Waterjet Seminar

Waterjet White Paper

Can Waterjet help your business?

Flow

Introduction

In the battle to reduce costs, engineering and manufacturing departments are constantly on the lookout for an edge. The Waterjet process provides many unique capabilities and advantages that can prove very effective in the cost battle. Learning more about the Waterjet technology will give you an opportunity to put these cost-cutting capabilities to work.

Beyond cost cutting, the waterjet process is recognized as the most versatile and fastest growing process in the world (per Frost & Sullivan and the Market Intelligence Research Corporation). Waterjets are used in high production applications across the globe. They compliment other technologies such as milling, laser, EDM, plasma and routers. No noxious gases or liquids are used in waterjet cutting, and waterjets do not create hazardous materials or vapors. No heat effected zones or mechanical stresses are left on a waterjet cut surface. It is truly a versatile, productive, cold cutting process.

The waterjet has shown that it can do things that other technologies simply cannot. From cutting whisper thin details in stone, glass and metals; to rapid hole drilling of titanium; to cutting of food, to the killing of pathogens in beverages and dips, the waterjet has proven itself unique.

History of Waterjets

Dr. Norman Franz is regarded as the father of the waterjet. He was the first person who studied the use of ultrahigh-pressure (UHP) water as a cutting tool. The term UHP is defined as more than 30,000 pounds per square inch (psi). Dr. Franz, a forestry engineer, wanted to find new ways to slice thick trees into lumber. In the 1950's, Franz first dropped heavy weights onto columns of water, forcing that water through a tiny orifice. He obtained short bursts of very high pressures (often many times higher than are currently in use), and was able to cut wood and other materials. His later studies involved more continuous streams of water, but he found it difficult to obtain high pressures continually. Also, component life was measured in minutes, not weeks or months as it is today.

Dr. Franz never made a production lumber cutter. Ironically, today wood cutting is a very minor application for UHP technology. But Franz proved that a focused beam of water at very high velocity had enormous cutting power—a power that could be utilized in applications beyond Dr. Franz's wildest dreams.

How high pressure water is created

The basic technology is both simple and extremely complex. At its most basic, water flows from a pump, through plumbing and out a cutting head. It is simple to explain, operate and maintain. The process, however, incorporates extremely complex materials technology and design. To generate and control water at pressures of 60,000 psi requires science and technology not taught in universities. At these pressures a slight leak can cause permanent erosion damage to components if not properly designed. Thankfully, the Waterjet manufacturers take care of the complex materials technology and cutting-edge engineering. The user need only be knowledgeable in the basic waterjet operation.

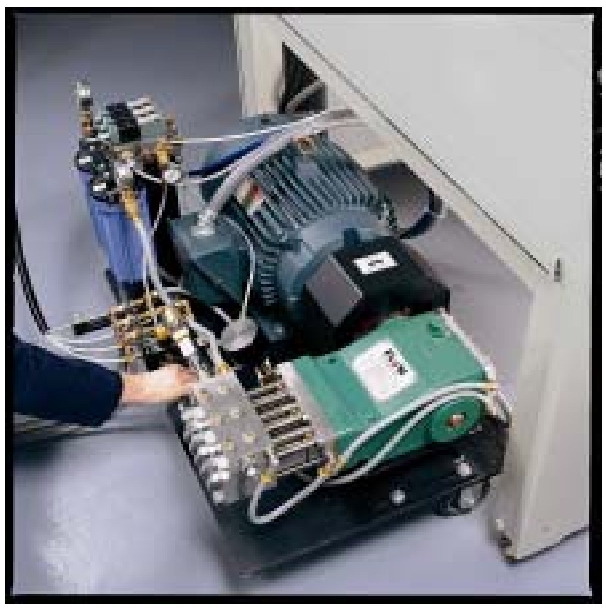
Essentially, there are two types of waterjets; (1) pure Waterjet and (2) abrasive Waterjet. Machines are designed to employ only Waterjet, only abrasive Waterjet, or both. With any type, the water must first be pressurized.

The Pump

The pump is the heart of the waterjet system. The pump pressurizes the water and delivers it continuously so that a cutting head can then turn that pressurized water into a supersonic waterjet stream. Two types of pump can be used for waterjet applications – an intensifier based pump and a direct drive based pump.

Direct Drive Pump

The direct drive pump operates in the same manner as a low-pressure “pressure washer” that you may have used to pressure wash a house or deck prior to repainting. It is a triplex pump that gets the movement of the three plungers directly from the electric motor. These pumps are gaining acceptance in the Waterjet industry due to their simplicity. At the time of this writing, direct drive pumps can deliver a maximum continuous operating pressure 10 to 25% lower than intensifier pumps units (20k to 50k for direct drive, 40k to 60k for intensifiers).



Direct Drive pump is a relatively new type of high-pressure pump (commercially available since late 1980’s).

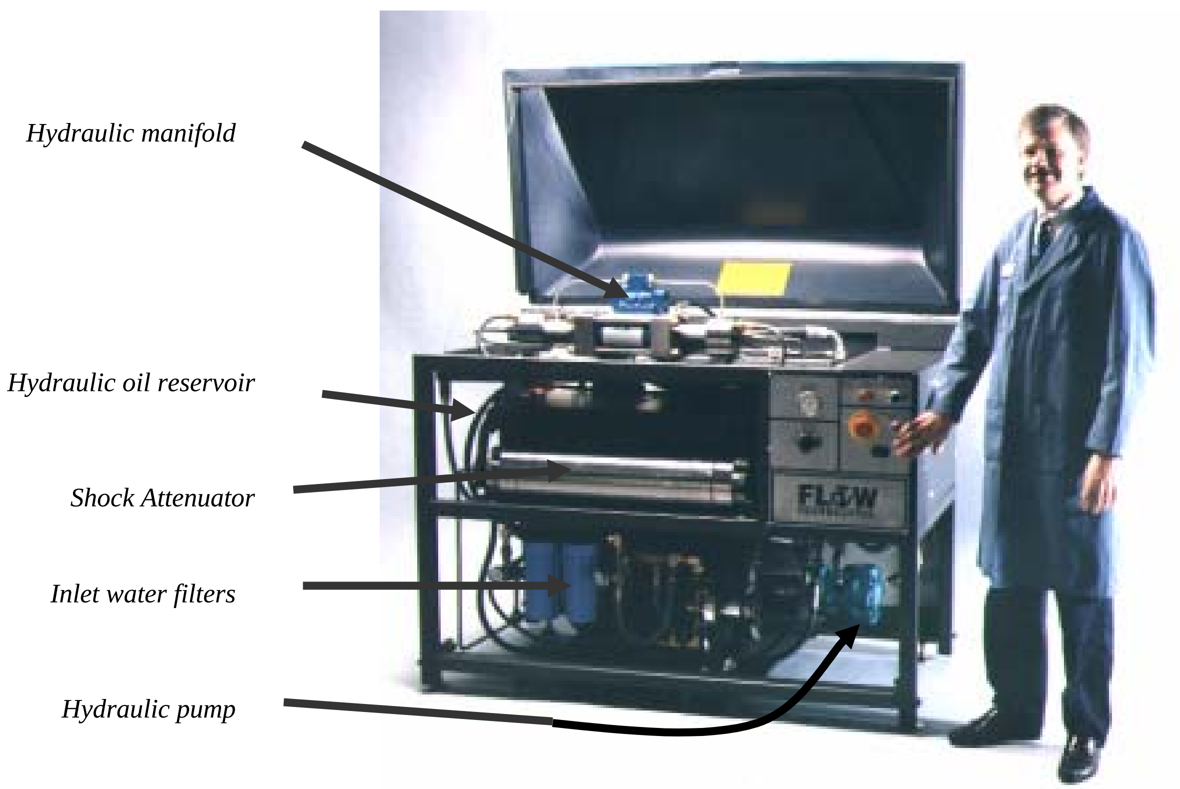
Though direct drive pumps are used in some industrial applications, the vast majority of all ultra-high pressure pumps in the waterjet world today are intensifier based.

Intensifier based pumps

Two fluid circuits exist in a typical intensifier pump, the water circuit and the hydraulic circuit.

The water circuit consists of the inlet water filters, booster pump, intensifier, and shock attenuator. Ordinary tap water is filtered by the inlet water filtration system – usually comprising of a 1 and a 0.45 micron cartridge filter. The filtered water then travels to the booster pump, where the inlet water pressure is maintained at approximately 90 psi – ensuring the intensifier is never “starved for water.” The filtered water is then sent to the intensifier pump and pressurized to up to 60,000 psi. Before the water leaves the pump unit to travel through the plumbing to the cutting head, it first passes through the shock attenuator. This large vessel dampens the pressure fluctuations to ensure the water exiting the cutting head is steady and consistent. Without the attenuator, the water stream would visibly and audibly pulse, leaving marks on the material being cut.

The hydraulic circuit consists of an electric motor (25 to 200 HP), hydraulic pump, oil reservoir, manifold, and piston biscuit/plunger. The electric motor powers the hydraulic pump. The hydraulic pump pulls oil from the reservoir and pressurizes it to 3,000 psi. This pressurized oil is sent to the manifold where manifold’s valves create the stroking action of the intensifier by sending hydraulic oil to one side of the biscuit/plunger assembly, or the other. The intensifier is a reciprocating pump, in that the biscuit/plunger assembly reciprocates back and forth, delivering high-pressure water out one side of the intensifier while low-pressure water fills the other side. The hydraulic oil is then cooled during the return back to the reservoir.



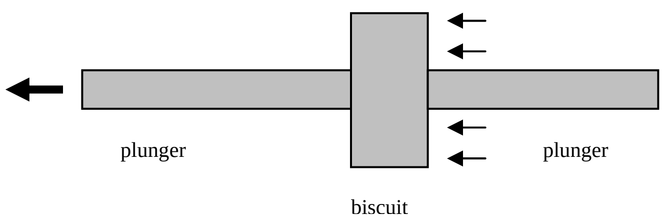
Typical intensifier pumping unit. This unit is designed to stand alone, rather than integrated into motion equipment.

The advanced technology in the pump is found in the intensifier. As mentioned briefly in the description of the water circuit, the intensifier pressurizes the filtered tap water to up to 60,000 psi. Intensifier pumps utilize the "intensification principle."

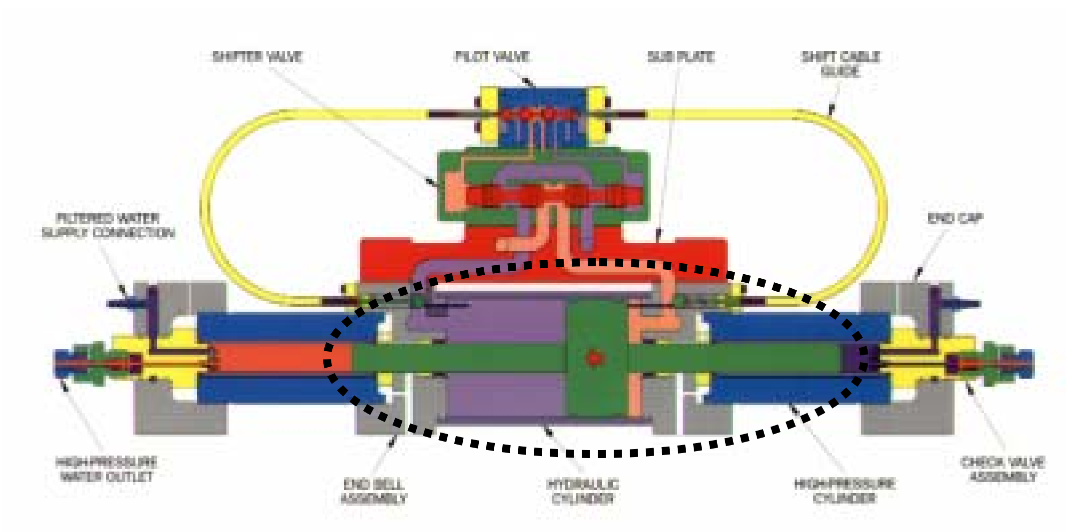
Hydraulic oil is pressurized to a pressure of, say, 3,000 psi. The oil pushes against a piston biscuit. A plunger with a face area of 20 times less than the biscuit pushes against the water. Therefore, the 3,000-psi oil pressure is "intensified" twenty times, yielding 60,000-psi water pressure. The "intensification principle" varies the area component of the pressure equation to intensify, or increase, the pressure.

Pressure = Force / Area

If Force = 20, Area = 20, then Pressure = 1. If we hold the Force constant and greatly reduce the Area, the Pressure will go UP. For example, reduce the Area from 20 down to 1, the Pressure now goes up from 1 to 20. In the sketch below, the small arrows denote the 3,000 psi of oil pressure pushing against a biscuit face that has 20 times more area than the face of the plunger. The intensification ratio, therefore, is 20:1.

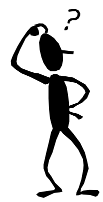


In the illustration below, the biscuit and plungers are circled. The biscuit contains the small arrow suggesting movement to the left. The two water plungers extend from either side of the biscuit. High-pressure water is delivered out the left side while low-pressure water refills the right. At the end of travel, the biscuit/plunger assembly sequence is reversed.

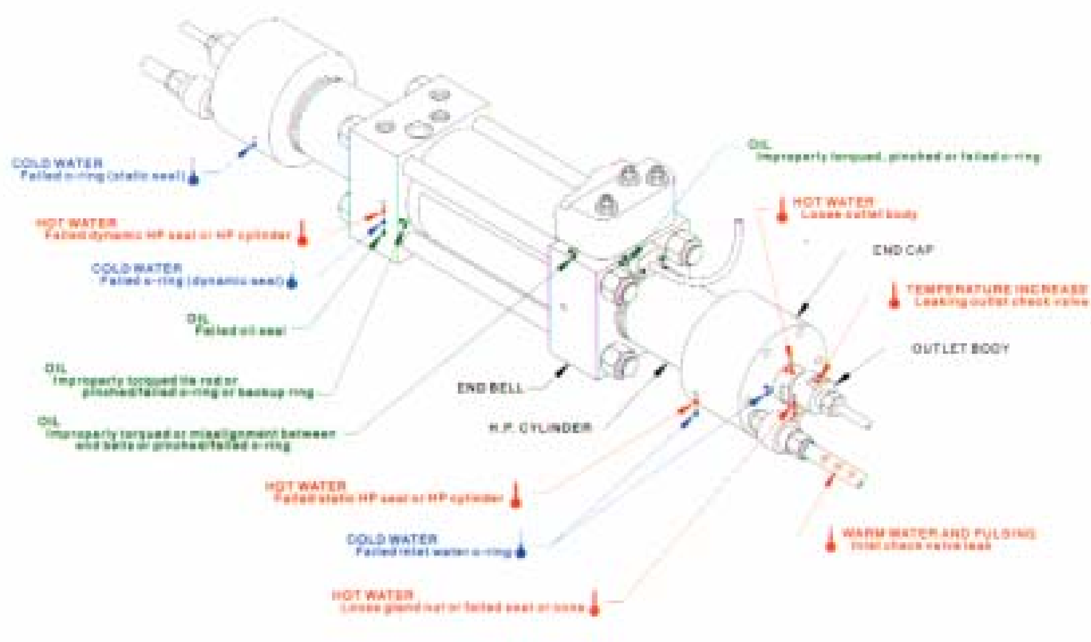


Cross section of a typical reciprocating intensifier.

Sophisticated check valves ensure the low pressure and high-pressure water is only allowed to travel one direction. The high-pressure cylinders and end caps that encase the plunger and biscuit assembly are specially designed to withstand the enormous force and the constant fatigue.

	With a 10:1 intensification ratio and 3,000-psi oil pressure, what is the resultant water pressure? *The resultant water pressure would be 10 times that of the hydraulic oil pressure. The quick answer is 30,000 psi.*

The entire unit is designed for long life, while also designed to fail in a safe way. Waterjet systems fail in a gradual, rather than instantaneous way. The seals and connections begin to leak slowly through specially designed weep holes. The operator or maintenance person can see a drip escaping from a weep hole. The location of the drip and the amount of water indicate when maintenance should be performed. Usually, the maintenance person can schedule the periodic maintenance of seals and check valves out 1 to 2 weeks into the future by simply monitoring the gradual weeping. Warning and shutdown sensors also cover the pumping unit to further safeguard against pump damage.



Troubleshooting of an intensifier is quite simple. Dripping of hot water from a weep hole indicates a high-pressure leak, cold water indicates low-pressure. In the actual image, those drops labeled hot or warm are in red, cold is in blue.

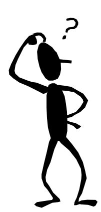
High Pressure Plumbing

Once the high-pressure pump has created the water pressure, high-pressure plumbing delivers the water to the cutting head. In addition to transporting the high-pressure water, the plumbing also provides freedom of movement to the cutting head. The most common type of high-pressure plumbing is special stainless steel tubing. The tubing comes in different sizes for different purposes.

- 1/4 inch steel tubing – because of its' flexibility, this tubing is typically used to plumb the motion equipment. It is not used to bring high-pressure water over long distances (for example, from pump to base of motion equipment). Long lengths of 10 to 20 feet are used to provide X, Y and Z movement (called a high-pressure whip). It is easily bent. This tubing can be bent into a coil (coils provide greater flexibility over short distances).

- 3/8 inch steel tubing – typical this tubing is used to deliver water from the pump to the base of the motion equipment. Can be bent. Not normally used to plumb the motion equipment.

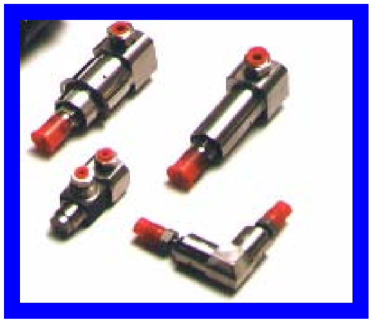
- 9/16" steel tubing – this tubing is typically used to transport high-pressure water over long distances. The large internal diameter reduces pressure loss. When very large pumps are present, this tubing is especially beneficial (the larger the volume of high-pressure water needed to be transported, the larger the potential pressure loss). This tubing is not bent. Fittings are used to created corners (T's, elbows, etc.).



If cool water is slowly leaking from the intensifier End Cap, are you beginning to see a failure of a low pressure or high pressure seal?

High-pressure seal failures generate heat from squeezing the water out through the tiny opening (friction), low pressure leaks do not create enough heat to notice a warming of the water. The quick answer is low pressure.

More than tubing is needed to transport the water and provide movement; other fittings are also needed. T's, straight connectors, elbows, shut off valves and swivels may be required.



Swivels – different joint styles provide different types of movement.

This 3D Machine Tool with a 5-axis wrist uses swivels to provide movement of the head. This particular machine employs a point catcher to catch the jet. Cutting of aerospace composites.

Two Types of Waterjets

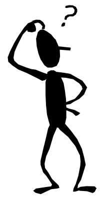
The two types of waterjets are the pure waterjet and the abrasive waterjet. Both have unique capabilities proven a benefit to industry.

Pure Waterjet

Pure Waterjet is the original water cutting method. The first commercial applications were in the early to mid 1970s, and involved the cutting of corrugated cardboard. The largest uses for pure waterjet cutting are disposable diapers, tissue paper, and automotive interiors. In the cases of tissue paper and disposable diapers the waterjet process creates less moisture on the material than touching or breathing on it. Unplanned down time, common to other cutting processes, cost over $20,000 per hour in some diaper or tissue plants. The waterjet provides the 24 hour per day, 7 day per week, 360 day per year operation required by such applications – maintenance can be scheduled into production.

Pure Waterjet attributes:

VERY THIN STREAM (0.004 TO 0.010 INCH IN DIAMETER IS THE COMMON RANGE)
EXTREMELY DETAILED GEOMOETRY
VERY LITLE MATERIAL LOSS DUE TO CUTTING
NON-HEAT CUTTING
CUT VERY THICK
CUT VERY THIN
USUALLY CUTS VERY QUICKLY
ABLE TO CUT SOFT, LIGHT MATERIALS (E.G., FIBERGLASS INSULATION UP TO 24” THICK)
EXTREMELY LOW CUTTING FORCES
SIMPLE FIXTURING
24 HOUR PER DAY OPERATION

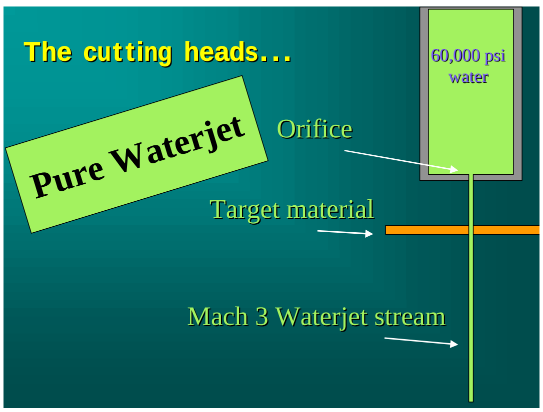


How hot is the water in a Mach 3 waterjet stream?

The water is warmed as it is accelerated to high speed. Frictional forces and other factors warm the stream as it exits the orifice. In let water temperature provides the starting point. Water temperature is then raised 2 to 3 degrees for each 1,000 psi. The quick answer is the Mach 3 jet is approximately 170 to 180 degrees F.

Pure Waterjet Cutting Heads

As you may recall from an earlier section of this document, the basic waterjet process involves water flowing from a pump, through plumbing, and out a cutting head.



In waterjet cutting, the material removal process can be described as a supersonic erosion process. It is not pressure, but stream velocity that tears away microscopic pieces or grains of material. Pressure and velocity are two distinct forms of energy. But how is the pump's water pressure converted to this other form of energy, water velocity? The answer lies in a tiny jewel. A jewel is affixed to the end of the plumbing tubing. The jewel has a tiny hole in it. The pressurized water passes through this tiny opening changing the pressure to velocity. At approximately 40,000 psi the resulting stream that passes out of the orifice is traveling at Mach 2. And at 60,000 psi the speed is over Mach 3.

Pure Waterjet orifice diameter ranges from 0.004 to 0.010 inch for typical cutting. When waterblasting concrete with a nozzle traversing back and forth on a tractor, a single large orifice of up to $1/10^{th}$ of an inch is often used.

The three common types of orifice materials (sapphire, ruby, diamond) each have their own unique attributes. Sapphire is the most common orifice material used today. It is a man-made, single crystal jewel. It has a fairly good quality stream, and has a life, with good water quality, of approximately 50 to 100 cutting hours. In abrasive Waterjet applications the Sapphire's life is ½ that of pure Waterjet applications. Sapphires typically cost between $15 and $30 each.

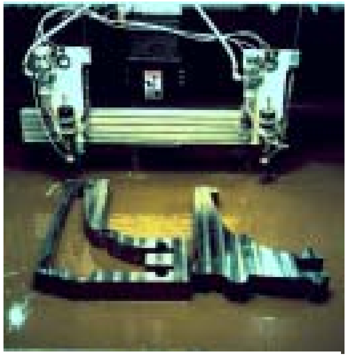
Ruby can also be used in abrasive Waterjet applications. The stream characteristics are well suited for abrasivejets, but are not well suited for pure Waterjet cutting. The cost is approximately the same as the sapphire.

Diamond has considerably longer run life (800 to 2,000 hours) but is 10 to 20 times more costly. Diamond is especially useful where 24 hour per day operation is required. Diamonds, unlike the other orifice types, can sometimes be ultrasonically cleaned and reused.

	Life	*Use*	*Comments*
Sapphire	50 to 100 hours	Pure Waterjet	General purpose, though life reduces by ½ for abrasive waterjet applications
Ruby	50 to 100 hours	Abrasive Waterjet	Stream not suitable for pure waterjet applications
Diamond	800 to 2,000 hrs	Primarily Waterjet	10 to 20x more expensive than Ruby or Sapphire

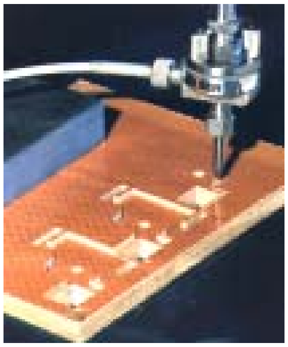
Abrasive Waterjets

The abrasive waterjet differs from the pure waterjet in just a few ways. In pure waterjet, the supersonic stream erodes the material. In the abrasive waterjet, the waterjet stream accelerates abrasive particles and those particles, not the water, erode the material. The abrasive Waterjet is hundreds, if not thousands of times more powerful than a pure Waterjet. Both the waterjet and the abrasive waterjet have their place. Where the pure waterjet cuts soft materials, the abrasive waterjet cuts hard materials, such as metals, stone, composites and ceramics. Abrasive waterjets using standard parameters can cut materials with hardness up to and slightly beyond aluminum oxide ceramic (often called alumina, AD 99.9). In the next section we will explore abrasive waterjet attributes and how the abrasive waterjet cutting head works.



4" titanium shown, courtesy of TCI Aluminum

Stone and glass



Composites, graphite/epoxy and ballistic

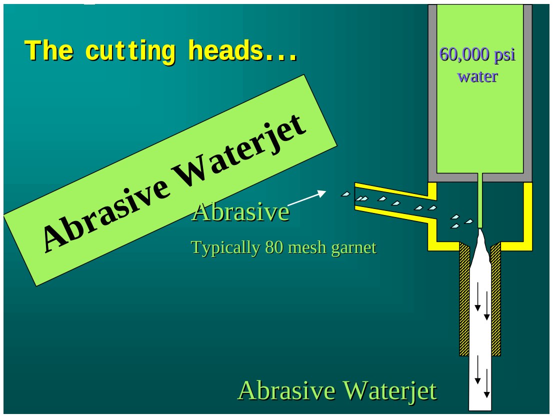
From china bowls to aluminum oxide (alumina)

Abrasive Waterjet attributes:

EXTREMELY VERSATILE PROCESS
NO HEAT AFFECTED ZONES
NO MECHANICAL STRESSES
EASY TO PROGRAM
THIN STREAM (0.020TO 0.050 INCH IN DIAMETER)
EXTREMELY DETAILED GEOMETRY
THIN MATERIAL CUTTING
10 INCH THICK CUTTING
STACK CUTTING
LITTLE MATERIAL LOSS DUE TO CUTTING
SIMPLE TO FIXTURE
LOW CUTTING FORCES (UNDER 1 LB. WHILE CUTTING)
ONE JET SETUP FOR NEARLY ALL ABRASIVEJET JOBS
EASILY SWITCHED FROM SINGLE TO MULTI-HEAD USE
QUICKLY SWITCH FROM PURE WATERJET TO ABRASVIE WATERJET
REDUCED SECONDARY OPERATIONS
LITTLE OR NO BURR

Abrasive Waterjet Cutting Heads

Within every Abrasive Waterjet is a Pure Waterjet. Abrasive is added after the pure Waterjet stream is created. Then the abrasive particles are accelerated, like a bullet in a rifle, down the mixing tube.



The abrasive used in abrasive waterjet cutting is hard sand that is specially screened and sized. The most common abrasive is garnet. Garnet is hard, tough and inexpensive. Like the pink colored sandpaper found at the hardware store, different mesh sizes are used for different jobs.

120 Mesh – produces smooth surface
80 Mesh – most common, general purpose
50 Mesh – cuts a little faster than 80, with slightly rougher surface.

The mixing tube acts like a rifle barrel to accelerate the abrasive particles. They, like the orifice, come in many different sizes and replacement life. Mixing tubes are approximately 3 inches long, ¼ inch in diameter, and have internal diameters ranging from 0.020 to 0.060 inch, with the most common being 0.040 inch.

Although the abrasive waterjet machine typically is considered simple to operate and 'bullet proof,' the mixing tube does require operator attention. A major technological advancement in Waterjet was the invention of truly long-life mixing tubes. Unfortunately, the longer life tubes are far more brittle than their predecessors, tungsten carbide tubes. If the cutting head comes in contact with clamps, weights, or the target material the tube may be broken. Broken tubes cannot be repaired. Today's most advanced systems incorporate collision detection to spare the mixing tube.

	Life	***Comments***
Standard Tungsten Carbide	4 to 6 hours	These were the original mixing tubes. They are no longer used, due to their poor performance and cost per hour ratio. They tend to wear out of round, require very frequent replacement.
Low cost composite carbide	35 to 60 hours	Good for rough cutting or when training a new operator. -*Qbic 10*-
Mid-life composite carbide	80 to 90 hours	A good all around tube. -*Qbic 20*-
Premium composite carbide	100 to 150 hours	The top-of-the-line. This popular tube exhibits the most concentric and predictable wear. Used for both precision work and everyday work.-*Qbic 30*-

The standoff distance between the mixing tube and the target material is typically 0.010 to 0.200 inch. Larger standoff (greater than 0.080 inch) can cause a frosting to appear atop the cut edge of the part. Many Waterjet systems reduce or eliminate this frosting by cutting under water or using other techniques.

The consumable items in an abrasive Waterjet are the water, abrasive, orifice (usually Ruby) and mixing tube. The abrasive and mixing tube are exclusive to the abrasive Waterjet. The other consumables are also found in the pure Waterjet.

Motion Equipment

Many different styles and configurations of Waterjet motion equipment, or machine tool, exist. Besides just providing motion, the machine tool must also include some means of holding the material catching the jet and collecting the water and debris.

Stationary and 1-Dimension machines

The simplest of machines is the stationary Waterjet. Looking much like a band saw, it is usually used in the Aerospace industry to trim composites. The operator feeds the material through the stream much like a band saw. After the material has been cut, the catcher collects the stream and debris. Usually outfitted with a pure waterjet, some stationary waterjet machines are equipped with abrasive waterjets.

Another version of a stationary machine is a slitter. Here a product such as paper is fed through the machine, and the Waterjet slits the product into specific widths. A cross cutter is another example of a machine that moves in one axis. Although it is not truly stationary, this simple machine often works in conjunction with a slitter. Where the slitter cuts product to specific widths, the cross cutter cuts across a product that is fed beneath it. Often the slitter and cross cutter work together to create a grid pattern in materials such as vending machine brownie cakes.

It is generally not recommended to use an Abrasive Waterjet manually (either moving the material by hand or the cutting head by hand) – it is very difficult to manually move at a specific speed. Most manufacturers will not recommend or quote a manually operated abrasive Waterjet. Only in special cases were operator safety is not in question should an abrasive Waterjet be used in a manual mode.

Slitter - 7 stations, with 2 heads at each station. (provides 24-hr./day operation)

Cross Cutter - usually angled across and timed with the travel path of the product. Precise speed control can then produce a perpendicular cut.

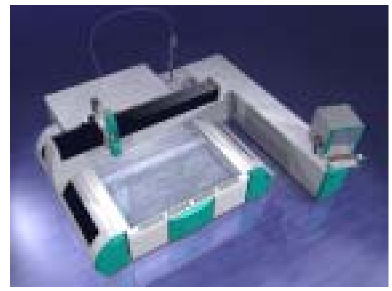
XY tables for 2-Dimension cutting

XY tables, sometimes called "Flatstock machines," are the most common forms of Waterjet motion equipment. These machines are used with pure waterjets to cut gaskets and plastics, rubber and foam. Abrasive waterjets utilize these tables to cut metals, composites, glass stone and ceramics. Flat patterns are cut, in every imaginable design. Abrasive Waterjet and pure Waterjet tables may be as small as 2 x 4 feet or as large as a 30 x 100 ft. The basic components of an XY are:

- Controlled by either CNC or PC
- Servo motors, usually with closed-loop feedback to ensure position and velocity integrity.
- Base unit with linear ways, bearing blocks and ball screw drive
- Bridge unit also with ways, blocks and ball screw
- Catcher tank with material support

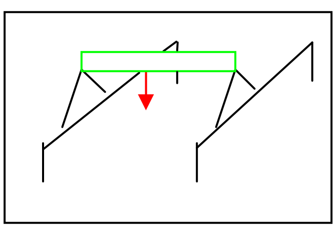
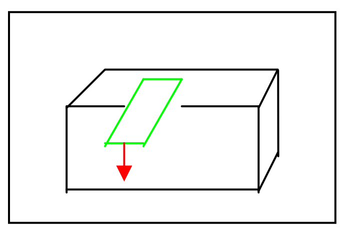
Many different machine styles are available, however two distinct styles dominate the industry; mid-rail gantry and the cantilever.



Flatstock machines (often called XYs) come in a variety of configurations to match specific applications. Some are small precision machines, while others are large production machines.

The mid-rail gantry machines have two base rails and a bridge. The cantilever system has one base and a rigid bridge. In each of the sketches below the green bridge moves in one direction while the red arrow (signifying the cutting head) moves in the other. All machine types will have some form of adjustability for the head height (the head height is controlled by the Z-axis). The Z axis adjustability can be in the form of a manual crank, motorized screw, or a fully programmable servo screw.

The catcher tanks on flat stock machines are usually water filled tanks that incorporate grating or slats to support the workpiece. These supports are slowly consumed during the cutting process. Catcher tanks can either be self cleaning, where the waste is deposited into a container, or manual, where the tank is periodically emptied by hand.

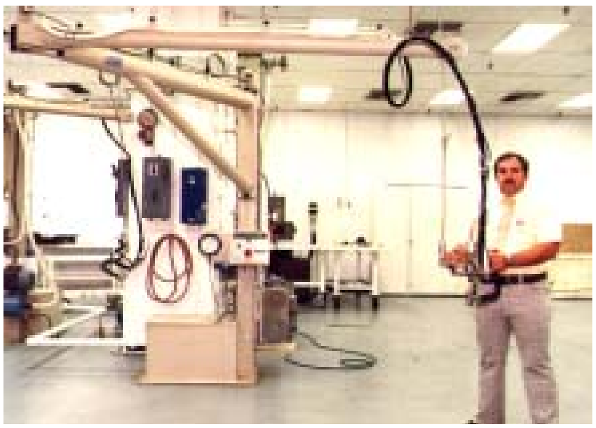
All XY tables have critical specifications in the following areas that suggest, but do not guarantee, the performance of the machine on your shop floor.

Envelope size	The length of travel found in each axis of movement. The most common sizes for flat stock cutting on a Waterjet or Abrasive Waterjet machine are 2m x3m x 0.3m, or approximately 6x10x1 ft. The catcher tank is usually at least 6 inches larger than the travel length and width, aiding in heavy plate loading, allowing for clamping, and allowing for variability in raw sheet size.
Linear Positional Accuracy	Measures how accurately the machine can move. One axis is measured at a time from one point to another. Speed is not a consideration here.
Machine repeatability	Ability of the machine to return to a point.
Rapid Traverse Speed	Rapid traverse is the top speed a machine can move without cutting. The control system simply sends a signal to the drive motors saying, "go as fast as you can in that direction." The accuracy of machine motion is usually compromised during rapid traverse. Rapid traverse is used to move from one cut path (e.g., a hole cutout), to another cut path (e.g., another hole cutout).
Contour Speed	The top speed that the machine can move while maintaining all the accuracy specifications (i.e., accuracy, repeatability, velocity). This is a critical specification as it relates to part production cycle times and part accuracy.

Brief descriptions of Waterjet machine tool motion specifications commonly found in quotations and literature.

5+ axis machines for 3-Dimension cutting

Many man-made items, like airplanes, have few flat surfaces on them. Also, advances in complex 3D composites and metal forming technologies suggest fewer flat parts are in our future. Thus, the need for 3-dimension cutting increases each year. Waterjets are easily adapted to 3D cutting. The lightweight heads and low kickback forces during cutting give machine design engineers freedom not found when designing for the high loads found in milling and routing. And the thin, high-pressure plumbing -- through use of swivels -- provides freedom of movement.



Handheld "Universal WaterRouter." A point catcher safely stops the jet immediately after cutting the thin material.

The simplest of the 3-dimensional cutting systems is the Universal WaterRouter. This device is moved by hand, and is only intended for pure waterjet cutting of thin materials (e.g., aircraft interiors and other thin composites). The handheld gun is counterweighted, and provides all degrees of freedom. This device was popular in the 1980's as a superior method of trimming composites. As a replacement for the router, the operator would press a special nozzle against the template, turn on the jet with dual thumb triggers, and trace the template with the nozzle as he/she walked around the part. The jet would shoot into a point catcher as after cutting the material. Many of these safe and effective tools are used today in thin aerospace composite cutting and other applications.

The need for enhanced production and the desire to eliminate the expensive templates required for routers and Universal WaterRouters lead to the use of fully programmable 5 axis machines. With these machines a programmer creates the tool path in an office and downloads the program to the operator's machine control system that then cuts the material.

A large 30x15x4 ft. machine cuts tail components for the Boeing 777. "Pogostick" tooling unscrews to specified height, then vacuum cups hold the part in place.

Even with the improvement of advanced 3-D offline programming software, 3D cutting proves more complex than 2-D, regardless of whether the cutting process is Waterjet, router, or another process. For example, in the composite tail illustration at left, many steps are taken to trim the part. First, the programs for the cut path and the flexible "Pogostick" tooling are downloaded. Then the material is flown in via overhead crane while the pogosticks unscrew to their pre-programmed height. After the part has been roughly located and the pogostick vacuum tops have secured the part, a special Z axis (not used for cutting) brings a touch probe into location to precisely locate the part in space. The touch probe samples a number of points to ensure the part elevation and orientation is known. Then the program part transformation takes place. Here the program is re-oriented to match the actual location of the part. Finally the touch probe Z is retracted and the cutting head Z swings into action.

C-frame holds the unique point catcher. This catcher can stop a 50 HP abrasive Waterjet in just 6 inches. A vacuum constantly removes the slurry.

The cutting of relatively thick composites (>0.05 inch) or any metal requires the use of abrasive. So how do you stop a 50 horsepower jet from cutting up the pogosticks and tooling bed after cutting through the material? The only way known to date is to catch the jet in a very special point catcher. A steel ball point catcher can stop the full 50 HP in under 6 inches, then the slurry is vacuumed away to a waste handling tank. A C shaped frame connects the catcher to the Z-axis wrist. This C-frame (shown in bright orange) can rotate to allow the head to trim the entire circumference of the wing part.

The point catcher consumes steel balls at a rate of approximately ½ to 1 pound per hour. The jet is actually stopped by the dispersion of kinetic energy. As the jet enters the small container of steel balls, the balls spin. The spinning balls then rub their neighbors and they spin. The spinning balls in the point catcher will consume the energy of the jet, leaving the cutting slurry to harmlessly leak out the screened catcher bottom. These point catchers have proven so effective that they can run horizontally, and even sometimes completely upside-down.

The complexities of locating the part in space, adjusting the part program, and accurately cutting a part are magnified as the size of the part increases. Many shops effectively use 3D machines for simple 2D cutting and complex 3D cutting every day. Although software continues to get easier and machines continue to get more advanced, parts continue to get more complex. Keep in mind that the complexities associated with 3D cutting are present regardless of the cutting process.

How machine tests are conducted

Machine tools should be tested for positional accuracy, repeatability, dynamic path accuracy, speed range, and smoothness of motion.

How linear position tests are conducted

Linear position accuracy and repeatability are tested with a Laser Interferometer. Each axis on the machine tool is tested individually. In essence, a Laser Interferometer splits a laser beam of light and measures the wavelength change between the unchanged portion and the changed portion. Because the wavelength of laser light is very small, this measuring approach is extremely accurate.

Laser interferometer

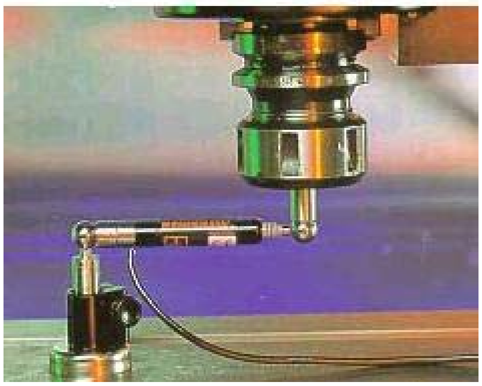
A laser is used because laser light is coherent, meaning all aspects of the light have exactly the same wavelength and are exactly in phase. Optics (special mirrors) are used. One set of optics is attached to the cutting head. The other optic is placed past the end of the machine travel. The laser is shot through the cutting head optics where the vertical component is sent back. The rest of the beam (the horizontal component) continues on to the stationary optics at the end of the machine, and then is also reflected back. Comparing the two wavelengths give precise measurements of the mobile optic, to an incredible accuracy of a few millionths of an inch.

Linear positional accuracy tests are performed by moving the head 1 or 2 inches at a time on one axis over the full travel length, pausing for a second, recording the deviation, moving to the next position, recording the deviation, and so on. The entire process of testing linear positional accuracy and repeatability with a laser takes from 6 to 12 hours, depending on the size of the machine and the quality standards the manufacturer is following.

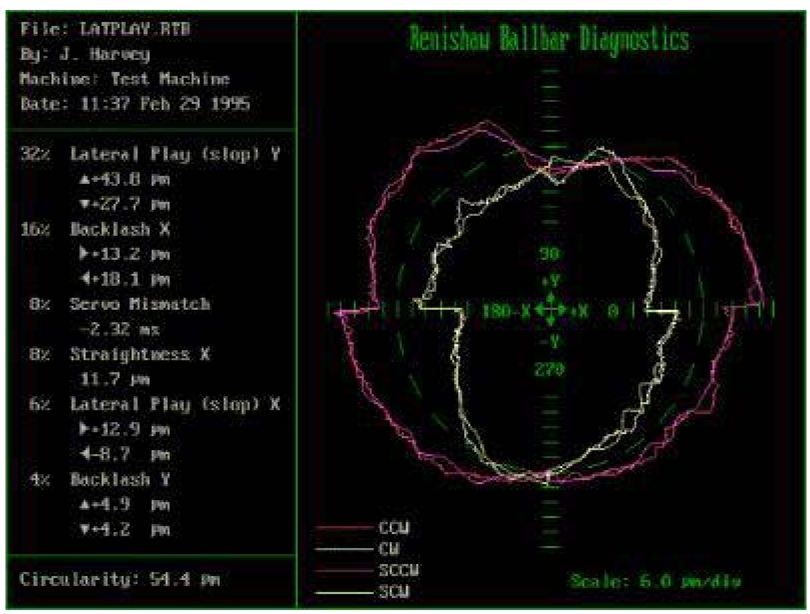
How dynamic accuracy tests are conducted

Dynamic path accuracy is tested by either cutting of parts or, better yet, by a device called a Ballbar. A magnetic base (shown in gray) is placed on the worktable at the desired test location. A precision bar (red) of known length is attached to the magnetic base. The machine is moved first precisely overtop the center of the magnetic base. Then, the machine is programmed to move to a radius exactly the length of the rod. The bar is then attached to the cutting head location (green). The machine is then programmed to move in a circle about the magnetic base.

RENISHAW



The telescoping Ballbar is ready to begin recording. The machine will execute a circle around the base and errors will be recorded.



Printout of a test. Images courtesy of Renishaw (www.renishaw.com)

An electronic measuring device (usually a high accuracy displacement sensor housed in a telescopic bar) reads the deviation from a perfect circular path as the machine negotiates the circle. This testing method can test the dynamic path accuracy at slow or fast speeds. It will detect servo following errors, motor tune problems, axis perpendicularity, and other mechanical or electrical errors. Ballbar testing takes between 1 and 3 hours to perform. Since the Ballbar is easily carried, quick to set up, and quick to conduct a test, it has proven an excellent means of checking machine performance at factory, at installation, and thereafter.

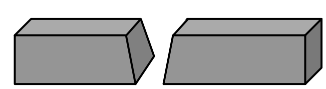
Ballbar testing is included in a number of standards for machine tool accuracy i.e. ISO 230, ASME B5.54 and BS3800. It is accurate to approximate +/- 0.5 microns, or 20 microinches at 20 degrees C.

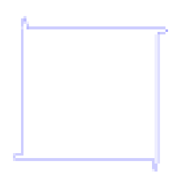
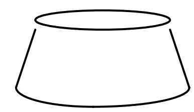
Characteristics of part accuracy

A distinct difference exists between part accuracy and the accuracy in which a machine can move. Simply buying a 0.00000000000001” accurate machine, with perfect dynamic motion, perfect velocity control, and dead-on repeatability will not mean you will cut perfect parts. It will, however, mean you will spend a lot of money on the super-accurate machine. Finished part accuracy is a combination of process error (the waterjet) + machine error (the XY performance) + workpiece stability (fixturing, flatness, stable with temperature).

The table below describes part errors which would occur even if the waterjet machine was perfect. The Waterjet beam has characteristics that greatly effect part accuracy. Controlling these characteristics has been the focus of Waterjet suppliers for many years. Simply put, a highly accurate and repeatable machine may eliminate machine motion from your part accuracy equation, but it does not eliminate other part errors (such as fixturing errors and inherent Waterjet stream errors).

When cutting materials under 1 inch thick, waterjet machine typically cuts parts from +/- 0.003 to 0.015 inch (.07 to .4 mm) in accuracy. For materials over 1 inch thick the machines will produce parts from +/- 0.005 to 0.100 inch (.12 to 2.5 mm). A high performance XY table is designed to have an accuracy of about 0.005-inch linear positional accuracy or better. So where do the part inaccuracies come from?

Part Errors	**Description**
Beam Deflection or “Stream Lag”	When the Waterjet, or other beam type cutters like laser or plasma, are cutting through the material, the stream will deflect backwards (opposite direction of travel) when cutting power begins to drop. This problem causes: increased taper, inside corner problems, and sweeping out of arcs. Reduce this lag error by increasing cutting power or slowing down the cut speed.
Increased Taper	A “V” shaped taper is created when cutting at high speeds. Taper can be minimized or eliminated by slowing down the cut path or increasing cutting power. Image is exaggerated for descriptive purposes. 

Inside Corner Problems	When cutting an inside corner at high speed, the stream can dig into the part as it comes out of the corner.  This image is of the hole that is left when cutting a square cutout, viewed from the exit (or bottom) side. The image is exaggerated for descriptive purposes.
Sweeping out of arcs	When cutting at high speed around an arc or circle the stream lag sweeps out a cone.  Image is exaggerated to illustrate the error.
Fixturing	Even though the Waterjet delivers under ½ pound of vertical force when cutting a high quality part and under 5 pounds when rough cutting, proper fixturing is required to produce accurate parts. The part must not move during cutting or piercing, and it must not vibrate. To minimize these errors try to butt the workpiece up against the edge of the catcher or a solid bar stop secured to the table slats. Look for material vibration or movement during cutting the first article.
Material instability	- Some materials, like plastics, can be very sensitive to temperature changes. Called thermal expansion, these materials may expand when slightly heated or shrink when cooled. During waterjet cutting the material does not get hot, but it can get warm. - Also, be especially careful of air gaps in cast material, as the stream tends to open up in air gaps. - The AWJ will not induce warpage in sheet material. It will, however, relieve stresses. If you are working with a sheared material <0.125 inch thick and you start your cut path off the part, enter into the part, and then cut the part, you may see the material twist and warp. Avoid this warpage whenever possible by beginning cut paths from within the material (pierce a hole and begin cutting) as opposed to beginning from outside of the material.
Pump issues	Beyond the obvious pump issues such as ensuring that the pump is delivering water at the set pressure, other issues can also impact part accuracy. If the pump has 2 or more intensifiers, do the intensifiers always stroke at the same time? If so, then look on the part for vertical marks on the cut edge that match in frequency with the stroking. Check valves should be in good working order.

Water pressure at the nozzle	- Cut speed can be lost if excessive pressure drops (greater than 2,500 psi) exist in the high pressure plumbing run from pump to head. - Ensure the in-line filter, usually located near the cutting head, is free of excessive buildup. - If you have made any changes to the plumbing run (changed the route, replaced a large line with a smaller replacement line, etc.) then ensure that you have not created larger pressure drops. Any loss of pressure between the pump is to be minimized. Pressure is cut speed, cut speed is money.
Cutter Comp error	Cutter compensation is the value entered into the control system that takes into account the width of cut of the jet; in effect, you are setting the amount by which you are enlarging the cut path so that the final part comes out to proper size. Before you perform any high precision work where finished part tolerances are better than +/- 0.005 inch, cut a test coupon and ensure you have properly set the cutter compensation. Many a good drawing has been cut wrong because the operator did not take the time to establish the best cutter compensation value.
Programming error	Often the most difficult of all part accuracy errors to find is a programming error where the dimension of the part program does not perfectly match the dimension of the original CAD or hand drawn drawing. Part programs that appear graphically on the screen of an XY control typically do not display dimensions. Therefore, this error can go undetected. When all else fails, double check that the dimensions on the part program match exactly those of the original drawing.
Abrasive Mesh Size	Typical abrasive mesh sizes are 120, 80, and 50 (similar to sand paper you might use for woodworking). The different mesh sizes do not have a significant impact on part accuracy. They have a greater impact on surface finish and overall cut speed. Finer abrasives (larger mesh number) produce slower cuts and smoother surfaces.
Machine Motion	The positional accuracy and dynamic motion characteristics of a machine have an impact on the part accuracy. There are many aspects to machine motion performance. A few are <u>backlash</u> in the mechanical unit (changes in direction, is there slop in the gears or screw when the motor changes from clockwise to counterclockwise?), <u>repeatability</u>, will the machine come back close to the same point over and over? Servo tuning is important. Improper tuning will cause backlash, squareness, repeatability errors, and can cause the machine to chatter (wiggle at high frequency) when moving. <u>Position accuracy</u> is important, as well as <u>straightness</u>, <u>flatness</u>, and <u>parallelism</u> of the linear rails. Small part, under 12 inches in length and width, do not demand as much from the XY table as larger parts. A large part measuring, for example, 4x4 ft, will be greatly impacted by machine performance. A small part will not see position accuracy, or rail straightness as a major impact on finished part tolerance simply because the small part masks machine errors. Large parts expose such errors more evidently. Remember that a machine motion characteristic does not directly correspond to finished part tolerance. An expensive super-precision machine (linear position accuracy of, for example, +/- 0.001" over full travel, will not automatically generate a finished part of +/- 0.001" – other part accuracy factors are still there (see above).

Selecting a Waterjet

As with any purchase, the wants and needs must be weighed with a practical eye. A variety of machines exist, yielding a number of different price levels. By closely examining your production needs and matching the machine to it, you can minimize unnecessary expenditures.

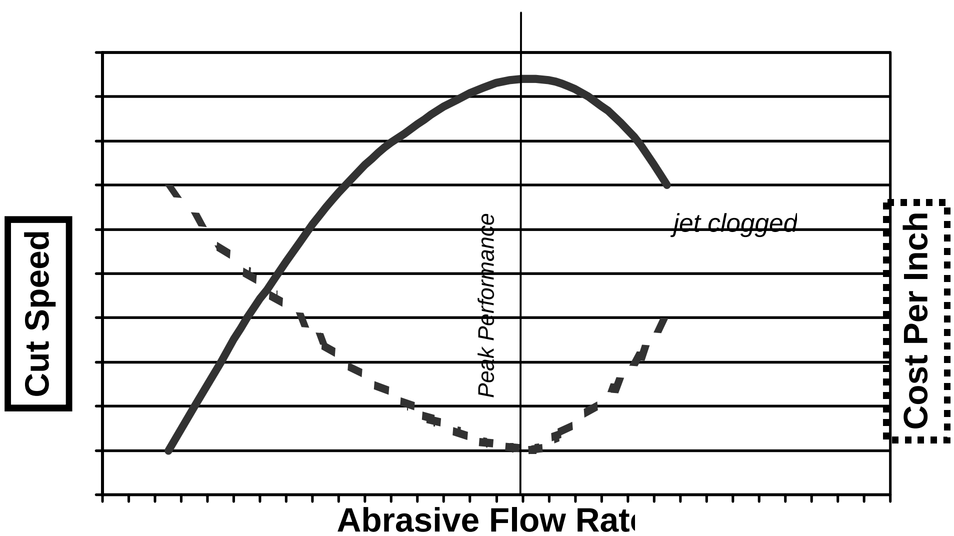
Application workup:

In my shop	***Comments***
Materials and thickness I intend to cut with WJ 1) 2) 3)	*This list suggests pump size. Parts over ½ inch thick should be cut with at least 50 HP per head. Smaller heads are more expensive per inch.* *However, sometimes it can be very effective to run two small heads instead of one large head. Examining cycle times and cost per part for each configuration will help show whether one or two heads is most productive.*
Stock plate sizes (in priority) 1) 2) 3)	*Sizing a machine for an oddball large plate size can be an expensive approach. It is often cheaper to cut an oversized plate down before putting it on a Waterjet, or letting the oversized plate overhang out of the catcher.*
Finished part accuracy required	*As with the plate size, you should consider the majority of the work you do, not THE most accurate.*
Is a 100 to 250 RMS sand blasted surface finish acceptable "as cut."	*If you do not have to perform secondary operations to obtain a very smooth surface (better than 100 RMS), then your costs per part should be quite low on a Waterjet. In hard materials, like hardened steels, titanium, nickle allows, ceramics, the roughing out of a part with a Waterjet still may save significant cost, even when final finishing is required.*
Operator proficiency	*Are your operators also your programmers? Is it difficult to get and to hold programmers and operators? If so, then an intelligent control will improve your productivity greatly over the more complex and hard to learn CAM to CNC based systems.*
Who will perform maintenance?	*If the operator is also the maintenance person, then ensure adequate training is provided. You may want to consider purchasing an additional on-site operator and maintenance training day (or two) 60 days after installation.*
Will the operator run just the Waterjet machine, or other machines too?	*If the operator will be running more than just one machine at a time, then look into technology that aids automated operation. For example, from some manufacturers you can purchase a cutting performance*

	monitor that will automatically stop the machine if any deviation from peak efficiency occurs. Or, if your batch size permits, loook to stack cutting. The jet on-time is extended but part production is very high. The operator can be running another machine while the jet is cutting.
Will you be nesting parts on a plate?	*Many nesting packages are available. Although a generic nesting package can create a nest for a Waterjet machine, it is typically understood that nesting packages (and machine tool controls) that are designed for a specific process are more powerful and easier to use than the generic, multi-process version.*
Do I have the facilities?	*Be prepared to discuss with the manufacturer all facilities issues. Floorspace, power, water, compressed air, drainage, material storage, material loading, clean shop area for high-pressure maintenance, programming office area.*

The effects of power

A common misconception in Waterjet and especially Abrasive Waterjet cutting is that it is best to use as little power, as little pressure, as little abrasive as possible to get the job done. Nothing could be further from the truth. The key is to cut as fast as possible. For most applications, the operating cost increase when running your system "flat out" is far outweighed by the money saved by producing more parts in a given time period. The generic curves in the figure below have been generated by countless Universities, waterjet manufacturers, waterjet users, and research companies. The curves always show the same tendancy – as abrasive flow rate is increased from zero, cut speed goes up and cost per inch goes down until a peak point is reached, a point where cut speed and cost per inch are both at their optimum. Of course with every "rule of thumb" there are exceptions. However for virtually all cutting in the world today, *fastest cut speed = lowest cost per inch.*



For any given set of parameters (pressure, orifice size, etc…), the cut speed goes up and costs go down as the abrasive flow rate is increase Eventually a Peak Performance is reached.

To cut as fast as possible, the system should be operated using the maximum horsepower available. If you have a 60,000 psi pump with 50 HP, then whenever possible use all 50 HP. If you have a 100 HP system but can only effectively run a cutting head that consumes 50 HP, consider running two heads.

Abrasive constitutes 2/3 of the machine operating cost of the equipment. Machine operating cost does not include labor, lease or depreciation, facilities, or other overhead costs. It does include power, water, air, seals, check valves, orifice, mixing tube, abrasive, inlet water filters, long term spares (hydraulic pump, high-pressure cylinders, etc). Basically, these are all the items that need replacement regularly or over the life of the Waterjet system.

In Abrasive Waterjet cutting it is often thought that to reduce the abrasive flow rate saves money. On the contrary, it wastes money. There is a peak performance point that abrasive waterjets operate. When you include all overhead the cheapest cutting is always found at the fastest possible speed. This fact is independent of the material you are cutting, or the power of the system.

To select the right pump, first begin by examining how you answered the Application Workup (see above). If you are cutting prototype parts and do not foresee heavy production requirements, then a large pump is likely waste of capital. On the contrary, if you are to perform in-house production of high volume parts and are in the fortunate position of being able to afford the ideal machine, then a larger pump with multi-head cutting capability is the right choice.

A variety of pump sizes are available. Some manufacturers produce just a few sizes, others make a full range. The full range is listed below in the output and multiple head table (below).

Pump Power	**Output gallons per minute**	**Maximum single orifice (diameter) it can power at full pressure**	**Multi-head options**
25 HP	0.5 gpm	0.010 inch diameter	Multi-head with this pump is highly unusual -- heads become small.
50 HP	1.0 gpm	0.014 inch	2 each 0.010”
75 HP	1.5 gpm	0.017 inch	3 each 0.010”
100 HP	2.0 gpm	0.21 inch (seldom use all 2.0 gpm because largest abrasivejet heads are 0.016 or possibly 0.018 inch)	4 each 0.010” 2 each 0.014”
150 HP	3.0 gpm	0.28 inch (seldom use all 2.0 gpm because largest abrasivejet heads are 0.016 or possibly 0.018 inch)	2 each 0.017” 3 each 0.014” 6 each 0.010”

Simplified pump capacity table. Although other pump sizes exist from some manufacturers (40HP, 60HP, 200 HP, etc.), those in the above table are most common.

In the table above the most common pump size is the 50 HP pump powering one head. From there, the order of popularity follows 100 HP, 25 HP, and 150 HP. Over 60% of all pumps produced today are 50 or 100 HP.

Since 1999, there has been a steady increase in the number of multi-head systems using 100 HP and even higher. The upgrade to 100 HP costs a little more ($30,000 to $50,000), but are more productive than 50 HP single head systems. If you can fairly accurately predict your machine utilization, then you can use a Return On Investment analysis to help decide whether the larger capital investment is justified.

Return On Investment Analysis

ROI stands for Return On Investment. An accurate ROI analysis can be quite an eye opener. ROI can clearly show you the relationship between your capital investment, operating cost, and production capability. A solid ROI analysis can help predict whether purchase of equipment will result in profit or loss.

Any accountant has general ROI analysis capability. Some waterjet manufacturers can offer ROI analysis specific to operating the waterjet system. Whether you use your accountant for a general analysis, or the manufacturer for detailed analysis, you will be asked to enter conservative data on the expected performance of your Waterjet business. The results can estimate the number of hours you will need to run the machine per month to cover expenses, the return on investment percent for the first three or four years, and the month that the initial investment has been covered.

Although a good accountant can help you with an ROI analysis, a lack of intimate familiarity with the business of running a Waterjet may yield bad results. The better approach is to have the Waterjet manufacturer provide you with a full ROI analysis. Then have that analysis reviewed by your accountant, ensuring it all makes sense. This approach will help you get the right data into the equation, and your accountant can make sure the calculations and results are appropriate.

Installation and training

You must have installation and training with your first Waterjet system. You must have installation on your second, and training may still be a good idea. This author is aware of a handful of times that the buyer decided to perform all the installation procedures without aid of the manufacturer. More than half of the time the results were horrible. Even if you are familiar with machine tools, let those expert in that particular machine install the machine.

Installation should take no more than 2 weeks, one week for a simple standard system. A typical one-week installation should go as follows. The buyer is usually responsible for uncrating and locating the major components. Also, utility connections (power, water, air) are to be made. The manufacturer's field service engineer (FSE) will normally perform all interconnections and inspect the utility hookups you have already established. On-site start-up service for a period of up to 4 consecutive days should start on a Monday or Tuesday. The buyer supplies a maintenance technician to help the FSE assemble, level, and align the XY, as well as make all HP plumbing connections. Sometimes special brackets must be made on-site if special unexpected plumbing considerations arise. The system is started up with help of the buyers' electricians and plumbers. The system is flushed, and commissioned.

Flushing the system through an oversized scrap orifice helps remove debris from the high pressure plumbing lines. Even after extensive flushing, some debris can still come free in the plumbing and cause pre-mature failure of the orifice. An in-line filter should be placed as near to the cutting head as possible to minimize these failures. Check this filter often during the first few weeks (e.g., every 20 hours for 100 hours of pump run time) of operation.

Training should be 1 to 2 weeks at the manufacturer's facility. Training should cover maintenance procedures, troubleshooting, programming, and operation. It is recommended that the operator, maintenance staff, and programmer attend training. Some training courses can be chopped up so that you don't waste your programmer's time at the maintenance training. Whatever training comes with the system, ensure your staff attends every bit of it. You paid for it (regardless whether the manufacturer said training is free or not). The better your initial training, the faster you'll go up the learning curve, and the faster you'll be productive and profitable.

Installation and machine run-off recommendations

Before a Waterjet machine or any other relatively expensive machine tool is accepted, the buyer must obtain proof of performance. The supplier must show proof that the machine has passed all internal tests. Basic performance criteria must be met as specified in the final signed quotation. Any additional acceptance criteria should be mutually agreed upon prior to purchasing the machine. Below is a brief table listing the machine testing that should be required, and the preferred method of test.

Performance to be checked	***Method of test and comments***
Accuracy and repeatability	Obtain printouts for laser interferometer tests showing linear positional results for each primary axis. Match these results against the quotation. For high-precision machines (+/- 0.003 inch accuracy over full travel or better) the machine should be tested under ISO bi-directional standards, and to 3-sigma.
Maximum contour velocity	Obtain printouts of ball bar tests performed on the factory floor. Perform a similar test (perhaps simplified) on your floor after installation to ensure results are acceptably similar to the factory results. The dynamic accuracy test, via a ball bar, will show the top speed that the machine can traverse a circle while maintaining the quoted accuracy and repeatability.
Travel Length	Ensure the machine has full length of travel. If the machine is a 6 x 10 ft. machine with a 10 inch Z, then confirm those distances.

Operating Pressure	Ensure that the high-pressure pump can continuously operate at the quoted pressure. Keep in mind that some pressure is lost in the plumbing between the pump and XY table. Test the water pressure as close to the pump as possible. Pressure is productivity. Although the plumbing runs will impact the nozzle pressure, the pump should deliver exactly the pressure quoted, and in a continuous fashion (not dead-heading the pump, but while a cutting head is activated).
Cutting performance	If the supplier cut materials during the evaluation/quotation stage, re-cut these materials on your machine on your floor as part of the machine acceptance. Compare results. This test can often be rolled into the familiarization training. Familiarization training is not a substitute for a full training course given by a manufacturer at a manufacturer's facility. Familiarization training usually follows immediately after install, takes about ½ day, and is intended to ensure the operator and maintenance staff are comfortable with the machine. It is best to send your staff to the manufacturer's full training program prior to machine install and prior to this familiarization training.

Final Note: Rules of Thumb – Abrasive Waterjet Cutting Tips

Hopefully you will find that reading through these tips might provide you with more insight into the process. Some of the tips are obvious, while others are only seen through experience.

1. When cutting under 0.100 inch thick material little is gained by using medium (50 HP) or large (60 to 80 HP) cutting heads. Use a small parameter combination (25HP) and consider multiple head to increase production if needed.

2. Avoid cutting through air gaps greater than 0.020". The jet tends to open up in the gap and cut the lower layer roughly. When stack cutting, keep the sheets together.

3. Smaller abrasive grains (120 mesh or smaller) will produce a slightly slower but slightly smoother surface (as compared to 80 or 50 mesh).

4. Productivity is cost per inch, not cost per hour. It matters very little how much it costs per hour to run an abrasive Waterjet. What matters is how many parts you get off in a given length of time. Some users make the mistake of trying to reduce operating cost by minimizing the abrasive flow rate. Even though abrasive is 2/3 of the Abrasive Waterjet operating cost, you must produce parts quickly to consume your overhead (labor, facilities, lease payment). Cut as fast as possible, using all available horsepower and the peak abrasive flow rate.

5. If you intend to pierce composites, glass, and stone on a regular basis, ensure the system has the ability to have the water pressure lowered and raised by the controller. Also, you should investigate vacuum assist or other techniques to improve probability of successfully piercing these brittle or laminated materials.

6. Control systems specifically designed for a process are typically more efficient and easier to use than generic multi-process controls.

7. Most machines do not employ material handling automation, such as shuttles. Only when material handling constitutes a significant portion of part production cost should automation be considered. 90% of all Abrasive Waterjet machines are loaded and unloaded either by hand or with the aid of simple overhead cranes, jib cranes, or fork lifts. Approximately 50% of all Waterjet machines utilize material handling automation. WJ typically cuts thin, light material at very high speed. The time it takes to cut an entire sheet is fairly low, and the handling component of part production cost is high enough to justify the added capital expense.

8. Ordinary tap water is used to feed the Waterjet systems. 90% of all Waterjet and Abrasive Waterjet users require only water softening prior to sending that water through the pump's inlet water filters and then to the intensifier. Reverse Osmosis (RO) and De- Ionizers tend to make the water so pure that it becomes "ion starved." This aggressive water seeks to satisfy its' ion starvation by taking ions from surrounding materials, such as the metals in the pump and high-pressure plumbing lines. RO and De-I can greatly extend orifice life, while simultaneously performing very expensive damage to the intensifier and plumbing. Orifices are rather inexpensive. High-pressure cylinders, check valves, and end caps damage will far outweigh orifice life improvements.

9. Cutting underwater reduces surface frosting or 'hazing' found on the top edge of an abrasive Waterjet cut. Cutting underwater also greatly reduces jet noise and workplace mess. The only negative is that operators cannot see the jet clearly during cutting. If the operator objects to underwater cutting, consider electronic performance monitoring. These monitors will detect deviation from peak cutting performance and stop the system prior to part damage.

10. If you plan on using different abrasive mesh sizes for different jobs, consider adding a small (100 pound) or large (500 to 2,000 pound) bulk transfer. Without having a bulk transfer hopper for each mesh size you regularly run, you may produce downtime and nuisance along with your production.

11. Break out tabs can prove effective for cutting of materials under 0.3 inch thick. Although break out tabs generally guarantee you'll need a secondary operation of grinding off the tabs, their usage allows material handling to be performed faster – simply unload a cut sheet with the cut parts still in tact. The harder the material, the smaller the break out tab should be. Consult your manufacturer for detailed suggestions.

	Cut speed				
	60,000 psi			40,000 psi	
Orifice Water Abrasive Horsepower	.010/.030 .5 gpm .9 lb/min 25	.014/.040 .96 gpm 1.4 lb/min 50	.018/.050 1.6 gpm 2.5 lb/min 80	.010/.030 .42 gpm .6 lb/min 11	.013/.040 .71 gpm 1.0 lb/min 25
Aluminum 1/4”	53.6	76.1	100.7	27.1	39.6
1/2”	25.4	36.0	47.7	12.8	18.8
1”	11.3	16.0	21.2	5.7	8.3
Granite 1/4”	94.6	134.1	177.7	47.7	69.9
(generic) 1/2”	44.8	63.5	84.1	22.6	33.1
1”	19.9	28.2	37.4	10.0	14.7
Graphite/ 1/4”	145.6	206.5	273.5	73.4	107.6
Epoxy 1/2”	69.0	97.8	129.6	34.8	51.0
1”	30.6	43.5	57.6	15.5	22.6
Inconel 1/4”	18.1	25.7	34.0	9.1	13.4
1/2”	8.6	12.1	16.1	4.3	6.3
1”	3.8	5.4	7.1	1.9	2.8
Marble 1/4”	111.5	158.0	209.3	56.2	82.3
(generic) 1/2”	52.8	74.9	99.2	26.6	39.0
1”	23.5	33.3	44.1	11.8	17.3
Glass 1/4”	102.9	145.9	193.3	51.9	76.0
1/2”	48.7	69.1	91.6	24.6	36.0
1”	21.7	30.7	40.7	10.9	16.0
Steel 1/4”	21.3	30.2	40.0	10.7	15.7
(mild) 1/2”	10.1	14.3	18.9	5.1	7.4
1”	4.5	6.3	8.4	2.3	3.3
Steel 1/4”	19.8	28.1	37.3	10.0	14.7
(stnls) 1/2”	9.4	13.3	17.6	4.7	6.9
1”	4.2	5.9	7.8	2.1	3.1
Titanium 1/4”	25.8	36.6	48.5	13.0	19.1
(6Al4V) 1/2”	12.2	17.3	23.0	6.2	9.0
1”	5.4	7.7	10.2	2.7	4.0

Note: Maximum cut speed. For a quality surface finish, cut speed should be multiplied by 0.40. All materials listed above were cut with FLOW’s PASER 3 system and Paser® *Plus* Garnet.