WATER JET IN ROCK AND MINERAL ENGINEERING

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ABSTRACT

The paper gives an overview of the actual and potential use of waterjet technology in the field of rock and mineral engineering. Results of basic investigation are summarised and the chief aspects of cutting mechanism underlined. Then the main industrial achievements are illustrated and discussed, giving an updated state-of-art. Finally the prospects of industrial application are evaluated, taking into account the expected technological progress in the development of equipment and methods.

1. POTENTIAL OF WATERJET TECHNOLOGY

A high-velocity water jet is capable of carrying a considerable power (up to some hundreds of kW) concentrated in a small space (less than 1 mm^2). When this beam of energy is focussed against a given target the effects produced on the impacted material can be very important depending on the hydraulic parameters (pressure and flowrate).
The performance of the jet can be enhanced by the addition into the water stream of suitable components like, for instance, soluble polymers for improving the coherence of the jet over longer distances, and/or abrasives for increasing the erosion capability when cutting hard materials.
Accordingly, a water jet can represent an efficient tool, alone or in combination with other actions of different nature (mechanical, chemical, thermal, electric) for piercing, drilling, cutting, kerfing, slotting, milling, fracturing, crushing, cleaning any kind of solid material, to the characteristics of which the jet can be properly tailored, as well as for carrying, stirring, emulsifying, aerating, breaking, and blending multiphase mixtures.
Today the interest in waterjet technology is considerably increased and widely expanded owing to the development of suitable systems capable of generating a variety of jets for specific applications in different fields of science and engineering.

A rough classification of the water jets is represented in Figure 1.

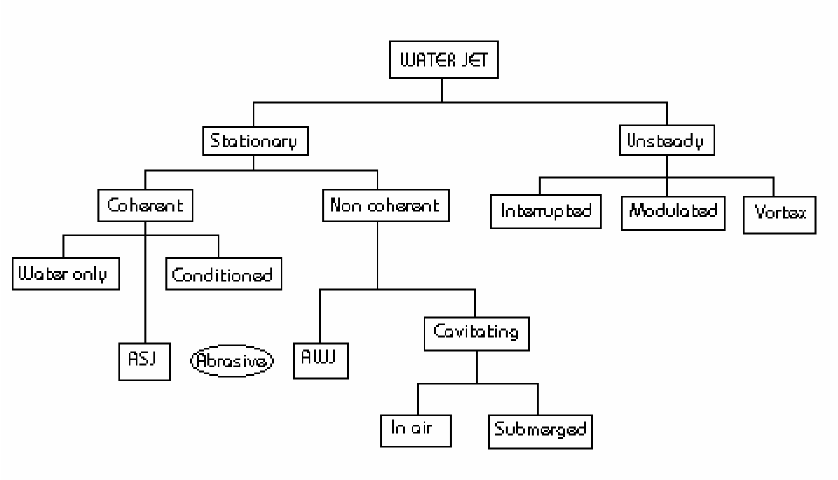

Figure 1. Classification of water jets

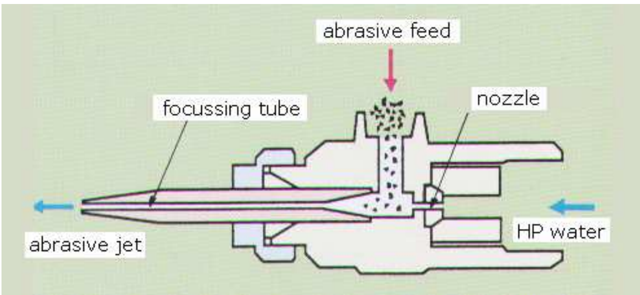

Figure 2. Device for abrasive jet generation

The AWJ cutting head is shown in Figure 2.
Limiting the scope to rock and minerals engineering, it can be said that some applications are already a reality, while others have good prospects to enter the commercial practice in the near future.

2. HYSTORICAL BACKGROUND

The possibility of taking advantage of the power of water in mining and mineral beneficiation is known since early times, although only very few instances of application of this technology can be found in the industrial practice of nowadays.
In Spain Romans used to disintegrate the gold-bearing soft formations by means of water streams forced to flow down the slope of the hills against the ore (*ruina montium*); the flushed solids in the slurry were then allowed to settle along inclined channels where heavier gold particles could be separated by gravity from the washed-away barren sand.
Much later, the same principle has been employed for digging the ore during the *gold rush* as well as for coal production in underground mines, using low pressure, high flowrate monitors.

More recently, attempts were made for winning hard rocks by means of high pressure water cannons, although the productivity is poor due to the discontinuity of the operation.
Today, waterjet is being widely employed for the direct disintegration of weak formations (exploitation of gold and diamond placers, tin, kaolin), for drilling into soft rocks (roof bolting in coal mines) and for deep slotting into hard rocks for the extraction of squared blocks in granite and sandstone quarries.
In surface and underground excavation, waterjet-assisted full-facers, roadheaders and shearing machines of variable design may enable to win harder rocks recalcitrant to conventional technology.
In stone working, entrained abrasive waterjet is the dominant technology for contour cutting of slabs according to complex profiles, whereas plain waterjet can be used for surface finishing as a substitute of flame or bush hammering. The application for 3-D carving is envisaged with very promising prospects.
In the oil industry, plain waterjet, either stationary or modulated, is already utilised for cleaning operations, while efforts are being made for developing the vortex concept for deep exploration drilling. Abrasive suspension jet is suitable for cutting metal and concrete submerged structures off-shore or in a flammable atmosphere.
Encouraging tests have also been made aiming at employing the technology for in situ or on-site decontamination of soils as well as for extinguishing underground fires.

3. APPLICATIONS IN MINING

3.1. Scientific knowledge

Rock disintegration with water jets has been intensively studied all over the world during the last 15 years.
However the results of scientific investigation, as far as rocks are concerned, are still insufficient to draw conclusions of general validity regarding the basic mechanism of material disintegration with the different kinds of jet (continuous, modulated, pulsating, cavitating, abrasive-laden), the influence of the different variables and target material properties on cutting performance and, above all, the assessment of economic viability for the various operations using water jets alone or in suitable combination with mechanical tools.
The main reason why discrepancies are found in the experimental results and field experience lies in the great variability of rock features, even within the same area, according to the genesis of the formation, the pattern of tectonic disturbances and even the effects of the excavation activity itself.
Moreover, the experimental conditions adopted are not rigorously standardized, especially as far as pressure and nozzle geometry are concerned.
In spite of a certain lack of general agreement, the following issues can be recognized:

A - Continuous plain water jets
- Cutting rate is proportional to the jet power, provided that the lance manipulation variables are optimized;
- a critical pressure must be passed before significant erosion becomes apparent;
- an increase in water rate is retained as more advantageous than a corresponding increase in pressure, jet power being the same;

- peak cutting rate is achieved for a particular value of traverse velocity, depending on jet power: optimum value moves farther as power increases;
- lance manipulation variables should be matched to the velocity of the jet (pumping pressure) for energy optimization to be achieved.

B - Pulsating and modulated water jets
- Specific energy per unit volume of rock removed is much lower than that of continuous jets of equal power;
- water hammer pressures can be up to ten times higher than the stagnation pressure of a continous jet.

C - Abrasive water jets
- A linear relationship exists between pressure and cutting depth;
- abrasive mass flowrate and grain size have significant effect on jet performance. For a particular abrasive, the system should be tuned by properly adjusting the operational variables;
- smaller focussing tube give deeper penetration and narrower slot width;
- the nature of the abrasive should be matched with the nature of the rock for optimum performance.

3.2. Basic investigation

Disintegration of rocks using high velocity plain water jets is strongly dependent on some fundamental material properties such as mineral composition, grain size, porosity features and mechanical strength. However, though their effect on specific energy is known to most waterjet experts, no reliable relationships of general validity have hitherto been made available as a predictive tool.
Porosity is retained as being the main factor governing rock erosion, though grain size, mineral composition, weathering conditions and elastic behaviour appear to be very important too. In the case of abrasive jet, hardness and elastic properties are the dominating factors.
Concerning plain jets, a good correlation has been found to exist between specific energy and the sound velocity that is a measure of the compactness of a rock. Actually data points are reasonably well gathered along a straight line with a very high correlation coefficient, as shown in Figure 3.
Specific energy for medium-hard rock disintegration with plain water jets varies greatly in the range from few to several GJ/m3, depending on jet parameters (pressure and water rate) and lance setting variables (rotation or oscillation speed and traverse velocity).
It is worth noting that in unisotropic rocks water jet performance is very sensitive to the presence of foliation. Poor results are obtained with rocks characterized by a very tight fabric with almost nil porosity.
In linear cutting of rocks at increasing pressure, typically three regions can be distinguished: at low pressure (generally below 100 MPa) penetration is not sufficient for the complete promotion of the cutting mechanism. In the intermediate region (from 100 to 200 MPa) the process is fully developed and minimum specific energy is achieved, while beyond this point efficiency falls progressively due to passive losses of power (jet friction on the kerf walls, interference between incoming jet and spent water).
The above limits strongly depend on the kind of rock: for soft rocks the process is fully developed even below 120-150 MPa; for tough rocks higher pressures are needed for

optimum specific energy to be attained.

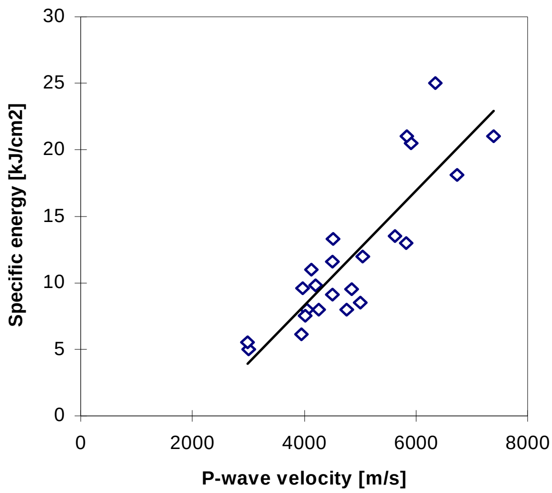

Figure 3. Correlation of specific energy with sound velocity of longitudinal waves.

Besides pressure, cutting efficiency is also affected by flow rate and traverse speed. For a given rock, the smaller the nozzle diameter and the faster the jet is traversed, the higher the optimum pressure.

Disclosing the influence of the main operational variables on cutting rate for the different rock types using proper nozzle configuration, is the basic step for designing a suitable waterjet equipment capable of meeting the requirements of advanced rock disintegration methods.

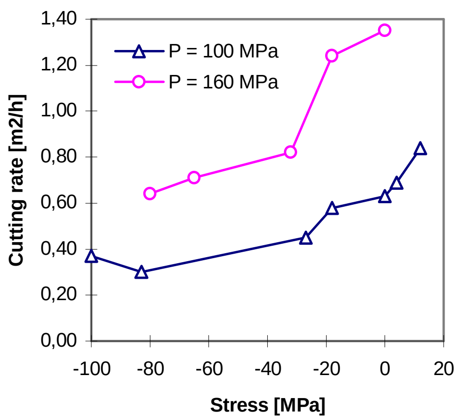

Figure 4. Cutting rate with oscillating waterjet lance as a function of stress at the slot bottom perpendicular to slotting plane (negative values are for compression)

The tensional state of the rock in situ, almost always underestimated in the prediction of cutting results achievable in the field on the basis of laboratory data, is also of a capital importance. In fact, if a rock element is subject to compression, more energy is required to remove it, since pores are more impervious to jet penetration and isolated fragments remain attached, due to a

stronger embedding. On the contrary, disintegration can be favoured in presence of tensile stresses as put into evidence by the experimental tests carried out al DIGITA's Waterjet Laboratory (Figure 4).
A flat jack can be placed into the slot in progress in order to relieve the compressive stress which would produce a progressive deterioration in slotting rate.

3.3.State of the art

3.3.1. Drilling

From the experience gained both in the laboratory and in the field it has been proved that the addition of water jets to conventional drill bits provided with carbide tips or buttons produces and increase in boring speed by a factor of 3-4 in soft rocks, 2-3 in medium-hard rocks, whereas it is insignificant in hardest rocks. Boring speed increases with pressure but there is an optimum pressure to minimise specific energy.
On this subject, considerable work has been carried out in Japan.
Waterjet drills can rapidly drill holes with smaller diameters better than conventional percussion drills. As a result, they are ideal for drilling resin-grouted roofbolt holes, owing to faster speed, resin saving and increased pull-out strength. Bolting productivity can be 50% higher with average resin saving of 40%.
The use of a waterjet device has considerable advantage for drilling long straight holes into rocks. However, the range of rocks which can be efficiently cut by waterjet alone is somewhat restricted. To overcome this limitation, the use of abrasives introduced into the jet to form a slurry has been found to be very effective.
For hard abrasive rocks, AWJ is competitive with conventional drilling methods on economic grounds.
Waterjet can be employed successfully for reclaiming a burning section of an underground coal mine. A method for containing and ultimately extinguishing the fire would consist in delimiting the area involved, monitoring the evolution of the process with thermocouples located into jet-drilled holes, removing the burning material, creating a slot ahead over the full section and backfilling it with inert material.
In civil engineering, a new concept for driving foundation piles has been developed whereby precast piles are sunk into the soil using a rotary jet for inner excavation; the bottom is suitably enlarged for hosting the supporting bulb. In easy-to-excavate soils, low pressures can be
Another very promising field of application is the directional drilling of holes through soil in order to locate service lines (cables, fluid pipes and so on), thus avoiding the need to excavate open trenches. The penetration progress and hole deviation can be controlled by a magnetic detector.
High pressure waterjet has the potential to provide a more efficient way for drilling long holes in coal seams for methane drainage and exploration than the present mechanical systems, which are rather costly and limited in hole length.

3.3.2. Shaft sinking

Underground trials proved that large diameter holes can be bored in granite using the water jet coring technology at an average advance rate of 30 to 60 mm/h with a pressure of 135

MPa delivered from a rotary twin nozzle. The core is removed in stages as the borehole is advanced, using expanding cement or some other ways of splitting.
Going deeper, penetration rate appears to be sensitive to in situ rock stresses and the confinement state. Under these conditions, there may be merit in pursuing the development of abrasive jets.

3.3.3. Cutting

Conventional methods of hard rock excavation and in demolition of big concrete buildings have largely relied on the use of explosive to break the rock and the concrete into disposable fragments. However this is not a practical answer in places near existing structures which need to be protected from any damage produced by the seismic energy of blasting.
The most practical tools are those very simple to operate and relatively easily manoeuvrable. Waterjet fulfils these requirements and therefore its future adoption in an increasing number of applications seems likely.
In processing hard rocks for deep slotting or drilling, the technique of abrasive slurry jets needs to be improved as nozzle size and wear are serious problems, although direct injection system may be promising.
With systems based on premixed abrasive slurry jets, at least four times the cutting performance of the entrainment method at any working pressure has been achieved owing to the high efficiency of nozzles producing higher jet coherence for a given stand-off distance. This allows comparable performance to ultra high pressure systems to be achieved at lower pressures, at which high efficiency piston pumps can be used with lower capital and running cost. Actually, inexpensive nozzle with tolerable wear rates and little attrition of abrasive allows the best abrasive for each application to be chosen.

3.3.4. Cut-and-shear mining

Cutting slots associated with some means of breaking is feasible as a mining method, especially in hard stratified stone. The presence of rock discontinuities (fractures, bedding planes) can be greatly helpful.
Similarly, drill-and-shear technique used in the preparation of blocks in stone quarries can be an interesting idea for selective mining, using waterjet for both drilling and splitting along the plane between ore and barren rock.
Based on the practice of conventional hydraulic coal mining, the technique of swing-oscillation water jet cutting is claimed to have the potential of reducing the energy consumption, while enhancing coal heading advance rate. The swing oscillation of the jet is obtained by adding a high frequency oscillating motion perpendicular to the traverse direction of the nozzle. In this way parallel slots are opened and the coal left between them is broken down by means of vertical impacts.
A mining machine has been designed and fabricated to mine coal from room and pillar operations, combining high pressure waterjet cutting and mechanical fragmentation. Waterjets are used to slot the coal face into large pieces which are then broken by an advancing ploughing wedge.
The advantages are inherent simplicity, application to existing roof support systems, coarser coal fragments, no dust generation and no risk of spark.
However, implementation of mechanization is hindered by conservative management and

dissenting workers union attitudes.

3.3.5. In situ extraction

In situ methods is an attractive way for extracting bitumen, salt minerals and other slurried substances, as an alternative to surface mining which requires huge capital investments and further processing of the run-of-mine. However traditional in situ methods generally permit low recovery due to difficulties in linking the extraction wells.
To this end, hydraulic jet cutting represents an interesting solution.
In the case of bitumen, it was found that, in addition to the mechanical work of the jet, thermal and chemical energies (hot alkaline solution) are of importance in jet disintegration of oil sands, especially for high grade deposits. Only bitumen-water emulsion needs to be transported for further processing and sands remain on place.

3.3.6. Heat mining

Heat mining is simply the extraction of geothermal energy from underground hot rocks. An interesting idea has been conceived and proven theoretically feasible, consisting in producing a series of deep vertical slots on the wall of a single borehole through the steel or concrete casing by means of water jets: heat can be extracted by recycling of water acting as the heat exchanger fluid.

3.3.7. Selective mining

The potential of waterjey technology for the purposes of selective mining by slotting along the seams or fragmentation within the orebody deserves consideration. Either plain, abrasive and cavitating water jets can be used. Further work is needed to optimise the nozzle system.
Borehole Mining is a suitable method to remove soft ore from shallow flat-lying deposits. The concept relies on a water jet without abrasive to disintegrate the material which is pumped to the surface. The technique has been successfully evaluated for mining coal, urainiferous sandstone, oil sand and phosphate ore.
Hydraulic Borehole Mining of coal has been proved in the field associated with the problem of gas freeing and strata relaxation. The HBM device, provided with one front and two radial jets, is introduced into a borehole and rotated. A coal slurry is produced as the result of waterjet disintegration of coal which flows away through the same hole to the collecting tank.
The Borehole Miner for vein-like orebodies developed by the US Bureau of Mines would be deployed from existing underground drifts. It has a built-in capability of propelling itself in and out a 20 cm borehole, cutting hard rock with an abrasive jet and finally transporting the material to the surface. Deviated boreholes can be negotiated making the equipment able to follow irregular veins. Sensors are being studied for discriminating the ore from the country rock in view of the automatic orientation of the cutting head.

3.3.8. Hydromining

The first modern hydraulic mining device was built during the California gold rush for flushing out the gold-bearing sands and delivering the pulp to the concentration sluices.

From there the technology spread extensively owing to its economic advantages, not only for recovering alluvial gold but also for mining out and in situ beneficiating other ores like kaolin, tin, barite and coal.
Experience showed that lower pressure, high flowrate monitors are more effective, because they are capable of taking better advantage of the existing cracks, opening larger slots which facilitate the disintegration process.
Underground hydromining of coal using monitors has been used in the past, though with a number of serious difficulties resulting from large quantities of water.
A new generation of monitors makes use of high pressure jets to reduce the amount of water: the lance is manipulated across the workface according to linear or circular motion while traversing. In smaller operations hand-held equipment can be a suitable solution (Figure 6).
However, rock destruction with waterjet alone involves an extremely high specific energy requirement since waterjet, as an excellent means of cutting, is not suited to extract larger rock volumes.
Therefore, fragmentation of rocks by water power is rather expensive compared to mechanical cutting. This is the reason why, at the present state of the art, water jetting is no longer used for high production application in mining, even on coal.

3.3.9. Hydrodemolition of rocklike materials

Plain waterjet is now intensively used for concrete scarification purposes enabling to destroy selectively the worn material while preparing a new surface for the application of the new finishing layer. The main features of this operation consist in a faster treatment rate compared to traditional sand blasting or pneumatic hammering and in a much better quality of the surface. Steel rebars are thoroughly de-rusted and the dust is washed away making the adhesion of the cement very good.

3.3.10. Mechanised mining and tunnelling

In mechanized excavation using water jets, two modes of operation can be devised, i.e. waterjet-assisted and mechanical-assisted. In the first case most of the work is done by mechanical tools (picks, disks) applied to roadheaders, tunnel borers or shearing machines, availing of the help of water jets for pre-fracturing as well as for additional benefits such as tool cooling, debris flushing and dust suppression (Figure 5).


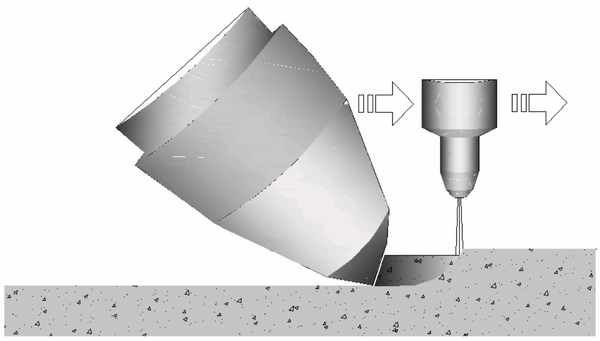

Figure 5. The concept of waterjet assisted mechanical excavation of rocks

There is some controversy among available data especially regarding the role of pressure and the decrease in efficiency of water jets at the high cutting speed adopted in the excavation practice.

In the second mode of operation, waterjet is the chief agent, while the role of the mechanical tool is simply that of helping in removing the ridges between slots. Mechanical energy is very low compared to the hydraulic energy of the jet. Large jet-power is involved at relatively high pressure, especially for breaking hard rocks.

Despite this, the assistance of carbide tips is capable of reducing by a factor of two the specific energy involved in granite drilling, though being less significant for tougher compact rocks. Cut quality is also enhanced and tool life increased.

Despite the efforts, cutting tools suitable for abrasive rocks difficult-to-disintegrate have not yet been developed, due to the fact that blunting caused by high contact stress usually results in the destruction of the cutting edge material.

A very promising solution is the application of abrasive water jets. In fact, mechanised mining and tunnelling using an abrasive water jet system offers many potential benefits over conventional drill-and-blast methods: improved face advance and labour productivity, reduced ore losses and better control of ore dilution, improved roof support and safety.

Jets can be applied either through the tool or in front of the tool. The behind position does not provide benefits due to a too large stand-off distance. The through jet solution has some advantages (shorter stand-off distance and better cooling efficiency) but poses sealing and blocking problems. Front jets are to be placed some distance away from the tip to be efficient in both cutting and cooling.

The greatest increase in benefit is gained by using moderate pressure so that all tools receive jet assistance, while cost and sealing problems are reduced. Higher pressures are not justified.

Development is on the way for phasing the jet with the movement of the cutting head, so that water is only injected at pick/rock contacts.

On weak friable bituminous coal a low-pressure, small power jet is sufficient to reduce the cutting forces on drag bits and to reduce the amount of fines produced. Less fines means considerable saving in subsequent beneficiation cost. High powered jet is not justified economically.

Also harder coals may receive benefits from jet assistance depending on the major cleat orientation and the wear conditions of the cutting tool. Reliability must be improved.

At optimum penetration the water jet is able to reduce energy-wasting crushing whilst still retaining the energy efficient chipping events. Below optimum, the effect on force reduction becomes insignificant; too deep penetration reduces chipping.

Less fines produced, suppression of respirable dust in the working ambient, reduced risk of methane ignition, increase in haulage speed, prolonged tool life, decrease in overbreak and reducing labour cost are considered favourable factors for extended employment of the water jet assistance concept.

Other advantages are: reduced vibrations, improved debris removal, increased cutting capacity of smaller machines.

However some disadvantages are also incurred, such as: creation of water problems, higher initial cost and increased overall energy requirements.

The hydromechanical mining technique of using water jets up to 250 MPa in addition to mechanical tools (picks or disk-cutters) finds application in building swinging-arm roadheaders and full-face machines and equipment for driving galleries, cross-cuts, shafts and tunnels through tougher formations. These new generation machines of high mining efficiency

will improve working conditions, protect the environment in the working place (Figure 10).
Tests conducted to improve the effect of water jets by using additives resulted in a considerable increase in cut depth at the same pressure or vice-versa.
Though water jet assisted drag tool rock cutting has been commercially available for nearly a decade it has failed to find favour with industry.
A possible reason for the discrepancy between laboratory and field results in waterjet assisted rock cutting is the use of much higher tool velocity and insufficient care in the position of the jet with respect to cutting tool. When attention is paid to appropriate nozzle placement and to optimisation of jet parameters (pressure and flow rate) the benefits of the technology can be dramatic.
It is believed that the range of rocks that can be cut with drag bit machines can be extended to rocks having a compressive strength of 170 MPa (from 80 MPa of the present technology), using appropriate water jet system to assist cutting operation. Machines featuring a rigid drive of the cutting head capable of taking deep, widely spaced cuts at low rotational cutting speed represent the viable solution.
Working at a pressure of 70 PMa, a 50% increase in mining advance can be achieved with waterjet-aided roadheaders, in comparison with the normal technique employing 7 bar water just for dust spraying and tool cooling. At the same time a 30% decrease in energy consumption is obtained, together with a dustiness reduction by 70% and a four times decrease in cutting tool wear.
A multiple boom roadheader with disks moving with various radii each supplied with two high pressure jets (200 MPa) generated by two side nozzles is being experimented with successful results.
Despite the limitations of pulse-producing technique, results have shown that pulsed jets possess a strong destructive power and are capable of enhancing the productivity and safety of continous mining machines. Unfortunately these devices are little reliable for evaluating the real benefit of pulsed jets in rock disintegration.

3.3.11. Deep slotting in granite quarries

In stone quarrying, traditional methods are becoming inadequate, since they are liable to cause a series of drawbacks regarding both the stone recovery and the quality of the material produced. Therefore the advent of novel substitute technologies of commercial availability in the stone quarries of the future will be welcomed, provided that the technical advances are accompanied by a proven economic profitability. Among them waterjet appeares to be very promising.
Water jet has been used for slotting granite in a number of quarries.
In France a sandstone formation is quarried using waterjet for all vertical and horizontal cuts except for the blind face which is sheared by pushing down each column of blocks by means of a fork lift machine.
Field experience put into evidence the necessity to improve the system in order to assure a sounder reliability and make simpler equipment commercially available.
For quarrying operations where the first problem is roughness, easy maintenance and cutting performance, working at moderately high pressures (150-200 MPa) with comparatively high water rates (30-60 l/min and more), the single stage plunger pump with multiple piston is preferable to the two-stage pressurization unit using intensifiers.
Driving a deep kerf inside the rock down to some metres, requires that the lance is penetrated into the slot.

Practically the problem is solved by using a traversing lance provided with one or more (generally two) jets, generated by rotating or oscillating nozzles, or with a number of angled jets from a fixed head (Figure 6).
The lance can be driven by either moving the equipment as a whole or manipulating the lance alone while the pumping station is fixed.
The first solution has the advantage of compact assembly, allowing the space engaged by the system to be reduced.
However such a heavy piece of equipment would require adequate power for operation, entailing, in addition, longer time for installation and adjustment on supporting rails. Machine

Figure 6. Waterjet slotting in a granite quarry, Sardinia.

weight means also higher purchasing cost.
The second solution is much more rational, taking advantage of the fact that the reaction force trasmitted by the jet is so small that the lance can be applied to a very light frame for manipulation. In this case the pump is in a stationary position at a central point within the working area and only the frame is displaced. Setting up thus requires a relatively short idle time
Water consumption is not very high even for the most powerful equipment, being of the order of 60 l/min (seldom higher), according to cases. This is not a major problem if enough water is available at the site. However, in case of shortage, spent water can be recycled after clarification by allowing suspended particle to settle in a still pond with the help of flocculants.
Nozzles are subjected to wear during operation and must be replaced in order that jets are properly generated allowing the equipment to give its optimum performance. Nozzle duration depends on the orifice diameter and on the material used for manufacturing. Internal wear is caused by abrasion of entrained particles and cavitation bubbles, external wear is due to the impact of bouncing cuttings.
Economic reasons suggest that moderate pressure and few nozzles of larger diameter made of hard metal should be used instead of dispersing the hydraulic power among a great number of smaller jets made of sapphire, which are more expensive and give a worse energy utilization (specific energy decreases as jet size increases, overall power being the same).

Despite the advantages, the use of waterjet in stone quarrying is slow to take off the ground. This fact is mainly due to a certain lack of confidence among quarriers who prefer to rely on traditional drilling-based techniques, on which they have gathered considerable direct experience, instead of coping with the problems posed by complex machinery calling for careful maintenance.
Besides kerfing, waterjet is suitable for drilling parallel holes for explosive or wedge splitting, taking advantage of a more precise drilling direction. Moreover, cut planarity could be better controlled by notching the holes in the pull-out phase.
To this end further improvements should be expected after the development of reliable abrasive jetting systems which look particularly promising for long small-diameter holes.
At the present state of the progress, the possibility of using abrasive water jets for deep kerfing of rocks in quarrying operations is far from being at hand. The problem stands in the difficulty of obtaining stable conical distribution of the abrasive at the nozzle outlet in order to drive a regular slot wide enough for lance penetration.
The solution of multiple jets can be envisaged but practical attempts were unsatisfactory up to now.

3.3.12. Contour cutting of slabs

At the present state of the art, the best prospects of applying abrasive water jets in stone industry are for slab contour trimming in processing plants, especially when curved or complex shapes are needed.
For this utilization commercial systems have been developed for precision cutting of a wide variety of hard materials like metals, glass and ceramic matter (Figure 7).

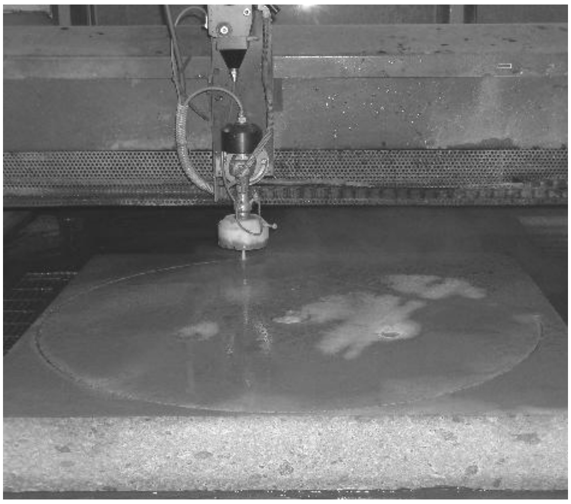

Figure 7. Computer-controlled waterjet robot.

The technological transfer to stone processing came at a later time with interesting performance results. With modern machinery of adequate power, slabs as thick as 6 cm can now be cut at a linear velocity higher than about 10 cm/min with very high accuracy and limited loss of material.
The waviness phenomenon inherent to the AWJ cutting process depends on the dynamic process parameters which are traverse rate, pressure and abrasive flow rate. Two zones

can be distinguished across the cut thickness: a cutting wear zone free of waviness and a deformation wear zone which may not exist according to the jet's capacity for cutting and the material thickness. Kerf taper is also observed.
Control parameters are more complex than in the case of plain water jets. In addition to water parameters, abrasive chemical (nature) and physical parameters (hardness, strength, shape, size) are to be optimised together with the feed rate. Mixing process must also be considered. It has been found that there are no significant differences in cutting capability of the various abrasives in the case of rocks, contrary to the statement that using garnet sand gives much better results than quartz sand.
Recycling abrasive material seems to be practical only in the case of through-cuts because of the high degree of particle crushing which takes place when slotting. Abrasive degradation depends on the type of target material and on jet and abrasive parameters.
The historic method is of including abrasive in a special mixing chamber after the water has been accelerated to final velocity. However during mixing abrasive is fragmented and the reduced size of particles hitting the target makes the abrasive jet less effective than it might otherwise be, except for steel grit which has the strength to remain intact.
Premixed abrasive suspension is an alternative technique that improves upon and extends the capability of abrasive waterjet. The advantage in rock cutting is that relatively small nozzles can be used for operations in tight space like deep kerfs in stone quarrying. Using the same abrasive flow rate, pressure and power, the depth of cut is at least double that achievable with the entrained-abrasive counterpart. In abrasive suspension jets higher pressure increases efficiency in terms of erosion factor, rendering the system more economical. However the comparison must be based on long runs and for each individual material to be cut.
Both systems have their advantages and disadvantages and the use of a specific type of system depends on the application, necessity and cost.

3.3.13. Surface finishing

Plain waterjet has been proposed as an alternative to flaming for obtaining a rough finishing of granite slabs. Some commercial machines are offered in the market but the acceptance has not yet been very enthusiastic due to the higher cost of processing. On the other hand the quality of the treated surface is very good owing to the selective action of waterjet that develops along the existing cleavage planes giving the material a natural appearance by preserving the original colours and the textural features of the stone.
In principle, all the available methods for surface finishing (smoothing and polishing, sand blasting, bush hammering, flaming, shoot peening, milling, laser beam burning, waterjetting) are technically viable for surface finishing of dimension stone, taking into account the need to preserve the ornamental potential of the material.
However their practical applicability can be restricted by a number of factors concerning the characteristics of the material and the end use of the stone element in presence of external constraints, with particular reference to climatic conditions.
Problems may arise especially for interior floors where the preservation of the aesthetic values must be matched to safety. A possible solution can be found in a combination of conventional polishing (for enhancing the textural and chromatic features of the material) with a light erosive action intended to produce a pattern of micro-craters capable of improving the grip without impairing the durability.

To this end a very interesting opportunity is offered by abrasive waterjet which can also be considered for other operations of stone working as a substitute to sand blasting and bush-hammering.

3.3.14 Stone carving

The AWJ process is capable of precisely machining complex parts. Automated multiple operations such as turning, milling, drilling and threading can be performed with the same tool to produce three-dimensional parts. Significant efforts are still needed for using abrasive water jets for fine surface finishing and polishing. With precise traverse mechanism accurate shape cutting can be accomplished.
There is a strong interest in using water jet in the field of stone for the manufacture of monuments, art objects, architectural components, urban fittings and elements of interior decoration as a substitute of manual operations which are slow and costly.

3.3.15. Well boring

As pointed out in the preceding paragraphs, the method of adding pressure fluid jets to rock cutting machines has been widely applied to various mechanical devices for mining, tunnelling and drilling.
As to oil well boring, advance rates and service life of drill bits are dramatically increased with the introduction of high pressure fluid jets. Efficiency is increased if:
- Chips are rapidly removed soon after they are formed thus avoiding overgrinding;
- hydraulic power is applied directly to the rock without attenuation;
- stand-off distance is decreased.

In brittle materials like rocks at a high temperature, drilling and cutting can be performed relatively easier with water jets, not only because of its hydrodynamic destructive power but also since in such conditions a large tensile thermal stress is transitionally generated in the rock (thermal fracturing).
Spiralling jet obtained by placing vanes into the non-rotating nozzle head has a very strong diffusion capacity, making it ideal for large holes required in oil exploration and production. Diffusion angle depends upon the geometry of the nozzle and the vane and have little relation with the pipe pressure.
A new type of nozzle for jet-bit drilling based on the principle of self-excited oscillation has also been experimented. During field tests, penetration rate and bit life have been increased by a factor of up to 15-50% and 10-15%, respectively, over the corresponding values for similar bits with steady jet nozzles.
In rock piercing with abrasive water jets, linear and circular movements of the jet can be applied, resulting in a reduction of penetration time by an order of magnitude. The reason for improvement in penetration rate by moving jets is a change in fluid dynamics at the bottom of the hole: while the eroding jet must strike the rock at a glancing angle, the exhaust stream must leave the interaction zone without direct interference with the incoming jet. There is an optimum range of speed and diameter for circular movement.
It is claimed that breakage by cavitation is the only technique capable of being implemented with current pumping facilities at great depth, using the hydraulic power available at drillsite in order to facilitate the work of mechanical tools.
For assessing the destructive performance of cavitation, a special nozzle called Radial Flow

Venturi has been developed and tested under simulated conditions at depth, proving the interest in the technology. Laboratory results confirm that erosive cavitation can be produced, whose efficiency is favoured by the highly compressed environment and by the presence of a drilling mud. The main drawbacks are the short stand-off distance required and the scanty operational flexibility.

4. APPLICATIONS IN MINERAL PROCESSING

As for mineral processing, good opportunities are open concerning comminution, desliming, oil agglomeration and flotation, although the development is still at the demonstration and pre-competitive stages in this field.

4.1. Rock comminution

4.1.1. Block splitting

The electrohydraulic technique of rock splitting and crushing seems promising on the basis of field testing results. It consists in provoking a shock wave into the water by means of high voltage sparks.
The possibility of enhancing the action of a water jet by adding an electrostatic discharge near the impact point deserves further investigation.
With a similar approach, attempts are being made to explore the viability of incorporating microcharges of explosive into a water jet.
Also the addition to the water of suitable chemicals (metal chlorides, for instance), capable of weakening the fracture toughness of rocks may be beneficial in waterjet disintegration.
Actually significant efficiency improvements have been achieved with other rock breakage techniques like percussion drilling, wire cutting, blade sawing and ore comminution.

4.1.2. Crushing

Rock blocks can be fragmented using impulsive high speed water jets with relatively good energy efficiency.
Claimed advantages are: low power, no wear problems due to the absence of a cutting tool, no reaction load and thence small dimension, ligth weight, structural simplicity and high mobility of the machine, ability to break abrasive rocks, improvement of labour and safety conditions.
In pulsed fluid technology, jet pressure does not have to be very high; high flow rates produce better results. Fracture toughness and elasticity modulus are the key rock properties which control fracture initiation and propagation. Based on specific energy criteria, materials are fragmented more efficiently by pulsed jets with sufficiently high energy than by conventional mechanical breakers. Sufficiently long impact time is necessary.
Specific energy can be as low as 5-10 J/cm3 for granite and sandstone, thus making jet splitting preferable to mechanical fragmentation which is subjected to considerable wear.

4.1.3. Grinding

Grinding of coal and ores down to very fine sizes is a challenging problem of nowadays,

from both the technical and economic point of views, calling for suitable methods and commercially available equipment.
Unlike coarse crushing, where the energy used per tonne is comparatively small, reduction of coal to fine sizes consumes substantial energy and grinding efficiency is of considerable importance.
A new revolutionary method of comminution consists in using high velocity water jets, capable of producing a thorough disintegration with negligible wear and reasonable energy consumption, though performance data are not yet available, being the research at its early stage.
Waterjet can be used either for assisting mechanical grinding in conventional mills or as a the only fracturing agent in specially designed machines.
Among the potential advantages of waterjet in mineral grinding, the following are worth consideration:

- High feed rate can be achieved due to the very rapid breaking action of the jet; capacity can be increased by feeding the material through a circular slit over which the jet is rotated;
- the size of the mill is very small in relation to its potential capacity;
- wear is greatly reduced due to limited frictional contacts; the only part subjected to wear is the discharge slit which can easily be replaced with minor cost incidence;
- noise level is low since the jet is completely encased into the mixing chamber of the mill;
- size classification can take place in the mill itself;
- selective comminution allowing the weak components to concentrate in the finest classes leaving the tougher minerals in coarser fractions can be achieved by proper pressure tuning. The useful mineral is separated from the gangue with a subsequent screening operation.

On the other hand, a waterjet mill requires a considerable amount of power for pumping the water to the desired pressure. However, in the case of coal which can be ground at moderate pressure (<80 MPa) specific energy is much lower, making waterjet potentially competitive with traditional mills. In addition, the capital investment for a pumping system in that range of pressure is not very high.
As pressure increases, product fineness improves. However, beyond a certain pressure the effect becomes progressively negligible. The coarser the feed, the coarser the product, experimental conditions being the same.
The assistance of water jets to the mechanical action of conventional gyratory crushers can considerably increase the throughput capacity for coal up to five times, although the solution attempted so far does not appear energy effective. As a result of the development in course, aiming at a substantial improvement of the performance, it is believed that the concept can offer a suitable chance for grinding the coal to be delivered via pipeline.

4.1.4. Micronisation

In the field of very fine grinding two lines can be followed:
In the case of coal, where the energy required is can be relatively small, interesting results have already been obtained with the double disk concept.
On the other hand, in the case of hard and brittle solids, micronisation can be achieved as a result of the collision of two opposite streams of particles carried and accelerated by high velocity water jets, taking advantage of the poor impact resistance of the material to be ground. In this kind of mill, wear is limited and energy efficiency is much higher than in the case of conventional methods. The approach seems also promising for the preparation of coal-water slurry as a substitute of oil in the steam boilers of power stations.

4.1.5. Destruction of tyres

A big quantity of tyres are put out of service yearly in big modern surface mines, posing environmental problems.
An alternative way to the mere disposal of this bulky material in conventional landfills consists in disintegrating the tyres aiming at recovering both the rubber matter in form of chippings and dusts and the reinforcing steel wire.
This can be accomplished using waterjet issued by powerful pumps in order to reduce the time needed to complete the operation.
On this subject a research has been recently undertaken at DIGITA's Waterjet Lab

4.2.Desliming

Owing to the strong agitation and to the onset of cavitation phenomena when water is injected at high velocity into a liquid, waterjet can be applied for removing the filling and coating clay from coarse mineral particles, allowing to reduce the silica content from the ore or to prepare a better surface for flotation. Satisfactory desliming results have been obtained with a bauxite ore.

4.3.Oil agglomeration

In oil agglomeration, coal particles are collected to form coalescent floatable aggregates, while mineral particles remain dispersed in the aqueous phase and can be eliminated by settling or screening. The mechanism involves the collision and spreading of oil droplets onto the coal surface, followed by the mutual attachment of the particles owing to the bridging action of oil.
In order to win the energy barrier that would prevent the particle-droplet collision, the process must take place in presence of a strong agitation.
In conventional vessels, stirring is provided by the mechanical action of fast-spinning impellers which however do not produce an even distribution of particles and droplets.

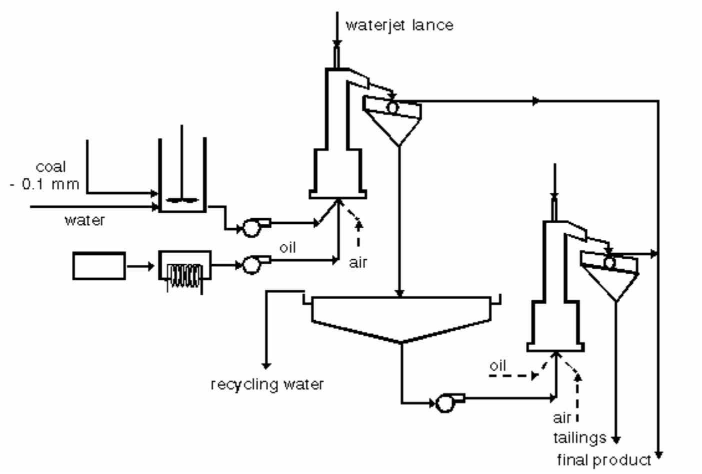

Figure 8. Flowsheet of oil agglomeration with waterjet

As an alternative, the use of water jets is believed to offer some distinct advantages regarding the expected improvement in recovery and product quality, like for instance:

- Efficient control of the agitation pattern characterised by fair trajectories;
- better separation between the agitation and the still zones in the agglomeration device;
- improved pulp circulation inside the vessel.

The validity of the above assumptions has been demonstrated using a laboratory scale apparatus consisting of a column-shaped cell hosting the nozzle head, a plunger pump, a still screen for the separation of agglomerated particles from the entrained mineral matter, the stirring vessel for the preparation of the feed slurry and the peristaltic pumps for the control of the circulating flow. The flowsheet for two-stage experiments is shown in Figure 8.

The nozzle arrangement inside the agglomeration vessel has been designed in order to generate a set of superimposing whirls resulting from the jets issued by up to four nozzles, 0.3 to 0.5 mm in diameter. Oil, moderately heated, is injected at the bottom of the vessel trough a central inlet and it is intensively emulsified owing to the strong shear action of the jets. Coal is fed through a co-axial pipe in the form of a thick suspension (10 to 20 % solids) which is diluted into the vessel down to 3-5 %. Solid particles are accelerated by the jets and the chance of collision with oil droplets is enhanced due to their high kinetic energy and the relatively short mutual distance. In the upper part of the vessel the turbulence gradually decreases, allowing the formation and up-lifting of the flocks. The overflowing suspension is finally discharged through a chute onto a static screen where flocks are separated.

Agglomeration tests have been carried out on samples of a high-rank coal (Walsum mine, Ruhr district, Germany) containing 18.10 % Ash (dry basis).

Peak recovery, accompanied by a minimum ash content, is achieved at an optimum pressure, suggesting that agitation should be strong enough for promoting the agglomeration process, until reaching a limit beyond which adverse effects eventually prevail.

Fuel recovery and separation selectivity are attained at lower pressures if compressed air is injected into the vessel, with a clear benefit in energy consumption. Overall fuel recovery can be substantially increased through an additional scavenging operation of the residual slurry after flock removal.

Although the research is still at an early stage, the expected advantages underlying the concept have been confirmed with encouraging prospects of improvement with a further development of the concept.

4.4. Flotation

Separation performance of available flotation machines gradually deteriorates as particle size decreases, resulting in low recovery, unsatisfactory quality of the product and a high specific consumption of energy and reagents. In order to create the most favourable conditions for the full development of collection and separation mechanisms, a new approach has been devised and tested according to which agitation is produced using high velocity water jets generated through a suitable nozzle configuration.

A water jet is issued from a nozzle with a velocity proportional to the square root of pressure, i.e. of the order of several metres per second even if the pressure is relatively low. Consequently a strong shear action is produced when a jet is injected into a volume of still liquid giving rise to an intense stirring effect.

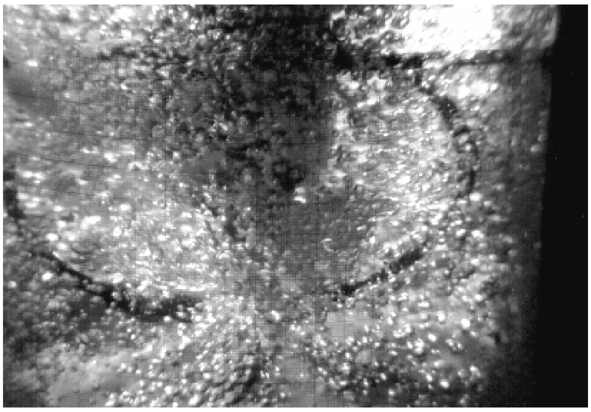

Figure 9. Pattern of bubble inside the waterjet agitated flotation cell

The pattern of flow is determined by the nozzle arrangement.
In this way distinct advantages are achieved such as a more favourable size distribution of bubbles and a higher probability of particle/bubble collision and attachment, resulting in improved separation results, especially for difficult-to-clean coals.
Experimental tests at laboratory scale show that results better than those with conventional mechanically agitated cells can be achieved although research is still at an early stage.
The following advantages can be predicted with the further improvement and the industrial scale-up of the technology, compared to conventional methods:

- more favourable bubble features in flotation (Figure 9)
- efficient control of the agitation pattern by optimising the nozzle arrangement and using fan jets
- higher recovery and better separation selectivity especially for the fine particle sizes
- less energy consumption using lower pressures
- reduced wear (no rotating parts are involved)
- expected higher capacity per unit volume of the cell owing to shorter residence time

Waterjet can be the base for the design of a new sparger device in column flotation.

5. CONCLUSIONS

High Velocity Waterjet Technology can be regarded as one of the major advances in the field of material disintegration. Thanks to its inherent flexibility and efficiency, the application has been rapidly extended to many branches of industrial practice for working almost any kind of materials, from soft to very hard ones.
As regards rock engineering, hydraulic energy was first used for excavating soft rocks using low pressure monitors. With the advent of the high pressure technology also harder rocks have been made amenable to waterjet disintegration, opening a new era in mining, quarrying, civil engineering, mineral processing, waste treatment and reclamation.
At present, waterjet lends itself to a variety of operations such as excavation, drilling, cutting, crushing and cleaning, alone or in suitable combination with mechanical tools. The prospects have been recently enhanced by the development of abrasive jet technology, especially for

precision cutting.
With particular reference to ornamental stone, the results of laboratory investigation and field trials lead to conclude that waterjet kerfing is viable and safe compared to flame torching and even to explosive splitting, with additional advantages in terms of automation and impact on the working environment.
Minimum specific energy is very well correlated with the ultra-sound velocity of P-waves. This parameter can, therefore, be assumed for assessing the amenability of rocks to waterjet cutting.

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