate the system of equations (13) to create a group of plots. Finally, we get charts **Fig. 7a, 7b, 7c**, which represent the dependencies of these parameters on water orifice size (flow) and high water pressure. As we can see the closing time by experiment and first of polynomial equation from system (13) are approximately 10 times bigger then calculated by formulas (7) - (10), which do not include friction as significant force.

The next step is to look over the more complicated model- the linear with an effect of interaction (mixed non-quadratic). We will follow the same procedure, and first of all look over the worst case for friction force when $X_1=1$ and $X_2=1$ ($P_w=355$ MPa, $D_0=0.3556$ mm) and recalculate the system of equations (14) for these conditions:

Friction Pressure, kPa	$FrPr2(AirP)=155.049-255.492\cdot AirP$
Equivalent Static Friction Force, N	$Fric2(AirP)=3.832\cdot FrPr2(AirP)$

For this model we can also see (**Fig.8**) a linear dependence between friction air pressure, or static friction force, and air pressure, with a full range of about the same 125 N. Notice, that in this case the force also decreases with an increase of the air pressure. For the other equations from (14), we will review the influence of just 2 parameters, in assuming that $X_3=0$ ($P_a=0.5327$ MPa).

Finally we get charts **Fig. 9a, 9b, 9c**, which represent dependencies of these parameters on orifice diameter and high water pressure. Notice, that the second model brings more accurate results and in investigated area of changes of the factors, the dependence of air pressure (when NCV is open) vs. water pressure and flow has almost a linear character. The dependence for Closing Time and air pressure (when NCV is closed) vs. high water pressure and water flow shows as non-linear.

For the most distant point of investigated factors (1,1,1) and (-1,-1,-1) the difference in results of calculation for the system of equations (13) and (14) could reach 10% for CT, 5% for AO, 10% for AC, and 30% for FP. According to a simple linear model the closing time changed between 30.5 - 77.75 msec, according to the linear model with an effect of interaction between 37.87 - 85.12 msec. As a first investigation, however, the equations (14) had demonstrated to be a fairly good approximation.

6. CONCLUSIONS

1. Two systems of polynomial equations for two different models, which define the closing time and other parameters of NCV were defined.
2. The system of equations (14) gives us a possibility to estimate the closing time and other parameters of NCV with higher accuracy than the simple model, if water pressure does not exceed 213...355 MPa, air pressure 0.49...0.57 MPa and orifice size 0.1524...0.3556 mm ranges.
3. Inside the area of the multifactor experiment (-1,-1,-1)...(1,1,1) the closing time is changed from 38 to 85 milliseconds and has a maximum for (-1,-1,-1) and minimum for (1,1,1).
4. Inside the area of the multifactor experiment (-1,-1,-1)...(1,1,1) the air pressure after opening is changed from 312,500 to 419,100 Pa and has a maximum for (-1,1,1) and minimum for (1,1,1).
5. Inside the area of the multifactor experiment (-1,-1,-1)...(1,1,1) the air pressure after closing is changed from 120,750 to 312,500 Pa and has a maximum for (-1,1,1) and minimum for (1,-1,-1).

6. Inside the area of the multifactor experiment (-1,-1,-1)...(1,1,1) the friction pressure is changed from 850 to 29,300 Pa and has a maximum for (1,-1,-1) and minimum for (-1,1,1). The static friction force is changed from 3 to 110 N.
7. The closing time is mainly caused by the high water and air pressure load. The effect of the orifice size load becomes significant, while the air pressure grows.

7. ACKNOWLEDGMENTS

The author gratefully acknowledge significant contributions of Jose Munoz for actively supporting the research and development over many years.

8. REFERENCES

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9. NOMENCLATURE

F_{hpw} - a water force (N);
F_{air} - a air force (N);
F_{sping} - a spring force (N);
F_{drag} - a drag force (N);
$F_{friction}$- a total friction force between movement components inside NCV (N);
F_{total} - a total closing force (N);
P_w - a water static pressure due the movement of the stem (MPa);
P_{air} - an air pressure due the movement of the steam (MPa);
x - a deflection of the spring (m);
s - a travel of the stem (m);

k - a rate of the spring (N/m);
S_p - the cross section of the piston;
S_t - the cross section of the stem;
S_{tn} - across-sectional stem area relevant to the drag force;
f_k - a friction coefficients;
ρ_0 - a density of the water;
W - an approximately weight of moved parts (N);
g - a specific gravity;
T - an estimation of closing time (msec);
δY_i - sum of the squared deviation from the mean;
Y_i - a current response for each experiment;
Y_{av} - an arithmetic average - mean;
s_y - a standard deviation;
s_{ad} - a standard error of estimate;
δb_j - a confidence interval;

TABLES, FIGURES, AND ILLUSTRATIONS

TABLE 1 VARIABLES IN ORIGINAL UNITS

		LEVELS		
Factor names	-1	0	1	Units
X_1-HWP	213.1	284.1	355.1	MPa
X_2-DWO	0.1524	0.254	0.3556	mm
X_3-AP	0.4972	0.5327	0.5682	MPa

TABLE 2

N	X_0	X_1	X_2	X_3	X_1X_2	X_1X_3	X_2X_3
1	1	-1	-1	1	1	-1	-1
2	1	1	-1	-1	-1	-1	1
3	1	-1	1	-1	-1	1	-1
4	1	-1	1	1	1	1	1
5	1	1	-1	-1	1	1	1
6	1	-1	-1	1	-1	1	-1
7	1	1	1	1	-1	-1	1
8	1	-1	1	-1	1	-1	-1

TABLE 3

X_1	X_2	X_3	Y_1	Y_2	Y_3	Y_4
30	6	70	88	45	58	2.775
30	10	80	55	42	58.5	1.4
30	14	70	60	45	57.7	1.7
30	6	80	60	45	55.8	1
30	10	70	60	48	58.75	1.7
30	14	80	45	43	59	0
40	6	70	70	32	50.5	2.25
40	10	80	40	28	55	2
40	14	70	60	34	52	2
40	6	80	45	34	53	2

40	10	70	55	40	54	2.25
40	14	80	50	38	56	0
50	6	70	50	18	50	4.25
50	10	80	40	16	50	3.25
50	14	70	50	22	47	4
50	6	80	45	20	46	0.75
50	10	70	50	28	50	2.5
50	14	80	35	30	44	1.5

TABLE 4

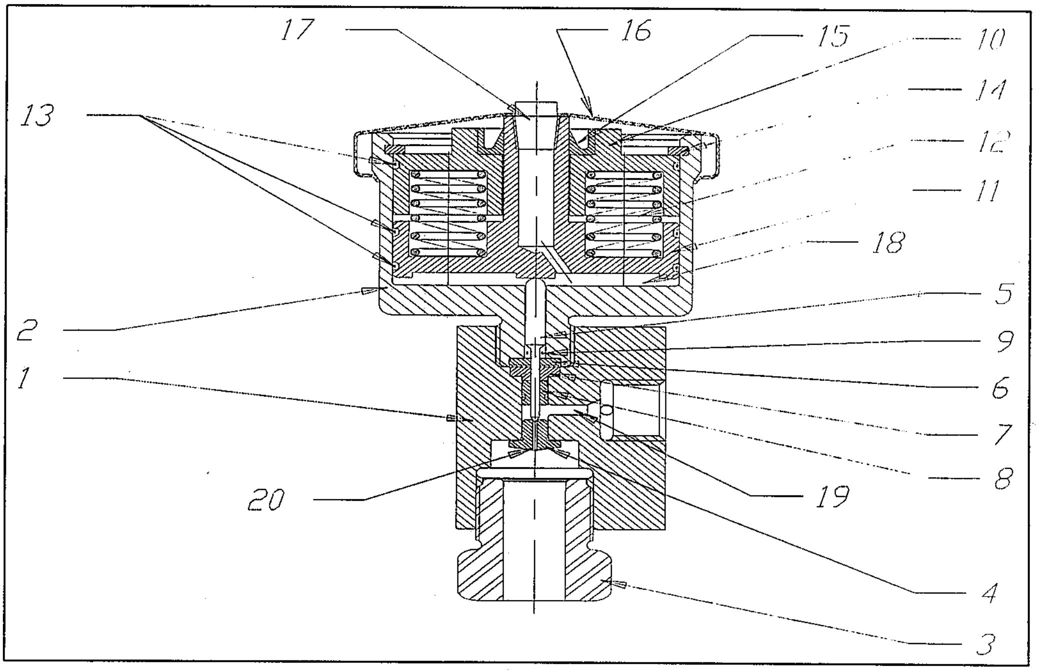
b_0	b_1	b_2	b_3
54.125	-9.125	-6.625	-7.875
0.238	-0.078	0.011	0.007
0.371	-0.039	-0.002	-0.007
0.014	0.004	-0.001	-0.008

TABLE 5

Y_1	Y_2	Y_3	Y_{av}	δY_1	δY_2	δY_3	$\sum \delta Y^2$	$(s_y)^2$
28	30	28	28.67	-0.67	1.34	-0.67	2.69	0.898
0.284	0.298	0.277	0.286	-0.002	0.012	-0.009	0.033	0.011
0.391	0.398	0.383	0.391	0	0.007	-0.007	0.014	0.005
0.014	0.012	0.016	0.014	0	-0.002	0.002	$8.88.10^{-4}$	$2.96.10^{-4}$

TABLE 6

b_0	b_1	b_2	b_3	b_{12}	b_{13}	b_{23}
54.125	-9.125	-6.625	-7.875	4.125	2.875	0.375
0.238	-0.078	0.011	0.007	0.014	0.011	0.004
0.371	-0.039	-0.002	-0.007	-0.007	-0.005	0.004
0.014	0.004	-0.001	-0.008	0.002	-0.002	$9.32.10^{-4}$


17
16
15
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19
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3

Fig1

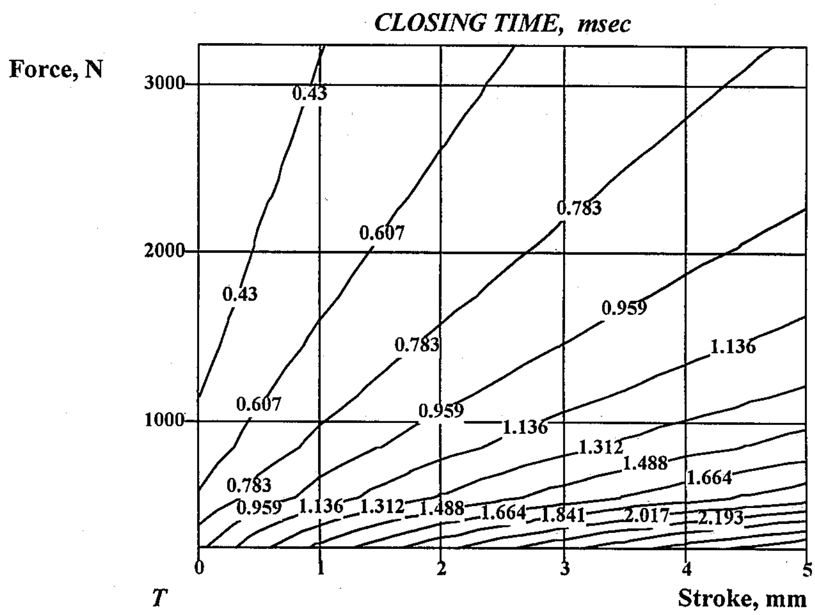

CLOSING TIME, msec
Force, N
3000
2000
1000
0.43
0.607
0.783
0.959
1.136
1.312
1.488
1.664
1.841
2.017
2.193
0
1
2
3
4
5
T
Stroke, mm

Fig2

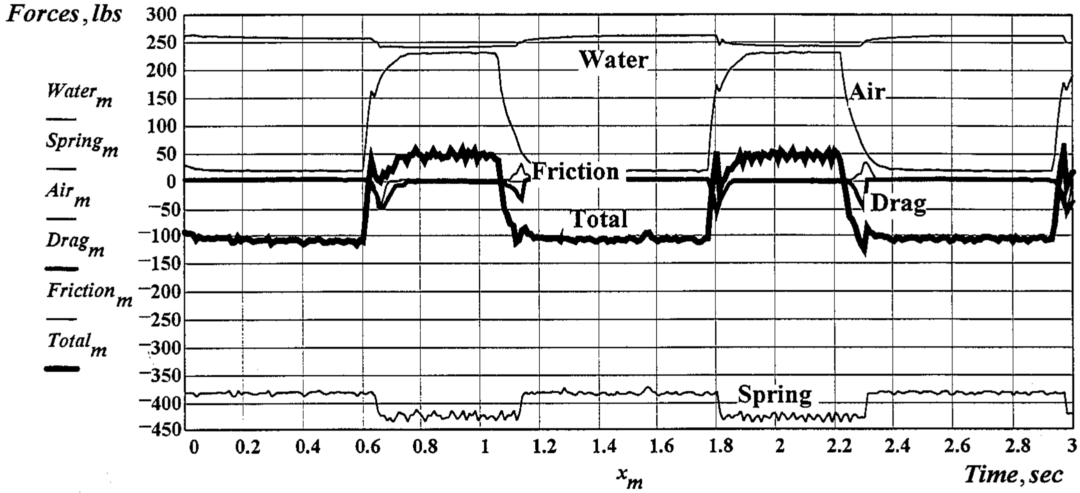


Fig.3.

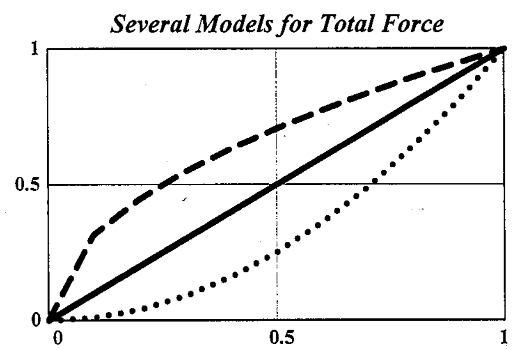


Fig4

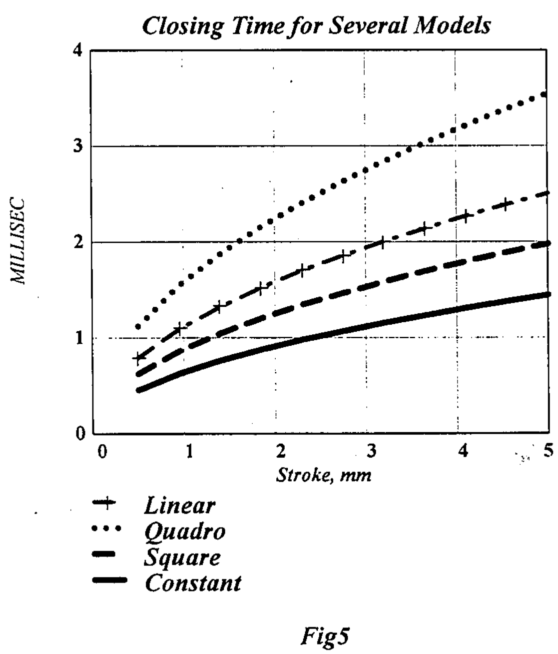


Fig5

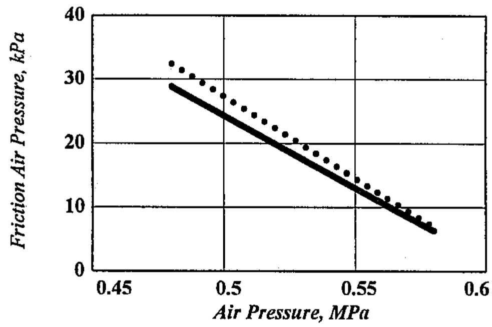


Fig.6.

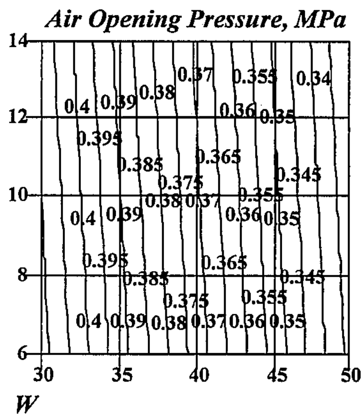


Fig7a

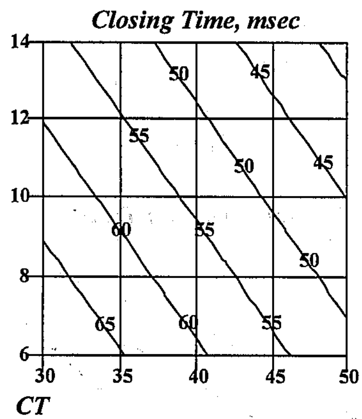


Fig7b

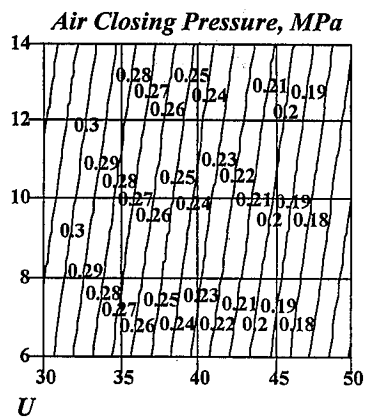


Fig7c

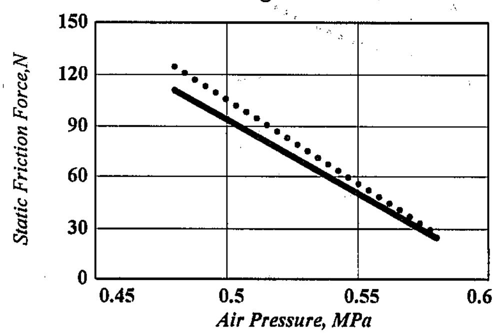


Fig.8.

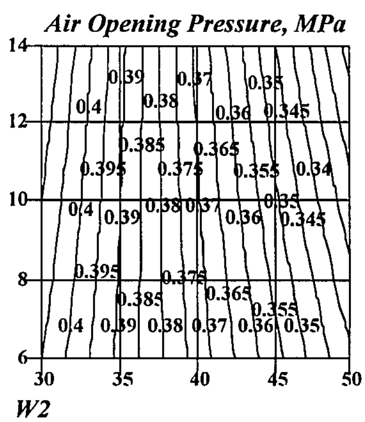


Fig9a

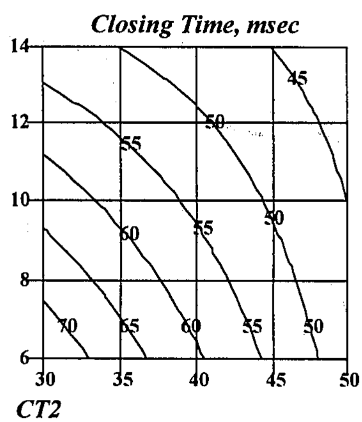


Fig9b

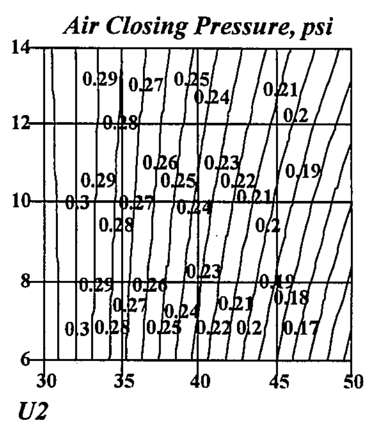
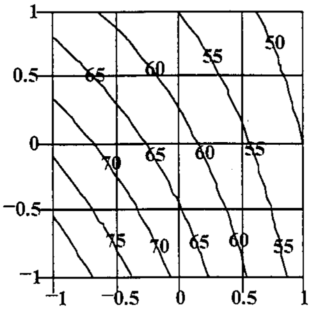
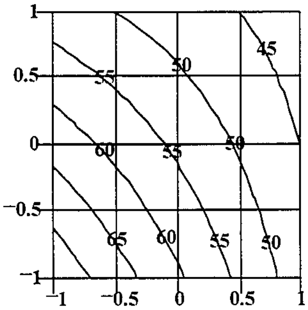


Fig9c

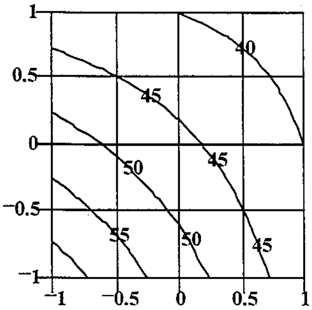
For CLOSING TIME (msec):



M11

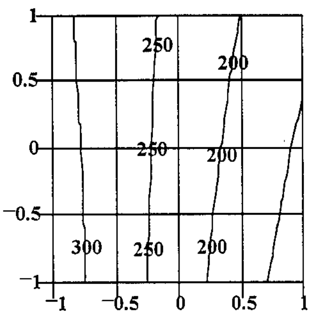


M12 $Y1(-1,-1,-1) = 85.125$

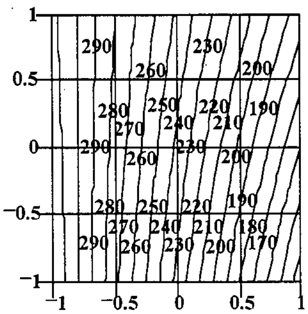


M13 $Y1(1,1,1) = 37.875$

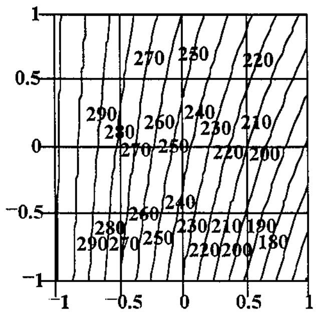
For AC (kPa):



M21

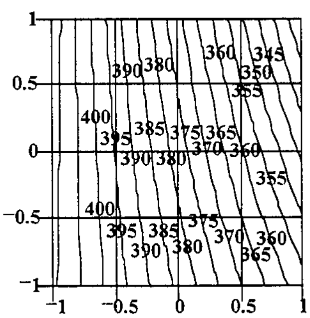


M22 $Y2(-1,1,1) = 313$

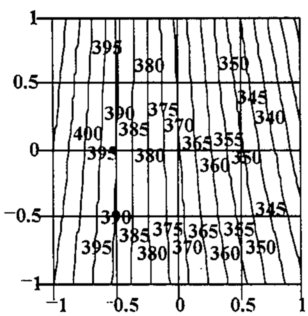


M23 $Y2(1,-1,-1) = 121$

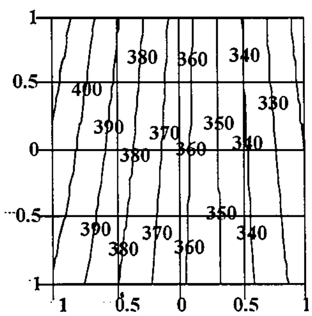
For AO (kPa):



M31

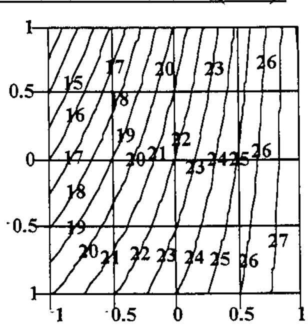


M32 $Y3(-1,1,1) = 417$

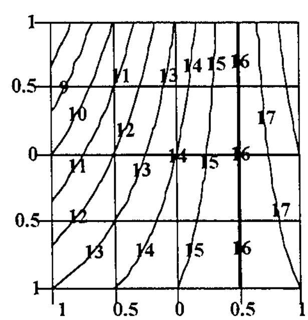


M33 $Y3(1,1,1) = 315$

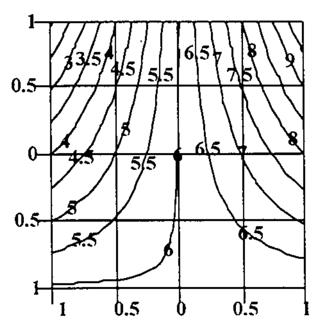
For FRICTION PRESSURE (kPa):



M41



M42 $Y4(1,\ 1,\ 1) = 27.93$



M43 $Y4(\ 1,1,1) = 1.93$

9th American Waterjet Conference
August 23-26, 1997: Dearborn, Michigan

Paper 62

AN ANALYSIS OF OPERATING COSTS FOR WATERJET CUTTING

Alan J. Bennett
Barton Mines Corporation
Lake George, NY, USA

ABSTRACT

As the waterjet industry continues to expand, waterjet users are facing increased competition from both traditional cutting methods and other waterjet operations. As a result, accurate job quotation will become more critical for the survival of the business. To quote accurately and profitably then, it is essential to know the true operating costs associated with the waterjet.

This paper will offer a comprehensive analysis of those costs based on a national wide survey of waterjet operations. The total cost will be broken into individual cost centers and evaluated with a cost analysis formula.

Organized and Sponsored by the Waterjet Technology Association.

Index By Authors

Subject Index

Papers Subjects Index

Paper Subject	Paper Number																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
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Experimental study	X		X	X	X	X		X		X	X	X	X	X	X	X		X	X	X
Hardware development						X							X	X	X	X			X	
Contractor case study																				
Manufacturing case study																				
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Legal																				
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Pulsed																				
Cavitation																				
Polymer jets																	X			
Ice jet																			X	
Cryogenic jets																				X
Process																				
Cutting	X	X	X	X	X			X	X	X	X	X		X			X	X		
Drilling			X					X	X		X	X								
Surface preparation																				
Cleaning																				
Stripping																				
Safety																				
Milling																				
Jet-assisted																				
Wear														X	X	X				
Fragmentation																				
Atomization																				X
Grouting																				
Material																				
Metal	X	X				X			X	X								X		X
Rock				X																
Glass									X											
Ceramic			X		X	X		X			X	X						X		
Composite			X					X			X	X								
Concrete																				
Polymer/Fiber											X	X					X			
Carbide														X	X	X		X		
Plastic/Rubber																				
Rust																				
Explosive																				
Related Industry																				
Generic	X	X			X				X	X			X	X	X	X		X	X	X
Shipyard																				
Mining				X																
Construction																				
Aerospace/Aircraft			X			X		X			X	X								
Automotive			X			X		X			X	X								
Oil/Gas/Refinery																				
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Paper Subject	Paper Number																			
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Type of Study																				
Modeling (theoretical)	x	x	x			x	x	x		x	x									
Experimental study		x	x	x					x			x	x	x	x	x	x	x	x	x
Hardware development				x	x		x							x						
Contractor case study																				
Manufacturing case study																				
Software development																				
Economic analysis																				
Legal																				
Production Implementation																				
Survey/general description																				
Jets																				
Waterjet	x	x	x	x										x	x	x	x	x	x	x
Abrasive-waterjet			x																	
Abrasive suspension jet																				
Pulsed									x	x	x	x								
Cavitation																			x	
Polymer jets																				
Ice jet																				
Cryogenic jets																				
Process																				
Cutting			x	x											x					
Drilling												x	x		x					
Surface preparation																				
Cleaning																	x	x	x	x
Stripping																				
Safety																				
Milling																				
Jet-assisted									x				x	x						
Wear																				
Fragmentation									x											
Atomization																				
Grouting																x				
Material																				
Metal														x			x		x	x
Rock			x	x					x				x	x	x			x		
Glass																				
Ceramic																				
Composite																				
Concrete									x									x		
Polymer/Fiber																				
Carbide																				
Plastic/Rubber																		x		
Rust																		x		
Explosive																				
Related Industry																				
Generic					x	x								x			x	x		
Shipyard																			x	
Mining			x	x					x				x							
Construction			x													x		x		
Aerospace/Aircraft													x							
Automotive																				
Oil/Gas/Refinery	x	x		x														x		x
Quarrying															x					
Military																				
Health Care																				
Nuclear									x											
Environment																				
Field work			x										x		x	x	x	x		
Factory work																				
Submerged	x			x															x	

Papers Subjects Index (Continued)

Paper Subject	Paper Number																				
	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62
Type of Study																						
Modeling (theoretical)																					x	
Experimental study	x		x	x				x		x									x	x	x	
Hardware development		x																x				
Contractor case study									x		x			x								
Manufacturing case study						x	x					x					x					
Software development															x							
Economic analysis														x								x
Legal																			x			
Production Implementation																x						
Survey/general description			x		x				x				x			x	x					
Jets																						
Waterjet		x	x	x		x	x	x	x		x	x	x	x		x		x	x	x	x	
Abrasive-waterjet			x						x					x	x	x	x	x			x	x
Abrasive suspension jet										x								x				
Pulsed	x																					
Cavitation																						
Polymer jets																						
Ice jet																						
Cryogenic jets																						
Process																						
Cutting			x							x					x	x	x			x	x	x
Drilling											x											
Surface preparation	x		x		x			x			x		x			x						
Cleaning	x		x	x		x	x				x	x										
Stripping	x	x					x									x						
Safety											x								x			
Milling																						
Jet-assisted																					x	
Wear																						
Fragmentation																						
Atomization																						
Grouting																						
Material																						
Metal	x	x	x		x		x	x		x			x		x	x	x	x	x			x
Rock																						x
Glass								x								x	x	x				x
Ceramic								x							x	x	x	x				x
Composite																x	x	x				x
Concrete									x													x
Polymer/Fiber																		x				x
Carbide																		x				
Plastic/Rubber																						
Rust			x		x								x									
Explosive											x											
Related Industry																						
Generic								x						x			x	x	x		x	
Shipyard	x	x	x		x								x									
Mining																						
Construction			x		x				x				x									
Aerospace/Aircraft	x	x			x		x								x			x				
Automotive	x				x										x		x	x				
Oil/Gas/Refinery	x		x	x		x																
Quarrying																						
Military											x											
Health Care																				x		
Nuclear										x		x										
Environment																						
Field work		x		x	x			x	x									x				
Factory work							x	x			x			x	x		x		x	x	x	x
Submerged																						