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An Investigation of Methods to Homogeneously Entrain and Suspend Abrasive Particles in a Low Pressure Dental Water Jet

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AN INVESTIGATION OF METHODS TO HOMOGENIOUSLY ENTRAIN AND SUSPEND ABRASIVE PARTICLES IN A LOW PRESSURE DENTAL WATER JET

by

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ABSTRACT

AN INVESTIGATION OF METHODS TO HOMOGENEOUSLY ENTRAIN AND SUSPEND ABRASIVE PARTICLES IN A LOW PRESSURE DENTAL WATER JET

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Master of Science

During the past several decades, the water jet cutting concept has developed from a novel concept into a well-accepted machine cutting tool. With the addition of abrasive particles and the improvement of high pressure pumps, the water jet stream is currently capable of cutting through metal, concrete, and composite materials.

Water jet systems have been utilized at a wide range of different pressures. Research performed at Brigham Young University has revealed that low pressure water jets have the ability to cut human teeth. Experiments have shown that when abrasive particles are added to the water jet stream, an greater amount of tooth material can be removed at lower input pressures. Many different methods have been proposed to entrain and suspend particles in a high pressure water jet system. The abrasive particles can be

entrained before the water is pressurized, while the water is being pressurized, or after the water jets stream exits the pressurized system. Each method has its advantages and disadvantages. Unfortunately, keeping abrasive particles homogeneously entrained and suspended in a water jet stream has proven to be difficult.

Research at Brigham Young University has encountered similar problems. Researchers are attemping to place abrasive particles in a low pressure water jet stream, but have not been able to maintain a suspended homogeneous slurry. It is the objective of this research to investigate and suggest several possible methods to entrain and suspend abrasive particles into a low pressure water jet system intended for a dental cutting application.

A broad review of methods to entrain abrasives in high pressure water jet systems was performed. A list of methods and concepts as possible solutions to entrain abrasives in a low pressure system has been generated. Product design principles were applied to screen, score, and rank these generated concepts to narrow down the list to the most viable concepts for BYU's low pressure dental water jet.

Several tests and experiments were also performed to validate the suggested concepts and to provide useful information for future research. It is anticpated that one or more of these methods will be applicable for the proposed dental application as well as other similar applications.

ACKNOWLEDGMENTS

We often hear that life is about the journey that we take and not merely arriving to a destination. It is the experience and knowledge that we have with us when we have finished a chapter of our journey that matters most. Many important individuals have made the journey of this research a valuable experience and this thesis is an acknowledgement to them.

I am most indebted to my wonderful wife, Stephanie, and her dedication to this research on my behalf. When days were long, she was ready to lend a supportive and loving hand with out expecting anything in return. She is an example of devotion and love.

Dr. Robert H. Todd has been a source of leadership and intellect; however, these attributes wane in comparison to his selflessness and service to others. He has spent countless hours helping me to learn and grow throughout this research. Years down the road, I hope to still be following in his footsteps, which would assure me success in all aspects of my life.

A special thanks to Dr. Kenneth Chase, Dr. Brian Jensen, and Susan Phillips for their advice and assistance during this research.

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1 Introduction

The purpose of this chapter is to introduce the historical advancements of handpieces used by dentists to remove decayed tooth material. The most common dental handpiece is the mechanical drill bur; however, new technology has produced alternative handpieces. This chapter will present the most common handpieces currently used in today's society and discuss each of their advantages and disadvantages.

Next, a low pressure water jet will be presented and considered as an alternative dental tool. A review of high pressure water jet systems and research previously performed at Brigham Young University with low pressure systems will be discussed to elucidate the potential of a water jet stream to cut tooth material. The final sections of this chapter will list the objectives of this research thesis and the methods that will be used to accomplish those objectives.

1.1 Dental Handpiece History

Scientists have discovered artifacts which provide evidence that dental work has been practiced for several millennia. In Pakistan, eleven human teeth were found that were treated with "flint-stone" tools. These teeth are estimated to be around 9,000 years old. It has only been in the last couple of centuries that noteworthy improvements have been made to dental tools. In the early 1800's mechanical hand drills were invented; however, their capabilities were minimal and the drills could only reach 15 rotations per minute. One of the first great advancements came in 1864 by British dentist George Harrington. He invented the clockwork dental drill named the *Erado*, as shown in Figure 1.1. It was relatively faster than previous drills but also much noisier. The noise has been and still continues to be a major disadvantage for mechanically driven dental drills.

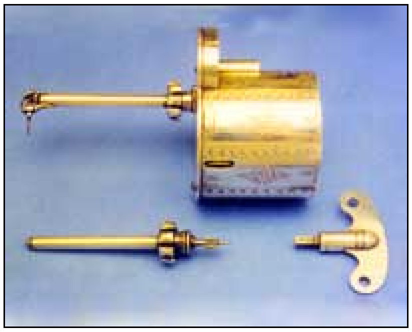

Figure 1.1 The 'Erado' clockwork (B.D.A. 2006).

As technology progressed, so did dental drill advancements. The first electric dental drill was patented in 1875 by Dr. Green. In 1914, this new tool revolutionized dentistry by reaching 3,000 rotations per minute. A second wave of dental drill developments occurred in the late 1950's with the introduction of the air turbine powered drill by John Patrick Walsh. Successors of the air turbine dental drill are the most accepted handpiece by professional dentists today. These drills can reach up to 800,000 rotations per minute, which results in a better surface finish, faster removal of tooth material, and less required cutting force.

Currently, a dental drill is defined as a small, high-speed drill used in dentistry, which is used to remove decayed tooth material or "build-up". This is performed in preparation to fill the hole/gap/crack in the tooth with dental filling material. Dental caries, more commonly known as a dental cavity, is decay damage to the structure of a tooth.

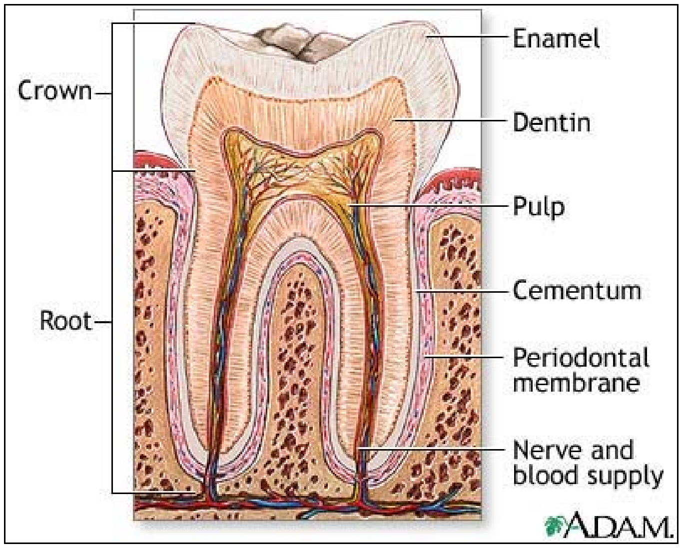

Figure 1.2 Structure of a typical human tooth (A.D.A.M. 2004).

Caries are considered a disease and their deteriorating consequences are permanent. The tooth itself is non-regenerative. Though the tooth will continue to grow into its mature state, provided its pulp is not damaged, areas of decayed or damaged enamel or dentin will not regenerate. A typical tooth structure is shown in Figure 1.2. In order to repair the tooth, the decayed material must be removed and a special filling material inserted to protect the rest of the tooth from continued decay. Currently, this process is reported to occur about 156 million times per year in the United States alone and has been performed for centuries by cutting away the decay with the cutting edge of a drill bit (American Dental Association, Survey Center 1990).

Modern drill bits are made of hard metal alloys such as steel, tungsten carbide, diamond-coated alloy, or a mixture of any of the three. This helps to provide longer tool life by maintaining a more durable cutting edge. The tooth decay is removed by a "cutting" action, which is accomplished by contacting the dental drill edge to the tooth itself. This type of high speed dental tool has been successful. However, in the 1990's a third wave of accepted technology introduced alternative techniques for removing dental caries. Though the drill has been effective in removing tooth material, it has several weaknesses that until recently have had no alternative design. Due to the introduction of new cavity removing tools, the term "dental drill" has become a colloquial form of the term "dental handpiece." Two of the most current alternative dental handpieces are the laser and air abrasion tools.

The drill remains a very popular choice among dentist for several reasons: It is the fastest cutting tool on the market and it has been around for many years; therefore, the tools are well understood, easy to clean and inexpensive to replace. A standard high speed handpiece typically sells for around $600. This method for removing dentin with a dental bur handpiece is taught in dental schools. Consequently, the drill is the first choice when the new dentist first begins work. However, with new methods of dentin removal continuously becoming more familiar and accepted among dentists and patients, the norm is slowly shifting to alternative caries removal techniques.

New hand tools are surging because the dental bur (drill) handpiece has several undesirable characteristics. Traditional dental drills are notorious for causing patient discomfort. Since the drill bur comes in direct contact with the tooth, friction occurs, which may cause pain. The enamel may also be weakened further due to the undesirable removal of excessive healthy material. The heat may cause tooth pulp inflammation and micro-crack propagation in the tooth's enamel. Drill vibration may also result in micro fracture.

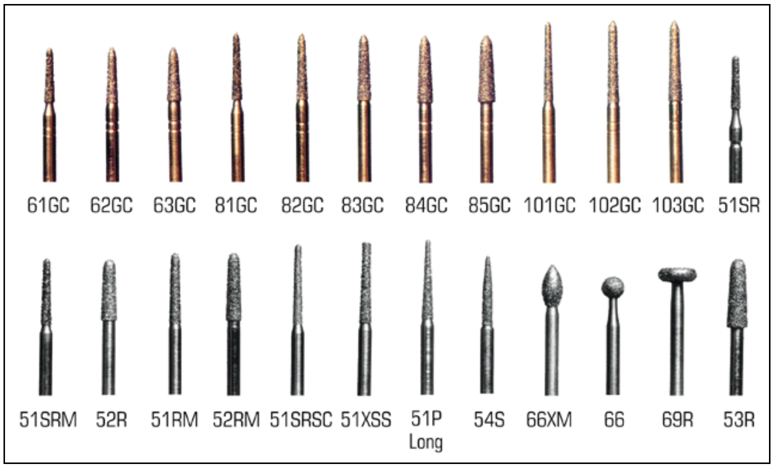

Figure 1.3 A set of common dental drill burs (Lasco Diamonds 2006).

A notable drawback of the traditional hand drill is that the minimal amount of cutting is limited to the diameter of the drill tip. Even the smaller tips are often too large to cut away just the decayed enamel, which results in excessive healthy enamel and dentin being removed from the tooth. Figure 1.3 shows a set of common dental cutting burs.

Due to the nature of traditional drilling, anesthesia is often required to minimize the pain and/or discomfort to the patient. Anesthesia is injected by means of a needle. This is generally painful and the dental operation has to wait until the area to be treated is numb. When surgery is complete, the patient has to endure until the numbness associated with the anesthesia dissipates.

Most modern drills are pneumatically driven. Due to the extremely high speeds of the bur tool generated, a distinct shrill and whine sound are produced. This sound has instilled a discomfort or fear into many patients' minds. A study by Willershausen et al (1999) at the University of Mainz shows that this paradigm of fear and paranoia has merit. Results revealed that 56% of patients felt fear caused by the noise and vibration of the drill and 47% felt fear at the sight of an anesthetic needle. Consequently, patients reported muscle tension (64%), higher heart beat (59%), accelerated breathing (37%), sweating (32%), and stomach cramps (28%). The study showed a stronger correlation in patients less than 35 years of age, typically more prominent in children. It may be reasonable to assume that if the fear of dental treatment is quashed at an early age that oral health would increase significantly as time progressed. It is probable that more patients would make and keep their appointments. To improve patient comfort at a dental office, the disadvantages of the traditional dental drill handpiece need to be overcome.

1.2 Alternative Dental Handpieces

Currently, there are two other approved and accepted dental handpiece options: the YAG:laser and the Microair abrasion unit. Both of these technologies gained general acceptance in the early 1990's and have been approved by the FDA. These alternative dental caries removal tools offer a variety of advantages and disadvantages. Understanding the strengths and weaknesses of each of these dental handpieces will provide further insight into what the patient is ultimately looking for.

1.2.1 Laser Dental Handpiece

The laser was initially approved for gum surgery in 1995 and then for “hard tissue’” in 1998. There are two companies that market the laser for dental caries: Biolase, of San Clemente, California; and Premier Laser Systems Inc., of Irvine, California.

The Erbium:YAG is an acronym for Erbium-doped Yttrium Aluminum Garnet (ER: $Y_3Al_5O_{12}$). It is a compound that is used as a lasing medium for certain solid state lasers. This particular laser emits light at a wavelength of 2940 nm. This is in the infrared zone and is intentionally at the resonant frequency of H_2O. The laser removes the tooth decay by vaporizing tooth tissue. This is accomplished by passing a stream of laser light through a fiber, which is connected to a pencil-like handpiece. The laser incorporates water and air to cool and clean the working area. The laser heats up the water, and as the water vaporizes, laser micro-bursts break up the decayed tissue and both are washed away.

Just as a dental drill bur can easily damage other areas in the mouth, a laser can also. It must be carefully controlled at all times so that healthy tissue is not damaged. Since the laser is harmful to the eyes, protective glasses are required for the dentist and sometimes the patient.

> The laser is a cutting instrument, says Susan Runner, D.D.S., branch chief of dental devices in FDA's Center for Devices and Radiological Health. And like any cutting instrument, dentists have to be careful any time they use it. The laser has many of the same risks as the drill.

Figure 1.4 The Biolase WaterlaseMD laser for use in dentistry.

One of the most prominent deterring factors for investing in the laser as a standard dental handpiece is the relatively high cost of the unit. Premier Laser Systems listed their laser for about $45,000 for its Centauri laser, which also includes training for the dentist. The extra cost is passed onto the patients since its use is not completely covered by insurance.

Data has shown that the laser takes more time than the conventional mechanical drill method of removing caries. A dentist has to decide if the initial costs and the extra time expenditure are worth the advantages. Also, the laser cannot be used on teeth that already have fillings. There is a current risk in which the laser will heat up the filling and cause tooth damage via heat transfer. It is also believed that silver fillings actually damage the laser tip due to reflection.

The laser is really ideal for virgin teeth--for new decay, Runner says. Dental lasers are a growing field, but they can't do everything. There's still a need for the standard handpiece.

Nevertheless, the laser offers several benefits over the traditional hand drill: The laser is typically painless and so there is no need for anesthetics. There are no vibrating or rotating burs, subsequently, there is no high shrill from the pneumatic driven motor. Also, there is no recurring direct contact with the tooth. The YAG:laser is capable of being more precise (smaller cutting diameter) and, consequently, is able to avoid cutting healthy tissue while removing the caries.

1.2.2 Air Abrasion Dental Handpiece

Another method to remove dental caries that has gained success is the air abrasion handpiece. The original idea was invented in the 1940's by Dr. Robert Black. It is only recently that air abrasion has become a feasible alternative method for dentin removal due to advancements in its technology. The process itself is considered conservative since no local anesthesia is typically necessary. Relatively small holes can be cut to shallow depths in the tooth enamel. It also avoids enamel micro fracturing that is possible with a rotary bur.

Air abrasion consists of an air compressor and a storage vessel for aluminum oxide particles, which are accelerated through a handpiece similar to a dental drill. Air abrasion is based off of the well-known sand-blasting principle, but with a focusing tip suited for dental applications. The opening of the tip ranges from 0.375-0.5 mm and the air pressure reaches about 160 psi. The decayed tooth material is removed by brittle fracture erosion.

Though a novel design, air abrasion has its weaknesses. The process has slower cutting rates when compared to the dental drill. It can also create heat affected stresses in a tooth if not properly handled. Another major concern is the fact that the abrasives create a cloud of dust that surrounds the patients' mouth and even the rest of the dental room. Consequently, the point of cut may become obscured, which can also lead to errors in material removed and more time used. Also, the dust may become uncomfortable for both the patient and the dentist. The dentist typically wears safety glasses to prevent eye irritation from the airborne particles. In response to the negative consequences of the airborne abrasive particles, a water stream has been added to wet the particles down. This helps maintain the particles inside the mouth. This type of air abrasion tool is illustrated in Figure 1.5.

Figure 1.5 Air abrasion jet with an assisted water stream for abrasive wetting.

Air embolism is a critical concern. The air abrasion process usually requires a *rubber dam* to stop the particles from colliding with the patients gums. Some patients give witness to inflation of the gums from the air when a protective rubber dam is not used. Air is forced into the gums around the tooth. The hazard is great if dentists are not well trained. In the most extreme cases, an embolism may be fatal.

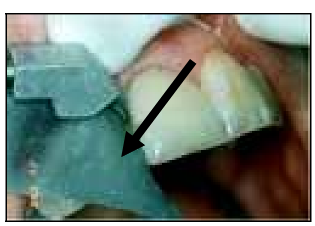

Figure 1.6 Air abrasion and a rubber dam to protect gums from particle impact

Generally speaking, there are advantages and disadvantages of using air abrasion as a caries removal tool, as suggested by *The Department of Dentistry at The Cleveland Clinic.*

What Are the Advantages of Air Abrasion?

Compared with the traditional drilling method, the advantages of air abrasion include the following:

- Air abrasion generates no heat, sound, pressure or vibration.
- Air abrasion reduces the need for anesthesia, particularly if the cavity is shallow.
- Air abrasion leaves much more of the healthy tooth tissue behind.
- Air abrasion leaves the working area relatively dry, which is an advantage during the placement of composite fillings.
- Air abrasion reduces the risk of micro-fracturing and chipping of the tooth, which some experts believe can lead to premature restorative failures.
- Air abrasion allows the dentist to treat multiple sites in the mouth during a single visit.
- The procedure is relatively simple.

What Are the Disadvantages?

- Air abrasion is not necessarily totally painless. The air and abrasive particles can cause sensitivity to the tooth.
- Air abrasion is not recommended for deep cavities (those close to the tooth's pulp). It is best suited for removing small cavities that form early on the surface of teeth.

- Only composite filling material can be used following air abrasion because it adheres well to the smooth surface created by the air abrasion cutting process (amalgam or silver fillings require drill-based cuts to prevent the filling from falling out).

1.2.3 Abrasive Jet Dental Handpiece

An alternative method that may become a successful candidate as a dental hand-piece for removing caries is a low pressure abrasive water jet. This proposed method is the basis for this thesis.

Industrial water jets have been a growing machine cutting tool for several decades. The drill, laser, and air abrasion tools each have inherent advantages and disadvantages. It is hypothesized that any new tool that is presented to dentists and their patients will have to overcome many of the disadvantages of current handpieces in order to be accepted.

The cost needs to stay competitive with the traditional drill, the process needs to be pain free for common dental caries removal (no anesthesia required), the stigmatism of a whining drill must be avoided, it needs to be quick and also cleaner than air abrasion, and the performance should match or exceed the handpieces currently employed. It is anticipated that a low pressure abrasive water jet has the potential to meet this criteria.

1.3 Literature Review

The purpose of industrial high pressure water jets (HPWJ) is to provide an effective method for cutting a wide range of materials. High pressure industrial water jets carry extreme amounts of momentum energy due to the high velocity of the exiting water stream. Currently, industry uses HPWJ's to cut through sheets of steel down to simple plastics, as well as textiles and paper. In order to increase cutting rates and precision, several advancements have been made to water jet systems. One method that has been used to increase water jet cutting ability is the addition of abrasives into the water jet stream. This particular process allows the HPWJ to cut harder and thicker materials such as metal, glass, and concrete, while maintaining the same input pressure (Flow 2006, Omax 2006). Conversely, the addition of abrasive material permits input pressures to be decreased, while maintaining the original cutting rate.

High pressure water jets are harmful and destructive to softer materials such as human skin. Research has shown that low pressure water jets (LPWJ) can be used in medical applications, which may or may not require abrasive particles to be entrained in the water jet stream (Hansen 2000, Memmott 2003). One such application may be in the dental field. To obtain safer (lower) water jet pressures that still cut tooth enamel, abrasives have been introduced into the water jet stream. Adding abrasive material allows the cutting pressure to be decreased sufficiently to merit further investigation. However, entraining abrasives into any water jet system presents difficult challenges, particularly in lower pressure water jet systems.

Research on designing and building water jet cutting machines has been performed at Brigham Young University (BYU). A mechanical engineering senior capstone project, led by Dr. Robert H. Todd, developed an "affordable water jetcutting system (Olsen & Todd 1992)." The designed and manufactured water jet is capable of high accuracy and repeatable tolerances. John Johnson, a BYU manufacturing engineering graduate student, developed a portable abrasive water jet cutting machine that was intended to minimize cutting time for refurbishing steam turbines (Johnson 1992).

Preliminary studies by Hansen and Memmott at BYU have demonstrated the potential of using LPWJ's for cutting teeth. Hansen's intermediate testing used a pneumatic piston pump. At the beginning of his experiments, a benchmark cutting rate was set by using a water jet without abrasives. When aluminum oxide (Al_2O_3) particles were added, piercing pressures dropped far below the benchmark. Using Al_2O_3 in a LPWJ system, however, proved to be problematic. As Hansen increased the diameter of the Al_2O_3 particles from 1 to 3 microns, the pump began to malfunction and interrupted the testing.

In order to continue his experiments with anticipated larger particle sizes, the abrasive particles had to be inserted after the pump. This involved pulling the testing apparatus apart, inserting a batch of Al_2O_3 material, and putting it back together for each test run. As the abrasives were inserted into the system after the pump, testing had to begin immediately, before the material settled and clogged the exiting orifice. This made it difficult to quantify any statistical error, since it was not possible to monitor the homogeneity of the abrasive mixture with sufficient accuracy.

Regardless, experiments performed showed that using abrasives was the most significant process parameter for a desirable depth of cut on ceramic tile plates, which were shown to simulate the hardness of tooth enamel. Within Hansen's testing parameters, he suggests 27 micron Al_2O_3 to achieve the maximum depth of cut. Realizing that the addition of abrasives was a significant factor for a successful LPWJ system, Hansen concludes his work by stating that an improved system should include the "the ability to meter the feeding of aluminum oxide abrasives, between 10 and 27 micron, directly into the system (2000)."

Follow-up research was performed by Joseph M. Memmott at BYU (2003). His work was intended to determine whether impinging jets could be used to focus the water jet's stream to a specific point to create a cutting point. This method of cutting would be safer than a single stream water jet and allow the dentist some freedom in performing the caries removal. Memmott discussed his attempts to recreate the testing conditions used by Hansen. He encountered similar difficulties in his research "due to the orifice becoming plugged," which was believed to be occurring due to the settling of Al_2O_3 particles. Some of his experiments showed that the addition of abrasives allowed the water jet to cut up to five times more effectively; however, his final testing could not include abrasives as one of the testing parameters. He concludes by suggesting that further work concerning abrasives will need to be performed to be able to take this LPWJ technology to market:

> The primary study conducted in this research has been done without the addition of abrasive material. A successful method to entrain the abrasive continuously in the fluid has not been determined. This is critical to the success of waterjets as applied to dentistry (Memmott 2003).

Both studies found that the addition of abrasives significantly improved cutting ability and cutting rates on teeth and ceramics with similar material characteristics. However, difficulties of entraining abrasives into the water jet stream to achieve homogenous slurry, and therefore, predictable cutting rates proved to be critical. The abrasive particles consistently settled and clogged the test apparatus. Tests involving abrasives could not be pursued, though several of the experiments proved that the addition of abrasives will be of great worth if a solution to entrain them practically and efficiently is achieved. As stated by Memmott in his research at BYU:

> This [entraining abrasives] is critical to the success of [low pressure] abrasive jets. Many of the problems of adding abrasive involves the ability to pump fluid with abrasive entrained and then controlling the flow of the fluid with the entrained abrasive. These challenges will have to be addressed in order to take this technology to market (2003).

Similar challenges have been approached in the HPWJ industry. Currently, there are several methods to entrain the abrasives into high pressure systems. Each of them has a valuable history that gives inherent insight into their advantages and disadvantages. These methods may assist in developing a method of entraining abrasives in a low pressure water jet system.

1.4 Thesis Statements & Objectives

Currently, the majority of water jet research being conducted is directed towards high pressure systems. There has been little literature that deals with using abrasives in low pressure systems in the range of 300-500 psi. More notably, there is no current research dealing with methods to entrain and suspend abrasives in a low pressure abrasive jet for a dental application. High pressure industrial water jets have had several decades to find a solution to the abrasive entrainment problem.

It is proposed that a solution to successfully entrain abrasive particles into a LPWJ system may be similar to, or a variation of, the HPWJ methods. It is anticipated that performing an in-depth literature review on the progress and science of the high pressure abrasive jets will influence and guide this thesis to a more viable solution, whether the method chosen is similar or not. Also, a variety of different types of entrainment processes will be reviewed and innovative designs generated to offer several potential solutions.

The objectives of this thesis are as follows:

- Investigate the advantages and disadvantages of several possible methods of mixing and suspending abrasive particles homogeneously in a low pressure water jet intended for a dental system.
- Investigate the feasibility of employing the suggested methods into a low pressure water jet system using good product design and development practices.
- Recommend one or two of the possible methods to entrain and suspend abrasives continuously and homogeneously in a low pressure water jet stream.
- Test and validate the entrainment and suspension principles of the suggested method(s) to determine whether it is a viable solution for a LPWJ for a dental system.

1.5 Research Approach

Primary research will begin by carefully examining the advantages and disadvantages of all the current methods of mixing abrasive into a high pressure water jet stream and other entrainment systems. This information will be organized and evaluated to determine the most effective candidates for a low pressure water jet dental system.

Concurrently, research efforts will also be focused on new and innovative methods to achieve a continuous and homogeneous abrasive flow in a LPWJ stream.

Other important literature topics that are deemed as valuable information for this thesis and for future research will also be included in chapter 2. One such topic is *material removal mechanisms*, which is intended to help validate the use abrasive erosion for the water jet application.

All of the results (literature, generated concepts, and experiments) will be organized, compiled, and presented in order to make an educated recommendation. To substantiate the recommended method of entraining and suspending abrasives into a low pressure water jet system, a basic apparatus will be set up to validate the concept.

1.6 Contributions to be Made

Development of a low pressure abrasive dental jet is currently waiting on a practical method to continuously and homogeneously entrain Al_2O_3 into the system. The research of this proposed thesis will provide useful information for selecting an appropriate method(s) for entraining and suspending abrasive material in a LPWJ system. It is anticipated that a final concept will be selected enabling further work to continue by others, with the intent of bringing this technology to market.

1.7 Delimitations

The delimitations for the LPWJ system are the parameters tested and presented by Scott Hansen's previous research at BYU. This continued research will use low pressures, which will be in the range of 300-500 psi. It is anticipated that aluminum oxide, which is approximately four times the density of water, will be used rather than other abrasive materials. A slurry of 11% Al_2O_3 (by weight) with water will be used for the tests. The low pressure water jet will be performed with nozzle orifice diameters of .004-.006 inches. A dentist is likely to be using a compressed cylinder or an air compressor in his office. This may influence the recommendation for entraining aluminum oxide abrasive material in a LPWJ to be used for dental applications. As will be discussed, it is anticipated that finding a concept that may be miniaturized will offer several advantages.

1.8 Review

The historical advancements of dental handpieces have been broadly covered in this chapter. Currently, the mechanical drill bur tool is the most commonly used handpiece for removing carious dentin, followed by lasers and air abrasion. Each of these dental handpieces has several disadvantages. It is suggested that a low pressure water jet handpiece may be an alternative handpiece that avoids these disadvantages.

The ability to entrain and suspend abrasive particles in a water jet system at any pressure has several difficulties. It is the objective of this research to investigate methods and generate concepts to entrain and suspend abrasive particles homogeneously in a low pressure water jet system. These objectives will be achieved by performing a broad literature review on high pressure water jets and their historical advancements. It is anticipated that through this research, several possible concepts will be inspired and generated.

2 Water Jet Technology

The objective of this chapter is to review the most pertinent history and research information with regards to entraining abrasives in water jets systems. For this reason, a large amount of effort will be spent reviewing the development and progress of the water jet entrainment methods that are currently employed in high pressure industrial water jet systems. It is believed that this will be the most productive and efficient course of action to find the most probable methods to entrain abrasives into a low pressure dental water jet. Also, related topics, such as *mechanisms of material removal*, will be explained to help confirm the benefits of adding abrasives to the water jet stream to improve cutting ability.

After a careful review of the HPWJ's entrainment methods, a review of research performed at Brigham Young University by Scott C. Hansen and Joseph M. Memmott will be discussed. Hansen's research specified the working parameters that are to be used for a low pressure dental water jet and presents his thoughts on improving this type of system.

Following the review of the research performed at BYU, an evaluation of similar dental concepts, which are currently patented or patent pending, will be performed. This review will help guide this research thesis in our effort to investigate methods to entrain abrasives in a low pressure water jet stream. Chapter 3 will include several of the methods that exist to entrain abrasive particles in a high pressure water jet that may be applicable for low pressure jet systems, and also any additional methods that may be appropriate.

2.1 Water Jet History

Abrasive water jet (AWJ) machining has been an up-and-coming technology for several decades. This relatively new machining process offers many desirable cutting characteristics which may be applied to a low pressure system for a dental water jet application. One of the greatest advancements made to water jet technology was the addition of abrasive material to the water jet stream. The addition of abrasives has revolutionized the water jet into a competitive machine cutting process. Whereas a plain water jet can only cut relatively soft materials, such as plastics, rubber, and wood, the AWJ can cut virtually any material ranging from reinforced plastics and glass to steel, titanium, concrete, and composites.

Though the addition of abrasives has evolved the water jet into a viable alternative machine cutting process, compared to existing or more traditional machine cutting processes, there have been many difficulties in efficiently and effectively entraining an abrasive material into the high pressure water jet stream. Over the years, several solutions have been offered to improve problems associated with abrasive entrainment. There are currently two commonly accepted high pressure industrial water jet designs and each of these methods of entrainment has their advantages and disadvantages.

- Post-Orifice Entrainment (AWJ, **Conventional Method**)
- Direct Injection Method (Abrasive Slurry Jet (**ASJ**))

The use of water as a powerful erosion material has been employed for centuries. Egyptians are the first recorded industrious people that directed large rivers of water over mineral and ore deposits to wash away the soil. Later on, the Romans built large reservoirs on high hilltops to store water. They would then maneuver the water to areas of mineral deposits below the hill and wash the precious materials down to the valley floors so that it could be easily retrieved. This same technique was revised and employed in the late 1800's in Russia and other coal mining countries to wash coal out of mines (Summers 1995). With the advancement of other technologies and equipment, higher water pressures could be transferred and utilized. As the pressure increased so did productivity, and as the productivity increased so did the desire for greater pressures.

It wasn't until the late 1960's, however, that this water jet concept was envisioned as an industrial cutting process. Dr. Norman C. Franz of the Department of Wood Science at the University of Michigan was the first to conceive of the idea of cutting wood with a high pressure water jet stream. The idea stemmed from the daily maintenance of high pressure steam pipes. It was necessary to find and fix any leaks in the steam pipes to assure constant operational pressure and also a safe working environment. In order to find the invisible leaks, the workers would simply pass a broom through the suspected areas. The unseen jet of steam would be detected when the straws on the broom were severed.

Dr. Franz was amazed at the cutting power of such a small jet stream. He hypothesized that a water jet stream should produce the same results for cutting lumber

(Miller 1991). His first tests included dropping heavy weights into large columns of water, creating high bursts of pressure and forcing the water out of a small orifice. He was able to reach sufficient pressures to temporarily cut lumber and other materials (Flow 2006). Unfortunately, with his crude model he was not able to achieve constant long term working pressures.

Dr. Franz contacted McCartney Manufacturing, a company which was designing high pressure intensifier pumps. In 1971, they jointly produced the first commercial water jet system. The new water jet was purchased first by Alton Boxboard in 1972 to cut paper tubes for the furniture industry. This was a major step towards the water jet becoming a new tool for the manufacturing industry. The water jet has advanced in its technology over the years and is currently known for cutting materials in production such as:

- Paperboard
- Cardboard
- Foamed Plastics
- Rubber
- Nylon
- Fiberglass
- Plywood
- Gypsum Board
- Fabrics
- Food Products

The topic of water jet technology quickly spread throughout manufacturing industry. Only a few years after the water jet purchase by Alton Boxboard, the first International Symposium on Jet Cutting Technology was formed. By 1974, over five countries participated in the 2nd conference and over 35 research papers were presented.

2.2 Principles of Pure Water Jet

The design and function of a pure water jet system is simple. A schematic of the basic components of a water jet circuit are shown in Figure 2.1. The water jet system begins with a water source. This can be a storage tank or a direct feed hose from a water main. The water is fed into a pump which typically generates pressures from 20-70 ksi for a water jet system.

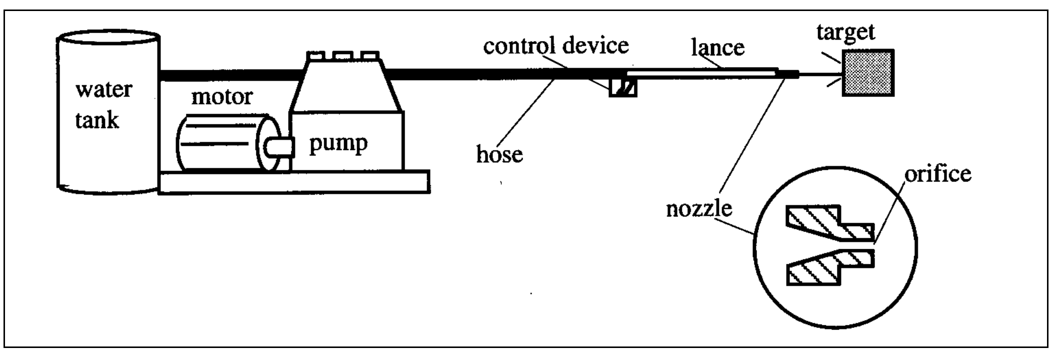

Figure 2.1 Schematic of the basic design and components of a pure water jet (Summers 1995)

The high pressure water is then directed through a series of pipes and hoses until it reaches the nozzle. The nozzle reduces the passage of the water flow until it arrives at the exit orifice. It is here that the extremely high velocity water jet stream is created. The nozzles vary in diameter. A system that is producing 60 ksi with an orifice diameter of

0.044 inches will achieve water jet velocities near 2450 mph! That is 3.3 times the speed of sound. It is easy to imagine the power and energy that the water stream is carrying. Because of these high velocities, special inserts called "jewels," such as sapphires, rubies or diamonds, are affixed at the end of the nozzle to help prevent erosion and also keep the water jet machine running efficiently for longer periods of time (Summers 1995).

2.3 Principles of Abrasive Water Jet

The pure water jet (no abrasives) has become a very useful industrial tool. The machine is capable of running 24 hours per day, 7 days a week, and 365 days a year (excluding maintenance). The water jet allows products to be cut with minimal material loss and it is a non-heating process, therefore, it avoids creating a heat affected zone (HAZ) resulting in little or no change in material properties. The cut is "clean" enough that there is usually no need for secondary machining operations. In most cases, it is able to cut very quickly, with a very narrow kerf width, and with low cutting forces, which results in minimal fixturing of the work piece. Notably, it requires little maintenance compared to other cutting tool options.

For early systems, the limiting factor of a pure water jet to cut harder and thicker materials was the pumps lack of ability to produce higher pressures. Some engineers estimated that using a pump that could produce 80-100 ksi would have the potential to cut thin aluminum metal pieces up to 0.020-in thick (Miller 1991). However, the pumps during the 1970's were relatively immature in design. Running them at such high pressures resulted in large amounts of maintenance and down-time.

The race for bigger and more powerful pumps would have continued to be the primary goal for the high pressure water jet industry, however, in the early 1980's a significant advancement in water jet technology occurred. A method to successfully entrain abrasive particles, such as garnet, was developed for a water jet system.

The new system was coined the Abrasive Water Jet (AWJ, conventional method). The addition of abrasives into the water jet stream opened an entire new realm of jet cutting technology. A system using a pump that is capable of producing 30-60 ksi could now cut hard steels and concrete blocks up to 12 inches thick. Though the AWJ revolutionized water jet cutting, it did not come without its negative consequences. Early attempts at using abrasives in a high pressure water jet demonstrated that many design innovations had to be achieved in order for it to be a viable and competitive machine cutting process.

2.3.1 Early Attempts at Employing Abrasives

One of the first notable attempts to develop a functional high pressure abrasive-jet drill (AJD) was performed by Gulf Research and Development Co. (GR&DC) from 1969-1973 (Fair 1981). Rock drilling abilities at the time were limited by the drill bit and the shaft's lack of ability to transmit torque. More clearly stated, the input force at ground level where the machine is located could not be fully transmitted to the cutting tool face far below the earth's surface.

It was theorized that using a water jet stream to assist the drill bit would be more efficient at cutting away rock. The tests GR&DC performed spanned a four year period with the abrasive jet project eventually being terminated due to "unsolved technical problems and marginal economic projections." The technical problems will be briefly discussed.

The study did show that significant cutting improvements were achieved by using an AJD and it had great potential for other markets. However, there were serious problems with the surface equipment that handled the abrasive materials. The abrasives were one of the primary causes of the project termination. Some of the challenges that resulted from using abrasives for the project were the inability to control the mud slurry (transport medium), failure of the head swivels, machine wear, and pump plunger failure.

Steel shot was used as the abrasive particles because it would not break on impact and could also be recycled. Since steel is relatively heavy, "mud" hydrocellulose slurry was used to suspend and transport the abrasive. The mud slurry made it very difficult to recycle the steel shot since the slurry had high gel strength. Also, separating the steel shot from the slurry required several centrifuges and high pressure cyclones. This was all done to enable the mud to be sent back through the intensifier pumps.

The process did not work well due to pump downtime. The primary reason for the downtime was the pump's poor plunger life. As the abrasives were pumped through the entire system, they eroded away pump liners, valves, and pipe walls. The project was formally terminated in early 1975.

Though the project ended, the experiments showed that the AJD improved cutting efficiencies sufficiently to inspire other continued research. Improvements on entraining and controlling the abrasives needed to be accomplished first, and it would take over a decade for a successful method to be developed.

2.4 The Advent of Industrial Abrasive Water Jets

Though the pure water jet continued its growth in popularity, methods to cut harder and thicker materials were ambitiously sought. A breakthrough in jetting technology occurred in 1980 when Mohammed Hashish of Flow International Corporation successfully implemented a technique to feed abrasives into a high pressure water jet stream after the water was pressurized by a pump. This method has come to be known as the abrasive water jet (AWJ) post-orifice method, considered now as the conventional abrasive water jet method. The technology was taken to market a few years later in 1983.

Just a short time after this development by Flow, BHRA tested a concept called the DIAjet, which stands for Direct Injection Abrasive jet. This method of metering abrasives into the water jet stream before the output nozzle was first introduced in a master's thesis with research conducted at Cranfield University (Kumar 2005).

In this approach, the abrasive particles enter the water jet stream after the high pressure pump and before the exit nozzle. It is also called an abrasive slurry jet (ASJ); however, it uses a different approach than Flow Corporation's method. BHRA of Great Britain produced their first system for market in 1986 (Momber 1998). These two concepts have continued to improve through the years. They are both accepted as the primary methods to entrain abrasives into the water jet stream of a high pressure system after which the water jet stream has been pressurized. Each design has its strengths and weaknesses and each system will be explained in some detail in the following sections.

2.5 AWJ, Post-Orifice Injection Method

One of the primary reasons for the termination of the development of the high pressure abrasive jet drilling project by Gulf Research (section 2.3.1) was the fact that parts kept failing due to the lack of control of the abrasive particles. The largest amount of downtime was caused by pump plunger failure and system component wear. Due to the erosive nature of the abrasive material, Flow International, led by Mohamed Hashish, developed a method to entrain the abrasives by injecting the particles after the water jet stream was formed.

The design is assumed to have been inspired by the aspiration concept used in sand guns, which utilizes Bernoulli's principle to entrain abrasives into the jet flow. By injecting abrasives in the nozzle region, the erosion effects on the pump and plumbing system could be avoided. A general AWJ nozzle design is demonstrated in Figure 2.2. The rest of the system is virtually the same as that of a pure water jet system. The key components of an AWJ are the high pressure pump, water supply, abrasive feed system and the specialized mixing chamber nozzle, abrasive and water catcher system, and typical supporting accessories.

Mohammed Hashish has explained some of the conventional AWJ components and their characteristics (Hashish 1984):

<u>High Pressure Pumps</u>

In order to cut the hardest of materials, a working pressure range of 25 to 45 ksi has shown to be effective. These extreme pressures require reliable single or dual intensifier pumps or direct-drive positive displacement pumps and are driven by motors/engines from 30-150 hp. With a nozzle orifice diameter of 0.010-0.012 inches for abrasive jets, water flow rates will reach up to 3 gpm. The high pressure seal and check valves are critical components that require periodic maintenance every 250-1000 hours.

Water Jet, Orifice

The water jet stream will reach speeds of around 2500 ft/sec with a stagnation pressure of up to 45 ksi. The high pressure forces water out of a jeweled orifice, typically a sapphire. As mentioned, the common orifice diameter sizes for most cutting applications are between 0.010 and 0.012 inches. Their life expectancy is between 250 to 500 hours. Replacement service takes about 5 to 10 minutes.

Abrasive Feed Systems

The abrasives are fed into the low pressure zone inside the mixing chamber. In order to regulate the flow rate of the abrasive material, a collector is used with an orifice, which helps provide precision and steadiness of the abrasive jet stream. An optional addition is a pressurized hopper, which also helps maintain a constant flow of abrasive material. The pressurized hopper allows the jet to be used in submerged water. Also, a slurry mixture of abrasive and water may be prepared in the hopper to increase flow control.

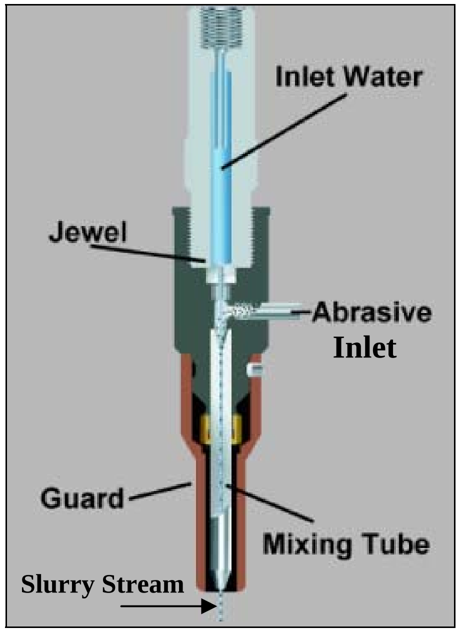

Figure 2.2 Abrasive water jet Post-Orifice method

<u>**Nozzles**</u>

The abrasive nozzle (mixing tube) is responsible for mixing the abrasives into the jet stream, refocusing the abrasive stream for cutting, and enduring erosion for a reasonable amount of time to maintain a steady cutting jet. The original design by Hashish implemented a single water jet stream that mixed with the abrasives as represented in Figure 2.2. Alternative variations have shown improvements in mixing efficiencies. One design utilizes multiple jets that are aligned in a circular shape and converge into a single stream (Zheng *et al* 1994). There are many other designs that continue to be tested.

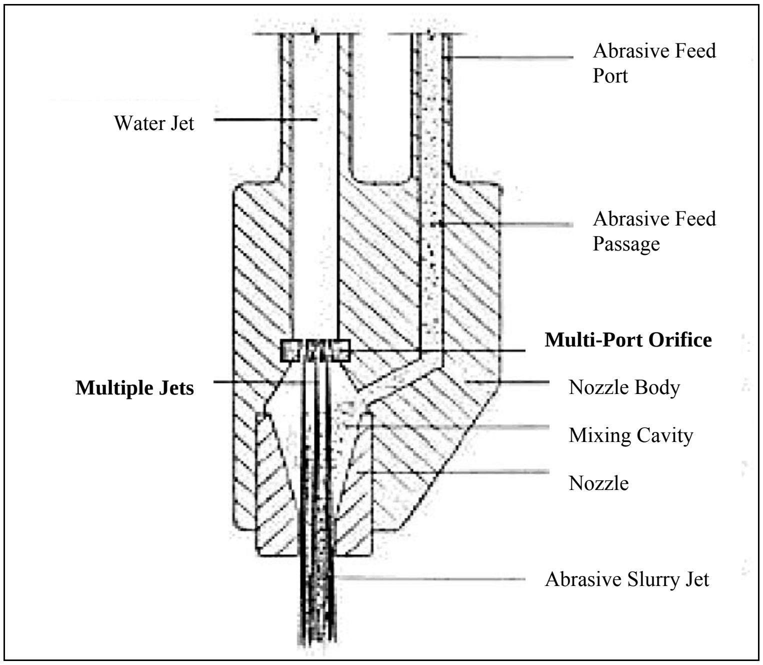

Figure 2.3 Schematic of a Post-Orifice Multiple Port Orifice

Abrasive and Water Catcher Systems

The type and size of the catcher system largely depends on the particular cutting application. As discussed, the AWJ reaches velocities several times the speed of sound. It is necessary to collect the water and abrasive particles in an efficient and safe manner, since there is still a large amount of kinetic energy in the AWJ stream after it cuts through the work piece. Generally, the catcher is a large tank that is filled with water as an energy absorber. The abrasives settle in the catcher and are removed periodically. Depending on the abrasive material being used, it could be reused or recycled.

The performance of the AWJ is affected by several independent parameters. To achieve improved cutting ability, it may require a great deal of data (tests) to determine which parameters optimize the cutting potential for a specific application. The parameters of greatest concern are listed (Hashish 1984):

- Hydraulic Parameters
  - -Water jet orifice diameter
  - -Supply pressure
- Abrasive parameters
  - -Material (density, hardness, shape)
  - -Size
  - -Flow rate
  - -Feed method (Pressurized hopper, or suction)
  - -Abrasive state (dry or wet)
- Mixing nozzle parameters
  - -Mixing chamber dimensions
  - -Nozzle material
- Cutting Parameters
  - -Traverse rate
  - -Number of passes
  - -Standoff distance
  - -angle of cut
- Material to be cut (brittle or ductile, section 2.8)

Careful observation of these parameters will produce a more optimal and efficient cut. The result will be a better product, savings in costs and expenditures, and ultimately longer component life.

The AWJ abrasives are entrained into the water stream by exploiting a low pressure zone that is created as the high velocity stream passes through the mixing chamber. This method has been explained in various ways and has caused some confusion.

The low pressure zone is explained by Bernoulli's principle. If you pass a perpendicular fluid flow over the end of a pipe with sufficient velocity, a low pressure zone will be created inside the pipe. To demonstrate this effect, simply set a straw in the water (not touching the bottom of the cup) and blow over the top of the straw. If the flow has sufficient velocity and is perpendicular, so as to not be blowing directly into the straw, the water will start to rise inside the straw.

Many other authors use different names for this same principle, including Venturi effect, aspiration, pneumatic transport, and jet-pumping. Regardless of the term used, the physics principle remains the same.

As the high speed water stream passes into the mixing chamber of the AWJ, a low pressure zone is created. Dr. Hashish invented the idea of attaching a pipe and abrasive storage tank to the mixing chamber, where the low pressure zone is created. The abrasives are then pushed in from a hopper tank and into the low pressure zone of the mixing chamber by the higher atmospheric pressures.

2.5.1 AWJ Post-Orifice Entrainment Advantages

The development of the AWJ was a breakthrough in water jet technology. It allowed a "cold cutting" machine process to cut through harder materials than a pure water jet system at the same pressure. The AWJ was now able to compete with traditional cutting machines such as milling and sawing. The abrasive laden jet presents several advantages over other machine processes. The most prominent are listed here (Sommer 2000, Hashish 1984, Jiang *et al* 2005):

1. No HOV (heat affected zone) or micro cracking - Little or no secondary machining is necessary
2. Minimal or no Dust
3. No dulling of the cutting tool (the jet or abrasives), unless abrasive is recycled
4. No special tooling required
5. Material non-specific, even composites without material damage
6. Material savings due to small kerf width of cut
7. No fire hazard incurred from cutting
8. Simple fixtures, water jet only applies a few pounds of force on work piece
9. No necessary "entry hole" to begin cut
10. No fumes
11. Cut quality higher than a diamond saw, without smearing, burring and chipping

The nature of these advantages has caught the attention of many manufacturers. The AWJ has grown to be a well-accepted machine cutting process since its origin in the early 1980's.

2.5.2 AWJ Post-Orifice Entrainment Disadvantages

The AWJ has its limitations. In order to achieve a sufficiently low pressure zone to entrain the abrasive particles into the water jet stream, the jet velocity needs to be extremely high. This requires a very powerful high pressure pump. Consequently, for the higher pressure systems, most of the plumbing is solid piping. It is difficult to use compliant hoses which are strong enough to withstand the pressures and are easily manipulated by a human operator, though progress in this area is being made. This makes the AWJ less useful for mobile applications, such as cutting reinforced cement pipes outdoors in a sewer line. In most cases the AWJ is not easily transportable; the part or work piece to be cut usually has to be brought to the machine and not vice-versa (Summers & Yazici 1990).

Another serious shortcoming of this particular design is the entrainment of air that occurs. The manner in which the abrasive particles are entrained is inherently air-flow driven. Since the birth of the AWJ, many studies have been dedicated to the understanding of water jet flow. Figure 2.4 shows how the water jet stream starts to spread immediately after it enters the mixing chamber. The jet stream breaks into tiny droplets that help create the pneumatic transport of the abrasives. The stream of water is entrained with both abrasive and air at this point and then refocused at the end of the mixing chamber in the mixing tube. At these extremely high pressures and velocities, the air is compressed into tiny bubbles while in the mixing tube. When the three-phase water/abrasive/air stream exits the tube, the air immediately expands and the jet stream widens radially.

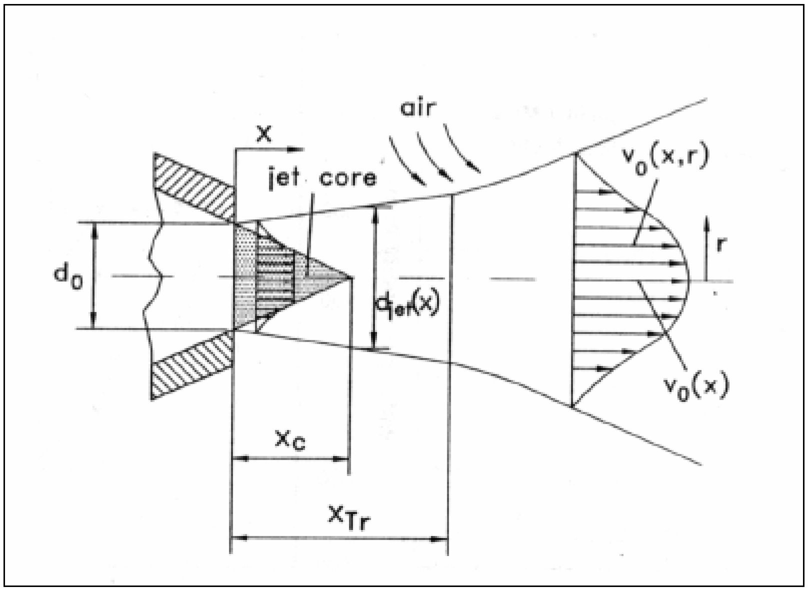

Figure 2.4 Expansion of a water jet stream upon exiting the orifice (Momber 1998)

An abrasive jet steam is typically described by its mass, which on average is 3% air, 23% abrasive, and 74% water. However, from a volume point of view, air is 90% of the jet. Consequently, the AWJ is transporting a larger amount of air which is "breaking-up" the jet stream as it expands, thus weakening its cutting potential. The more air entrained in the water stream results in a more rapid divergence of the three-phase jet. Figure 2.4 represents the three-phase profile of the AWJ. It can be seen that the jet expansion has a non-linear relationship as the stand-off (axial) distance is increased. Consequently, the abrasives are also being spread out. Figure 2.4 shows where the abrasives tend to be located radially while the axial distance is increased.

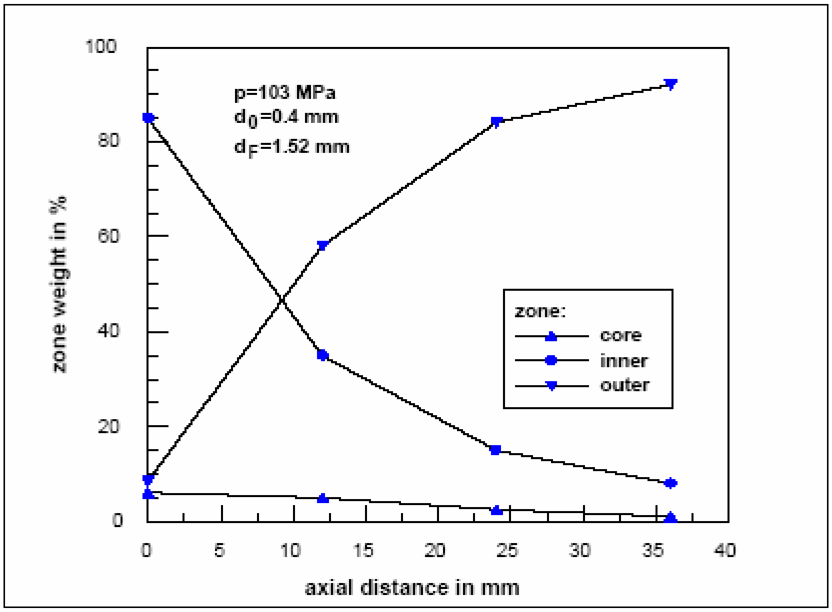

Figure 2.5 Location of abrasive particles relative to axial distance (Momber 1998)

The core zone is defined as the circular area equal to the exit jet diameter as diagramed in the phase distribution in Figure 2.4. The inner zone is the annular area found between the jet diameter and the actual focused diameter. The outer zone is defined as the annular area that is beyond the focus diameter. It is shown that very little of the abrasive is ever in the jet core itself, which will be explained hereafter. Most of the abrasives start in the inner zone and quickly spread into the outer zone as the axial distance is increased. This provides evidence that the highest quality cut will be achieved when the AWJ nozzle is as close to the target material to be cut as possible. The spreading of the abrasive particles to the outer zone is exacerbated with the increase of air into the jet stream (Momber 1998).

With the current design, the AWJ post-orifice method inherently uses air to create the low pressure zone in the mixing chamber in order to pull in the abrasives. To help minimize the air content of the water jet, the abrasives can be fed into the mixing chamber as a slurry by simply adding water to the abrasives while they are still in the hopper-feed system. Though this helps reduce the amount of air entrainment it also has the adverse affect of additional mass. This requires higher pumped flow rates of the high pressure jet, and consequently, a higher pressure pump to accelerate the abrasives to the same speed as dry feed abrasive.

Even when all of the AWJ parameters are optimized, there still exists a “brick wall” with the conventional method’s ability to cut more efficiently. As will be discussed in section 2.8, the mechanism that cuts or erodes the target material is principally the abrasive particle. The amount of material removed is dependant on the amount of energy that is transferred from the water jet stream to the abrasive particle before it impacts the target material. Since the abrasive particles have an initial velocity of essentially zero, it is difficult to entrain these abrasives into a water jet stream, which in a high pressure AWJ system has a velocity of several thousand feet per second. Also, this transferring of kinetic energy from the water to the abrasive particles must occur within a few inches of travel or less before they impact the target (Swanson *et al* 1987).

As explained previously in Figure 2.4, most of the particles never even enter the core zone where the peak velocity is sustained. The majority of particles have little chance of penetrating the center of the water jet. They usually bounce around inside the mixing chamber’s wall until they finally enter the outer zone of the jet and exit the nozzle.

Figure 2.6 demonstrates a post-orifice flow profile, which is more likely to occur. The purpose of entraining the abrasives post-orifice is to avoid wearing and eroding critical upstream valve and pump system components. Ironically, the damage of system and pump components, in which the post-orifice method was designed to avoid, has had critically similar problems in the nozzle region.

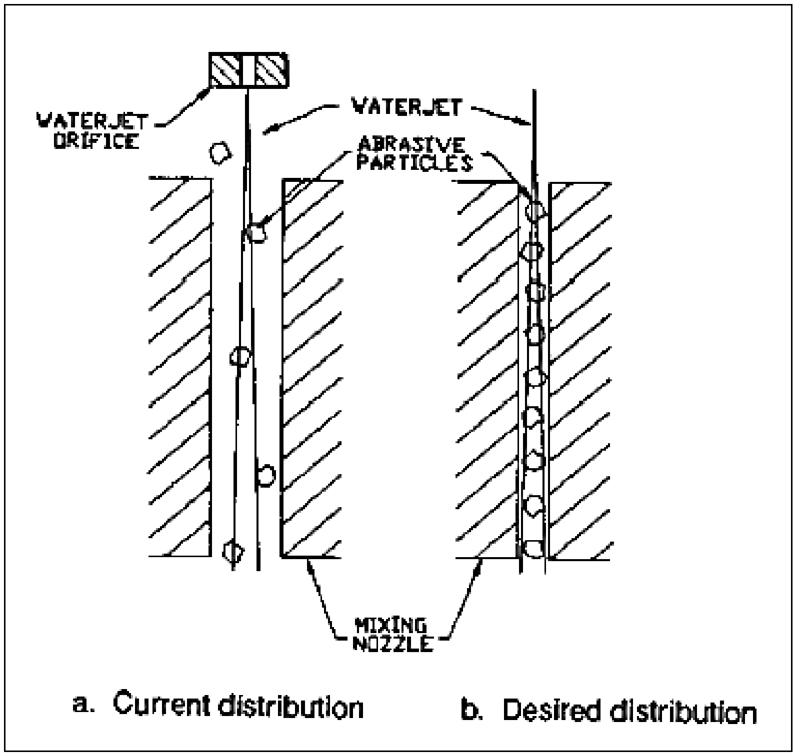

Figure 2.6 Typical versus desired particle distribution (Hashish 1991)

As the abrasives enter the mixing chamber, they tent to bounce around before actually entering the water jet stream. The particles have more than enough momentum and kinetic energy to cut almost any material, which includes the mixing chamber itself. With many hours of AWJ cutting, the erosion in the mixing tube or nozzle also becomes significant.

As mentioned previously, a small change in the jet flow or the exit nozzle orifice has an adverse affect on cutting performance. Fortunately, the nozzles are more resilient, do not require precision mating with other moving parts, are simpler to service, and are more easily replaced than the moving pump or valve components.

If a method to entrain the particles into the jet core were conceived, it is believed that the particles could attain the water jet's full velocity within an inch or less of travel (Swanson *et al* 1987). How beneficial of an impact does spending efforts on the improvements of abrasive mixing efficiencies have? Hashish (1984) has developed a simplified equation for predicting the depth of cut, or kerf width (h) for brittle materials:

$$h = \frac{2\left(\left(1-c\right)\dot{m}_a {v_a}^2\right)}{\pi d_j \varepsilon \mu_j} \qquad \textbf{(1)}$$

where:

c = μ/N
μ = traverse rate of the jet
N = number of passes
$\dot{m}_a$ = abrasive mass flow rate
v_a = average velocity of the abrasive particles
d_j = diameter of the water jet
ε = specific energy (amount to remove a unit volume of target material)

Another equation to help demonstrate the impact of particle velocity was developed by G.A. Bitter (1963). His study was aimed at determining the volume material removal (w) for an erosion of brittle materials:

$$h = \frac{1}{2}\frac{m_a\left[\left(\nu_a \sin\alpha\right) - K\right]^2}{\varepsilon} \quad (2)$$

where:

m_a = total mass of impinging abrasive particles
ν_a = average velocity of particles
ε = specific energy of target material
α = angle of particle impingement
K = a constant dependent on the material properties of both the abrasive and target material

Both equations predict that the amount of material removed by the abrasive is primarily dependent on the mass of the particle material and the square of the abrasive velocity. It is understood that improving the particle's ability to enter the water jet and achieve full velocity will improve the cutting ability of the AWJ exponentially. It may be a moot point since the nozzle improvements over the past few decades have been minimal; however, research still continues for an improved nozzle design. A list of nozzle types to improve particle mixing along with their strengths and weaknesses have been outlined by Hashish and Momber (1982, 1998), but are not listed here.

For a typical AWJ, abrasive particles impact the target material over one million times per second. As explained by Hashish, a 1 mm diameter orifice on an AWJ nozzle using an input hydraulic power (power transmitted from the pump to the fluid) of 15 kW will produce about 19 kW/mm^2 power density. The power density is defined as the particles' kinetic power per unit area, which conveys how well the cutting power is focused.

Due to the inefficient mixing of the particles, only 10-20% of this power is actually transferred to the abrasives. A jet with a velocity of 610 m/s (2000 ft/sec) will accelerate the particles to about 122 m/s (400 ft/sec). Also, due to the abrasive-water interaction upon impact of the target material, only 10% of the kinetic energy is actually used for material removal (Hashish 1991, Dorle *et al* 2003).

Despite the inefficiencies mentioned here, the conventional abrasive water jet post-orifice method of entraining abrasive particles is still able to cut through a steel specimen over 12 inches thick. The process itself offers a large number of advantages over traditional cutting processes. An abrasive jet system that is capable of overcoming these weaknesses presented would secure itself as a dominating cutting process for high pressure systems.

This method of abrasive entrainment may not be applicable to low pressure systems due to the low velocity of the jet stream. The low pressure zone created would be too weak to "pull-in" the abrasives particles. Also, it is anticipated that the mixing chamber would be larger than desired for the dental application. However, the development of this method offers important insight that will help guide the focus of this research.

2.6 ASJ-Direct Injection Methods

There are alternative methods to entrain abrasive material into a high pressure water jet system. Another accepted industrial high pressure water jet is BHRA's DIAjet method. There are three types of abrasive direct injection principles used to generate a slurry water jet. Each of these injection methods are illustrated in Figure 2.7.

2.6.1 Direct Pumping Method

The first to be tested was the "direct pumping" system by Gulf Research for drilling rock in the oil and gas industry. Here, pre-mixed slurry is pumped directly through the pump and out the nozzle. In many scenarios, this system requires a suspension medium to keep the abrasive from settling. The abrasives are often passed directly through the pump. Softer particles can be used to prevent premature erosion of pump parts. This injection principle allows for continuous cutting.

2.6.2 Indirect Pumping Method

The second principle is also called the direct-injection method. Recently, it has been termed "indirect pumping" (Brandt & Louis 1999). The only difference between the two direct pumping systems is the addition of a separator/isolator in a pressure vessel to prevent the mixing of the water and the slurry. This gives the added benefit of a constant ratio of abrasive-to-water mixture; however, it can also have a negative consequence. Most systems rarely maintain a constant working environment.

Pressures, water composition (softness etc.), valves, temperatures, materials, are all variable. It may be necessary to repeatedly adjust the abrasive concentration for a particular cutting application for which the indirect pumping principle cannot compensate. Short jet duration is also another disadvantage of the indirect pumping method. The duration of cut is dependent on the size of the pressure vessel and the working pressure. Again, this type of system usually requires a high viscous suspension medium to keep the particles from settling.

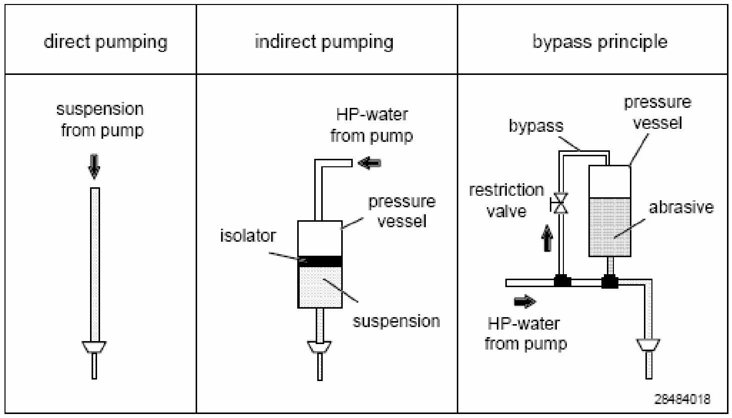

Figure 2.7 Three types of ASJ operation (Brandt & Louis 1999)

2.6.3 Bypass Method (DIAjet)

BHRA's DIAjet is based off the third principle, which is the "bypass system." This method was first presented in its entirety at the 8th International Symposium on Jet Cutting Technology by BHRA fluid engineering in 1986 (Fairhurst *et al* 1986). The idea behind the development of the DIAjet was provoked by the need to overcome some of the mixing inefficiencies of the conventional post-orifice AWJ method and the wearing out of pump parts in earlier direct-injection systems. Previous work in the oil industry showed that pumping abrasives continuously caused severe erosion damage to equipment and resulted in the termination of the project.

If introducing the abrasives into the system before the pump caused problems, and entraining abrasives at the nozzle had several short-comings, logically, the next best place to insert the abrasives is somewhere in between the pump and the nozzle. This principle was intuitive from the very beginning, and the initial design began with a master's thesis at Cranfield (Fairhurst 1982). It was not easy to design a system involving such high pressures. How do you insert abrasives into a system at this particular location while it is under high pressures and maintain the ability to adjust the abrasive concentration (amount of abrasives added per time)? This is where the difficulty lied. BHRA determined that it was feasible to accomplish an abrasive feeding system that lies after the pump and before the nozzle, if the abrasives were inserted in batches. This can be achieved by using a bypass line and a sequence of high pressure valves as a means to inject a slurry solution into the main water line as seen in Figure 2.7.

The machine is prepared by first adding the abrasives to a hopper. Here the abrasive is mixed with water (this might include mixing in a high viscous polymer additive for suspension purposes). After the abrasive is fluidized, a charging pump is needed to push the mixture through the plumbing into a pressure vessel. When the vessel is full, a valve closes to prevent any back flow. At this point, the hopper is no longer in use.

A schematic of a DIAjet system is illustrated in Figure 2.8. This system begins with a high pressure pump. After the pump, the water flow is split. The majority of the water flow is directed through a supply hose and out to the jet nozzle. Part of the water, about 10%, is "bypassed" into the top and bottom of the pressure vessel. The water supply at the top of the pressure vessel serves to pressurize the column of slurry. The bottom water supply is sprayed into the vessel in a manner that helps keep the slurry fluidized. The exit line at the bottom of the pressure vessel then reunites with the main flow of water and out to the nozzle. This design has some variation with each water jet manufacturing company; however, the principles are the same (Summers 2006).

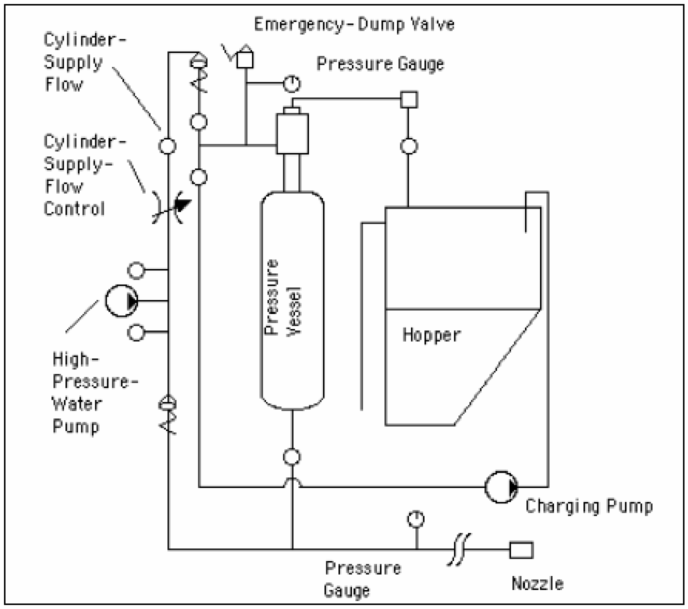

Figure 2.8 Representation of a DIAjet bypass water jet system (Summers et al 1991)

The ASJ was originally termed the abrasive slurry jet. However, a major weakness in the ASJ and other direct injection methods was that they all suffered from abrasive settling. Any time an ASJ stopped or too much abrasive was mixed with the water, the particles would begin to settle. This would result in inconsistent cutting rates. Mentioned previously, a polymeric additive has been used to help suspend the particles and produce a more homogeneous slurry. The name ASJ began to be called the abrasive suspension jet as termed by Hollinger et al. (Hashish 1991). The names are virtually interchangeable. The addition of polymers or other suspension mediums has had a major impact on the ASJ and will be discussed in subsequent sections.

More clearly defined, there are two methods to generate an ASJ, the "additive method" and the "carrier method." The ASJ additive method prepares a slurry by mixing the abrasives with water and a suspension medium (typically a polymer). When the proper consistency is achieved, it is pushed into a high pressure vessel by a charging pump. Next, the high pressure pump pushes the poly-abrasive slurry into the water jet stream and out to the nozzle. The carrier method is produced by the abrasives being fluidized in the high pressure vessel to maintain homogeneity as previously explained (Jiang *et al* 2005).

To help clarify the topic of ‘slurry’ and ‘suspension,’ Mohamed Hashish explained the difference between the two (Hashish 1997):

1. Slurry - A slurry is an immiscible system such as fine sand and plain water. If the water is continuously stirred, the sand will stay afloat. As the stirring is paused, the sand will settle out immediately. (This does not include ultra-fine particles which will not settle because of Brownian motion)

2. Suspension - A suspension is also an immiscible system in which solid particles, again like fine sand, are in the presence of a liquid. In contrast, however, if the liquid has sufficient viscosity, such as an aqueous solution of SUPER-WATER®, the abrasive particles will not settle out whether stirred or not. The sand stays suspended.

DIAjet’s original bypass system had a maximum working pressure of 35 MPa’s. Through the years the pressures have increased and currently, state of the art equipment can reach 200 MPa’s, which have been used for the dismantling of nuclear components (Brandt & Louis 1999). The DIAjet has found a sure place in the market for several reasons.

2.6.4 ASJ Advantages

The post orifice entrainment method has several weaknesses that the DIAjet avoids. Tests performed by Hashish and others (Hashish 1991, Jiang *et al* 2005) have shown that the ASJ has several potential advantages, which include the following:

- Smaller-diameter jets can be produced resulting in thinner kerf-width cutting.
- No air is entrained into the water stream, avoiding jet expansion. This results in thinner and more precise cuts.
- Jets with more power density (power per unit area of the nozzle) can be produced, thus reducing the required power levels.
- Lower power requirements and pressures allow smaller/less expensive pumps, thus reducing noise and allowing flexible tubing (hoses) to be used.
- Smaller nozzles can be used in tighter fitting areas.
- Abrasive feed is not restricted by the jet pump concept (aspiration), which allows higher abrasive flow rates to be utilized.
- Using the same abrasive flow rate, pressure, and power, the depth of cut of the ASJ at least doubles that of the AWJ.

With the many benefits that the ASJ offers, there are also a few disadvantages that need to be considered while determining whether this design may be applied to a low pressure dental system.

2.6.5 ASJ Disadvantages

In order to reduce ASJ pump pressures, the abrasive flow rate must be increased. A study was conducted by Mohamed Hashish (1991) to compare the AWJ with the ASJ. It has been suggested by Hollinger that a low pressure ASJ will reduce operating costs. Hashish discusses that this is only achieved if the abrasive flow rate is kept much lower. A decrease in abrasives will limit the cutting ability of the water jet to “thinner” materials. It was also shown that the ASJ is more effective at higher pressures; however, this resulted in significant hardware problems. To improve the performance of a low pressure ASJ, abrasive flow rates needed to be increased. Consequently, the cost of abrasives becomes a significant economical impact. A cost analysis is suggested to determine whether the ASJ or the AWJ will be more economical for a given cutting application.

Recall that the ASJ is a batch system. It is possible that a slurry refill will be necessary before an individual project is completed. Continuous running water jets may be more suitable than a “more efficient” abrasive jet system for a given application that requires constant or longer periods of cutting.

Since the ASJ is a batch system, it requires several high pressure valves to open and close, which poses reliability and trouble shooting problems. This becomes complicated and expensive, due to the maintenance issues, when dealing with abrasives.

As shown in Figure 2.8 of the DIAjet system, the high pressure vessel injects the slurry into the main water stream from the vessel. When the jet cycle is finished, a valve closes at the bottom of the vessel to avoid back-flow. In a pure water jet, this would be of no concern; however, the abrasives in the ASJ often produces severe erosion as the valve attempts to close on the slurry. Most systems require an inlet and outlet valve, de-pressurization and re-pressurization valves, and often a few others for flow rate control. There are several companies that manipulate the piping system to avoid areas where higher abrasive concentrations are found. Regardless, this is still a challenge in most current ASJ systems.

These types of hardware problems at high pressures have limited the ASJ to lower pressures (up to 70 MPa) for commercial systems. However, as these limitations are overcome, the ASJ will have many more benefits (listed above) that outweigh it's weaknesses. One principle advantage is that abrasive slurry enters the water jet stream after the pump and far before the nozzle. This allows the abrasive particles to attain the same speed as the water stream before impacting the target material.

In order to fluidize the abrasive particles and water into a homogeneous slurry for transport, significant flow rates are required. Most of the fluidizing designs are proprietary and the flow rates used are experimentally determined. It is suggested that creating a miniaturized version of the DIAjet system is likely not feasible, since the anticipated low pressure water jet flow is likely to be too slow to achieve fluidization. However, this method may be combined with other concepts, such as polymer suspension, to create a suspended homogeneous slurry.

2.7 Introduction of Polymers

A change in the water's flow and velocity by changing its composition or the transport material (i.e. pipe material) has been studied for years. In river and streams, it has been observed that water velocity increases as the water passes down a river bed when the ground material changes from “regular dirt” to fine clay. It did not take long until people started adding different chemicals to water to try and lower the friction the water encounters while traveling through pipes.

One of the early cases of adding long chain polymers to water occurred in the 1960’s (Summers 1995). While fighting fires, it is important to be able to direct as much water flow towards the fire as possible. Historically, this has been achieved by using a long hose with a nozzle at the end. It was reported that by adding polymers to the water, the reduction in friction was sufficient to pass the same amount of water in a 2.5 cm nozzle than in a 5 cm nozzle that was without the additive. This allowed firemen to carry lighter hoses and still transport a greater volume of water.

Dr. Franz, who conceived the idea of an industrial water jet, was the first to experiment improving flows of a water jet stream in 1970. Early tests were performed with gelatin and glycerin as additives, both of which improved the water jet performance. However, when long chain polymers were used, he found cutting improvements up to 300% over a plain water jet. Since early testing of polymers, there have been three distinct advantages gained by using additives in water jet systems:

1. Drag Reduction
2. Jet Stability
3. Abrasive suspension

Some of the most recent work with polymer additives has been conducted by Dr. Glenn Howells of the University California, Berkeley (Berkley Chemical Research, Inc.).

His work was initiated by Chevron USA in 1974. Chevron needed to clean hundreds of tubes, shell-sides, exchangers, evaporators, condensers, and other vessels. High pressure jets were being used, but the need to increase cleaning rates, cycle times, and efficiencies were needed. The project was funded when a hydro-processing reactor was shut down because over 1500 U-shaped tubes were completely clogged with hard deposits of fused coke. Six months of research concluded with the product development of SUPER-WATER®, which is water mixed with a polyacrylamide polymer. This polymer increased efficiencies up to 50 times that of a pure water jet. The tubes were cleaned in 24 hours, rather than the typical 3 months (Berkeley Chemical Research Inc. 2005).

2.7.1 Drag Reduction

The opportunity for reducing drag in pipe flow has been studied since the early 1950's. The applications started in areas that dealt mainly with long lengths of pipes and hoses, such as that found in firefighting, oil and sewer piping. Since the addition of a polymer increases the viscosity of the flow, very small concentrations are used. The long chained polymer molecules shear and elongate with a change in the velocity flow. These elongated polymers flow parallel to the water flow profile, and subsequently, act as energy absorber's to the fluid's turbulence and eddies.

A laminar sub-layer develops in a turbulent flow along the pipe's wall. In a Newtonian fluid, such as water, there exists a logarithmic flow profile with a relatively small velocity gradient. In a drag reducing fluid, the polymers molecule-eddy interaction forms an elastic layer between the laminar wall layer and the rest of the turbulent flow. The logarithmic profile diminishes as a much higher velocity gradient is attained (Louis *et al* 2003). Simply stated, the friction at the pipe wall is reduced.

The pressure drop due to wall friction in a pipe is related to the length of pipe and its diameter. It has been suggested by Labus (1989) that the following equation be used to calculate the pressure loss in transferring the water through a pipe, without considering pipe wall surface finish:

$$\Delta P(bar/m) = \frac{0.597 \times Q^2}{100 \times D^5 \times R_e^{\,0.25}} \tag{3}$$

where D is the internal diameter of the pipe (cm), and R_e is the Reynolds number for the flow of the fluid. As a general rule, about half of the initial pressure produced by the pump is lost by overcoming the many friction losses in the system by the time the water reaches the nozzle.

Tests conducted by H. Louis *et al*. (2003) show that appropriate proportions of polymer concentration need to be used. The graph in Figure 2.9 shows that the benefits of pipe friction are eventually overcome by the increase of viscosity of the fluid as the concentrations of polymer is increased. Note, however, that if the benefits of abrasive suspension and jet stream cohesion are the priority, then higher concentration of polymer may be acceptable. As shown in Figure 2.9, even when the viscosity begins to overcome the benefits of drag reduction, the pipe wall friction never exceeds its original value. For example, the affects of pipe friction at 0% concentration is virtually equal to pipe friction at 0.2% concentration.

Testing of the polymer polyethylene oxide (Polyox) by Dr. Summers (1995) showed improvements of flow up to 15 m/s over the same water jet without the polymer. This improved the jet performance; however, the polymer seemed to be affecting more than just drag reduction. It was also observed that performance improvements seemed to increase with greater stand-off distances of the workpiece from the nozzle. Initially it was believed that the reduction in friction of the water against the pipe walls, which allowed the input pressure from the pump to be more efficiently transmitted to the nozzle, was the only reason. Further research has shown that there are secondary benefits as a result of the addition of polymers.

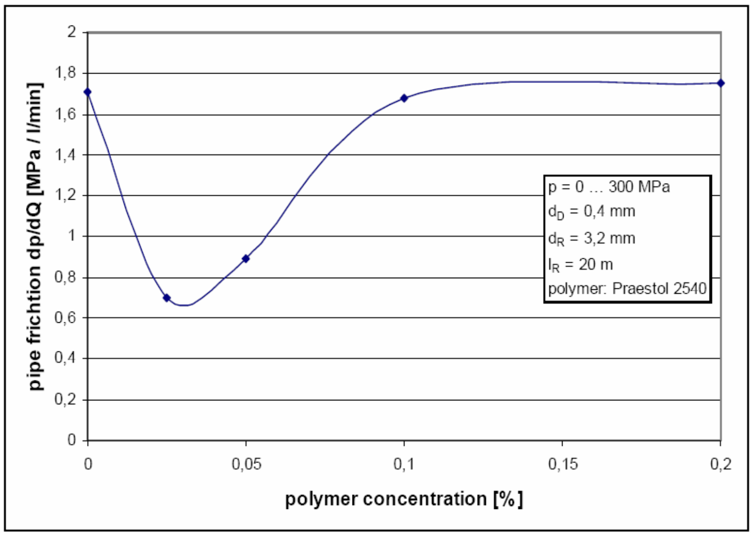

Figure 2.9 Pipe friction as a function of polymer concentration

Figure 2.10 shows a picture of a plain water jet, one with SUPER-WATER® being used and one without. The Polymer has the ability to improve the "cohesion" of the water stream itself. This allows the water to maintain its kinetic energy for greater stand-off distances from the workpiece while cutting.

2.7.2 Jet Stability (Cohesion)

An optimal kinetic energy level would occur if the water molecule (or abrasive particle) could arrive to the target material with the same velocity that it had just before it left the water jet nozzle. The water jet stream demonstrated in the bottom of Figure 2.10 shows that the jet stream actually starts to diverge immediately after it exits the nozzle, which results in an immediate decrease in velocity. Consequently, the kinetic energy of the abrasive particle also decreases. This is caused by fluid-on-fluid (air on water) interaction. In many cases, the expansion of air bubbles entrained in the water stream may be responsible for jet stream divergence.

An increase in jet stability by the addition of polymers was first reported by Dr. Franz in 1970 (Louis *et al* 2003). His work showed that the effects of the polymer increased the water jet power density, the standoff distance, and also resulted in a reduction of wetting on the work piece. This is all attributed to the manner in which the long chain polymer acts in the high pressure and velocity flow. Polymer chains behave in both a viscous and viscoelastic fashion.

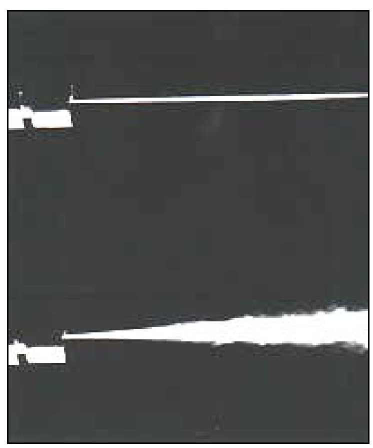

Figure 2.10 Water jet with and without SUPER-WATER® (Berkeley 2005)

Before entering the fluid flow and without any external forces, long polymer chains rest coiled together, resulting in a strong interaction with other surrounding chains.

This is why there is a significant increase in viscosity when they are added to water. As pressure is applied to the fluid and polymer mixture and flow is initiated, the polymer chains are stretched and strained. They eventually align orthogonally with the velocity gradient profile and parallel with the direction of the flow. Consequently, the viscosity in the direction of the flow decreases. Also, the turbulent eddies that are orthogonal to the flow are damped by the elongated polymer chains.

As the water stream exits the pipe/nozzle, the shear stresses along the stream profile are only subjected to the surrounding air, which are relatively minimal. Since the shear stresses from the pipe wall are no longer acting on the fluid, the polymer molecules begin to return to their original coiled position. After exiting the nozzle, the water attempts to diverge radially outward, but is held together by the shrinking coil interaction of all the polymer molecules. The polymer slurry viscosity increases and the jet stream becomes much more coherent. This results in better stand-off cutting distances and cutting precision (the smaller jet stream will cut less material).

Another benefit of the coherent jet is the ability of the water to "hold together" as it hits the target. This results in less "wetting" of the target material. Also, the ability of the water jet stream to not soak the target allows a greater variety of materials to be cut.

2.7.3 Abrasive Suspension

A third benefit that can be exploited by the use of polymers is the ability to suspend the abrasives during the cutting process. Without a suspension medium, water jets can either entrain the abrasive particles using the post-orifice method or use specialized equipment that "fluidizes" the abrasives in the abrasive slurry jet method. In an ASJ, if the water flow stops, the abrasives will begin to settle.

Special polymers may help eliminate the settling and clogging problem. The abrasive-polymer concentration is able to be more homogeneously metered into the water jet stream, which would cut more effectively. As previously discussed, the ability to entrain abrasives during water jetting is vital to the success of a water jet system. The inability to control the abrasives could result in damaged parts, inefficient mixing, or no abrasive jet at all.

2.7.4 Polymer Disadvantages

The use of polymer additives does come with its possible disadvantages. It is necessary to prepare the poly-abrasive solution before it is pumped into the machine's high pressure vessel. The steps required have been outlined by M. Hashish (1997) for suspension preparation:

1. A slurry storage tank with a propeller located near the bottom is filled with the desired amount of water. The shaft of the propeller blade is located off center of the tank. The propeller's speed is selected so that it forms a vortex around the propeller shaft.

2. The appropriate amount of SUPER-WATER® is poured gradually into the vortex. This entire mixing process may take about 10 seconds for every 500 grams of SUPER-WATER® added.

3. The abrasives are then added into the polymerized water in the vortex at a regulated rate. After the mixing is completed, the propeller speed is reduced to eliminate the vortex. Agitation is then stopped.

This process and time consumption may be unacceptable for a given cutting application or working environment.

Also, SUPER-WATER® cannot suspend the abrasive particles for extended periods of time; therefore, it cannot be pre-mixed and stored. Other studies by Dr. Summers have shown that some polymers decrease the performance of the jet stream when they are mixed and allowed to age (Summers 1995). Furthermore, the polymers often find their way onto the floor or equipment in the surrounding area. The result may be a slick and dangerous work surface. If this is of concern, a secondary set-up, such as a temporary floor or cover, could be necessary. These disadvantages are likely to be minimal in most industrial working environments; however, if the polymers are used in a small office area, there might be reason for concern.

Using polymers in a high pressure water jet does increase the initial costs; however, since the cutting ability usually increases several times, the productivity and performance characteristics usually saves money. In most circumstances, the advantages of adding a polymer such as SUPER-WATER® far outweigh the inconvenience of the disadvantages.

2.7.5 Polymers in Abrasive Water Jets

The SUPER-WATER® polymer has also been used for abrasive water jet cutting. Similar results have been found when using this additive with the ASJ where improvements have been shown to be up to five times greater than without SUPER-WATER®. This does not hold true for the AWJ. The AWJ generates its abrasive jet by adding the particles to the water stream after the nozzle and inside a mixing chamber. The high velocities of the water stream transform into droplets which are refocused in the mixing tube as it exits the orifice. The droplets increase the aspiration effect that is described by Bernoulli's principle. As previously explained, the polymer additive helps cohere the water jet stream and minimizes its divergence. Consequently, the low pressure zone that pulls the abrasives into the mixing chamber is significantly weakened. One study found that the air suction was reduced up to 70% for a .2% polymer solution of Praestol 2540, which is a co-polymer based polyacrylamide (Louis *et al* 2003).

Many tests and experiments have been conducted to determine which long-chain polymer is the most suitable for an ASJ. For a low pressure water jet system designed for a dental application, a polymer or similar product would need to be FDA approved. Dr. Lynn Ogden of the Food and Science department at BYU suggested that Xanthus gum may be suitable for a dental application. It has good suspension characteristics, is FDA approved (used in foods such as salad dressings and ice-creams), and is readily available. Xanthan is a polysaccharide that is produced by a bacterium called *Xanthomonas Campestris,* which is commonly found in plants such as cabbage. A comparative performance study between Polyacrylamide (SUPER-WATER®) and Xanthan for use in an ASJ was performed by professors of the University of Missouri-Rolla (Chacko *et al* 2003). The results of the tests are described in the following sections.

2.7.6 Xanthan versus Polyacrylamide (SUPER-WATER®)

Polyacrylamide has been successfully used with abrasives in an ASJ. However, this polymer has a limited ability of maintaining the abrasives suspended for extended periods of time. It has the same deficiency when larger particle sizes are used, which tend to settle too quickly without an agitation device. As mentioned earlier, Polyacrylamide spills are at times considered dangerous because of their slippery nature. For these reasons, an alternative polymer Xanthan was tested and compared.

The first experiment dealt with the suspension capabilities of the two polymers. Garnet mesh size of 80 (0.007-in) and 36 (0.0199-in) were suspended in solutions of polyacrylamide ranging from 0.25 to 0.75%. Results showed that when the smaller 80 mesh abrasive was used that it suspended well in solutions greater that 0.5% concentration, but only for a few hours. The 36 mesh settled more quickly no matter which concentration was used. A concentration of polyacrylamide greater that 0.75% could not be utilized since it became too viscous to work with and a concentration less that 0.25% would not suspend the particles long enough, even if used immediately.

Similar tests were performed using Xanthan. The results showed that this polymer was able to suspend both the 80 and 36 mesh garnet for several days using a 0.5% concentration. It may be assumed that a solution could be mixed far ahead of time and transported to a worksite. In order to obtain similar cutting performances, higher concentrations of Xanthan were required. Whereas 0.75% concentration of polyacrylamide is too viscous to be pumped, Xanthan concentrations can be up to 1.5%. As shown in Table 1, a higher Xanthan content results in a better cutting performance. Polyacrylamide achieves a maximum depth of cut with 0.25% concentration; however, it is impractical to suspend the abrasives in a real world working environment, since they tend to settle out too quickly. A concentration of 0.3-0.5% polyacrylamide has typically been used in ASJ. It was observed that Xanthan at 1.0% concentrations are comparable to the cutting performance of polyacrylamide at concentrations of 0.5%.

Table 1 Concentration of polymer versus depth of cut in a concrete block (Chacko *et al* 2003)

Xanthan Concentration, %	Depth of Cut, mm		Polyacrylamide concentration, %	Depth of Cut, mm
0.50	76		0.25	179
0.75	79		0.50	134
0.87	105		0.75	116
1.00	132			
1.25	130.3			

Another benefit lies in the fact that xanthan is biodegradable. Also, due to the shear thinning characteristics of xanthan, it is much less slippery and easier to clean up than the polyacrylamide polymer.

All polymers hereto mentioned help improve the efficiency of the abrasive and non-abrasive water jets. It is necessary to understand how polymers interact and change the water's rheology to be able to determine how to exploit their possible advantages.

2.8 Mechanisms of Material Removal

It has been suggested that abrasive material may or may not be beneficial in the low pressure dental water jet. The objective of this section is to discuss the pure water jet and abrasive water jet mechanisms that remove the target material. It is anticipated that understanding these mechanics will help solidify the decision to use abrasive particles in the low pressure water jet.

The mechanism that removes material for a pure water jet is fundamentally different for that of an AWJ. For a plain water jet, the initial water jet impact penetrates and fills the micro cracks and flaws of the specimen's material. The subsequent water jet stream pressurizes the voids and promotes fracture propagation and material removal (Summers *et al* 1991). This is the underlying reason that a pure water jet is not able to cut much harder (denser) materials, which have less tendency to contain pre-existing micro cracks. However, the initial impact of the pure water jet does produce enough impact pressure to generate some crack propagation. For this reason, pulsating water jets have been rigorously investigated for both plain and abrasive water jets.

The primary mechanism for removing material for an AWJ is due to particle impact. The name "abrasive" can be somewhat misleading. According to ASTM, the removal of material by an AWJ is more accurately described as solid particle erosion. ASTM defines this erosion as "the progressive loss of original material from a solid surface due to continued exposure to impacts by solid particles." The mechanism of material removal depends on the material being bombarded with abrasive particles.

The failure mechanism for ductile material differs from that of brittle materials. For abrasive water jets, there are two coexisting erosion mechanisms. Like the pure water jet, the high velocity of the water jet stream produces some crack propagation and carries away eroded material. However, the majority of erosion occurs from particle impact. The water jet stream can run at several times the speed of sound, resulting in enormous amounts of kinetic energy. The momentum of the water is transferred to the injected/entrained abrasive particles, which subsequently transfers the energy to the targeted material. The transmitting of particle energy to a localized contact point on the target material results in deformation/failure (elastic, plastic, or brittle), and the result is solid particle erosion.

2.8.1 Ductile Material Removal

If the material being removed by the AWJ is ductile, the material is only removed by material deformation flow or cutting after the material has transitioned to the plastic state. The amount of material removed depends on a large number of factors: how deep the surface has been stressed beyond its elastic limit, the amount of force that the particle is carrying, the angle and rate of the traversing cut, the shape, hardness, orientation, rotation and concentration of the particles in the abrasive laden water jet. When the abrasive impacts the ductile surface at a perpendicular/normal angle, the material will deform and "flow" around the abrasive particle. For this angle of attack, the material will only be removed after former abrasive particles have strain hardened the ductile material.

Strain hardening is when a material is strained beyond its yield point. The material becomes "harder" and subsequent water jet particles will then be able to remove the hardened material via brittle fracture mechanics. This is not the most efficient method for removing material that is ductile, since much of the impact force is lost because subsequent particles are colliding with former particles that are "pitted" into the target material. However, if the angle of attack (α) of the water jet stream is decreased to be shallower, the abrasives can cut and shear the material from the surface much more efficiently. At angles around 20°, the abrasives follow similar cutting patterns of a typical machining process. The particles act as a cutting tool's edge as represented in Figure 2.11.

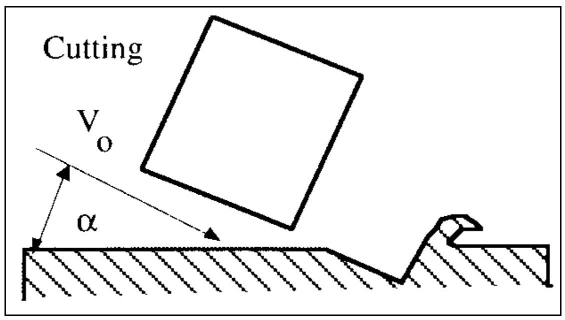

Figure 2.11 Representation of an abrasive particle acting as a tool cutting edge on ductile materials (Summers 1995)

A study was conducted which determined that there are three different types of material removal at shallow impact angles (20-30°), each one illustrated in Figure 2.12.

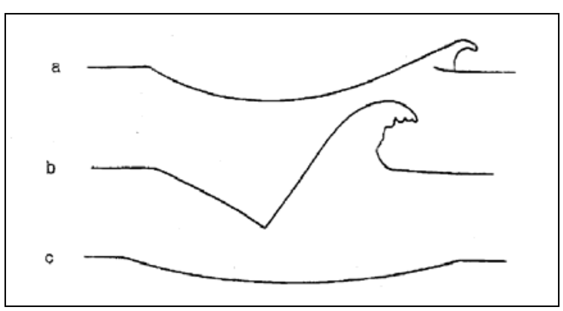

Figure 2.12 Three types of impact damage to ductile material at shallow angles (Bortolussi 1988, Ojmertz 1997)

a. Ploughing deformation by a sphere: Where the material is displaced to the side and in front of the particle, material removal is mainly caused by further impacts on neighboring areas, resulting in detachment of heavily strained material from the rim of the crater or from the terminal lip, formed in front of the particle.

b. Type I cutting: where an angular particle is rotating in a forward motion as it impacts the target surface. This typically forms a more prominent lip, which will be removed by subsequent particles.

c. Type II cutting: when an angular particle strikes the surface as it is rotating backwards relative to the target. The result closely resembles "true machining", where the abrasive may completely remove the chip from the target material (Ojmertz 1997).

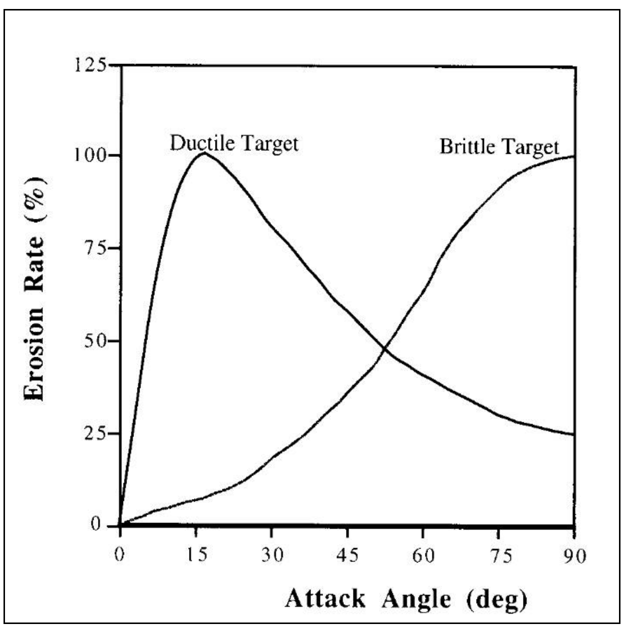

Figure 2.13 The effect of attack angle for material removal rates (Summers 1995)

As previously stated, the material removal mechanism for ductile materials varies with the angle (α) of impact of the abrasive material. The surface is eroded away by tearing, cutting, and shearing at more shallow angles. However, as the angle of attack approaches 90° (perpendicular to surface), the target case hardens and the majority of material would only be removed by fracture and crack propagation. This relationship of the angle of attack plotted against the percent of erosion rate is illustrated in Figure 2.13 for both ductile and brittle materials. Materials that are considered ductile, such as most metals, achieve a much greater erosion rate at these shallow angles. The opposite is true for a brittle target that is more efficiently eroded at perpendicular attack angles.

2.8.2 Brittle Material Removal

A material is typically considered brittle if it cracks under impact, such as glass, ceramic, and most rock. As explained earlier, as particles collide with a brittle target, fracture will occur via crack propagation. Material is ultimately removed when several cracks intersect each other and fragment off the target surface. This fragmentation of the brittle material is augmented by waves propagated by the particle impact force and the high pressures of the water jet itself.

Several brittle impact studies have shown that fragmentation is achieved by two types of cracking (Summers 1995, Ojmertz 1997). As a machine indenter is pressed into a brittle material, radial cracks tend to propagate outward perpendicular to the perimeter of the contact point. As the indention force increases, the creation of a lateral crack is formed propagating away from the impression in a cupping shape. These cracks continue to lengthen and spread out with increasing pressure. The lateral cracks are almost parallel to the target surface and eventually curve back up towards the surface (forming the cupping shape). Fragmentation is ultimately achieved when several of the cracks split into each other and propagate until a fragment of material is completely severed. This process is represented (though not perfectly) in Figure 2.14.

It was originally assumed that the AWJ could cut more efficiently, since it exploited the weaknesses in the target material's grain boundary. Research by Bortolussi et al. (1988) experimented with abrasive water jetting at different orientations around a sample of granite. His results showed that there were no statistical differences in the volume of material removed, despite the direction of attack. Pure water jets achieve their high cutting rates because they exploit existing cracks on the target's surface. By splitting these grain boundary cracks in this manner, much larger fragments are removed. It has been observed that the solid particle erosion caused by an AWJ occurs at a much smaller level.

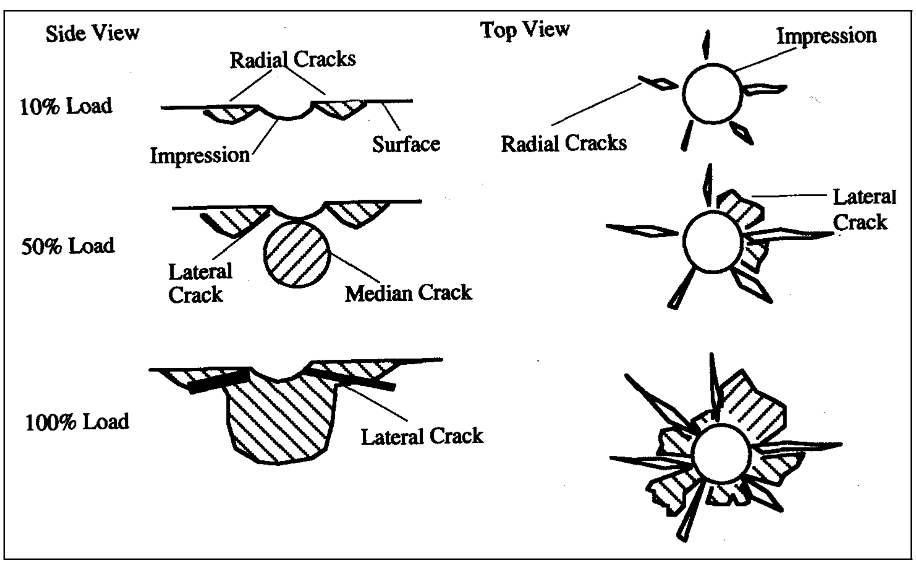

Figure 2.14 Crack propagation and fragmentation due to impression loads (Summers 1995).

The particle impacts create a network of micro cracks that are smaller than the typical grain boundary of rock. This results in much finer fragments that are being removed. In order to achieve greater cutting efficiencies (more material removed per time), a much larger amount of input energy is required, such as an increase in water jet velocity. Impact damage studies by Evans (1979) have shown a strong correlation of increased crack magnitudes with the increase of particle impact velocity. The data is graphed in Figure 2.15.

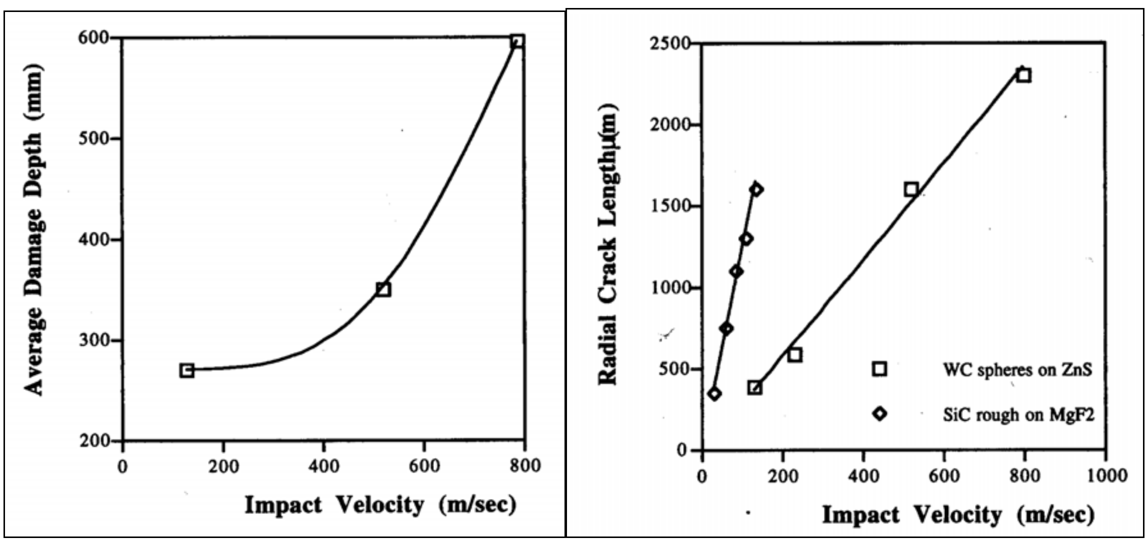

Figure 2.15 The effects of particle velocity on the length and depth of cracks (Summers 1995)

The amount of target material removed will be dictated by the "damaged zone" caused by particle impact. The larger and longer radial and lateral cracks that are achieved for each individual abrasive particle impact will result in much larger crack propagation networks and ultimately larger amounts of material removed. Again, it should be remembered that there are other factors involved, such as particle size and shape. The type of material to be cut will determine which parameters and techniques should be used.

It is suggested that the tooth material that would be removed by a dentist would behave more as a brittle material than a ductile material. As such, it is anticipated that the brittle mechanism for removing particles will accelerate the tooth "drilling" process. The addition of abrasives allows the input pressures to be decreased while the jet stream cutting rate is maintained. The addition of aluminum oxide particles in a low pressure water jet has shown to improve cutting rates (Hansen 2000).

2.9 Previous Research at Brigham Young University

Initial studies on the feasibility of using abrasives in a LPWJ system for a dental application have been conducted at BYU. The first research study was performed by Scott C. Hansen (2000). In his research, Hansen designed a statistical experiment to test several different factors and parameters. The factors that were studied include the following:

- Fluid pressure (500-2500 psi)
- Orifice size (0.004-0.006 in)
- Orifice type (Circular vs. Oval)
- Water vs. Water-Abrasive mixture
- Abrasive type (Al2O3 and Baking Soda)
- Abrasive size (1, 3, 10, 27 microns)
- Abrasive amount by weight (4, 11, 17%)

There are many different types of abrasive material used in high pressure ASJ systems. However, they tend to be low grade materials; therefore, they are too large and coarse for a low pressure system with an expected orifice diameter of only .004-.006 inches in diameter. Hansen determined that high grade abrasives were in the available size range that could work for a low pressure water jet system (LPWJ). Aluminum oxide (Al_2O_3) and baking soda (grade 1 and 3DF) can be found in a high grade form.

One of the greatest benefits of using Al_2O_3 as the abrasive is the fact that it is already used in the dental industry for abrasive air jets and cleaning pastes. Consequently, it is approved by the FDA, a major stepping stone. Baking soda was also considered because it is inexpensive, safe to consume, and readily available. Hansen performed intermediate testing on both of these abrasive materials to determine their usability for a low pressure (low flow rate) system for cutting tooth material.

Hansen reported in his intermediate testing that baking soda showed to be problematic. Hansen performed tests with only water as the cutting jet to set a benchmark cutting rate by which he could gage progress made while cutting with abrasives. To reach significant cutting rate improvements over a plain water jet, large amounts of soda needed to be added to produce a slurry solution. He was able to reach cutting rate improvements of up to 25% over water alone; however, it was necessary to increase the input pressure to over 5000 psi and increase the amount of baking soda in the slurry. The pressures were much higher than desired, and due to the large amount of baking soda saturation, the baking soda began to "settle-out." The fine powder would "clump together" as it entered into the feeding tubes of the prototype system and began to settle, which eventually caused clogging of the nozzle orifice.

Another drawback was the fact that baking soda decreased visibility while cutting a test specimen. The mist created from the water jet with baking soda left a haze around the cutting area after a short period of time. Though he was able to complete a few preliminary runs, the results showed that the cutting rate using baking soda slurry, with this current method, did not merit further investigation and was discontinued from his final testing

After eliminating baking soda as a feasible abrasive for LPWJ's, further experimenting and testing was conducted using aluminum oxide. Initial testing showed that there weren't the same problems for the Al_2O_3 which existed with the baking soda. This allowed higher abrasive-to-water ratios and a broader range of experiments. His intermediate testing using Al_2O_3 showed that piercing pressures dropped so far below the benchmark that the pump being used for the tests could not be used further because it could not achieve sufficiently lower fluid pressures. Using Al_2O_3 as a LPWJ abrasive, however, still proved to be problematic.

As Hansen increased the diameter of the Al_2O_3 particles from 1 to 3 microns, the pump began to malfunction and interrupted his testing. In order to continue his experiments with anticipated larger particle sizes, the abrasive had to be inserted after the pump. This involved pulling the testing apparatus apart, inserting a batch of Al_2O_3 solution, and putting it back together for each test run. As soon as the abrasives were inserted into the system after the pump, testing needed to begin immediately before the material settled. The setup was not ideal and the abrasives would still settle often and clog the exiting orifice. This made it difficult to make any concrete conclusions about how well the abrasives improved the cutting ability of the low pressure water jet. It was obvious, however, that there was substantial potential when the abrasives were added and cutting was performed before the abrasives settled.

Follow-up research was performed by Joseph M. Memmott at BYU (2003). His work was intended to determine whether impinging jets could be used to focus the water jet's cutting potential to a point. This method of cutting would give greater control to an operator's desired depth of cut and would be safer than a single-stream water jet. This is possible because the kinetic energy of the two jet streams would be largely eliminated once the jets collided with each other at the "focal point."

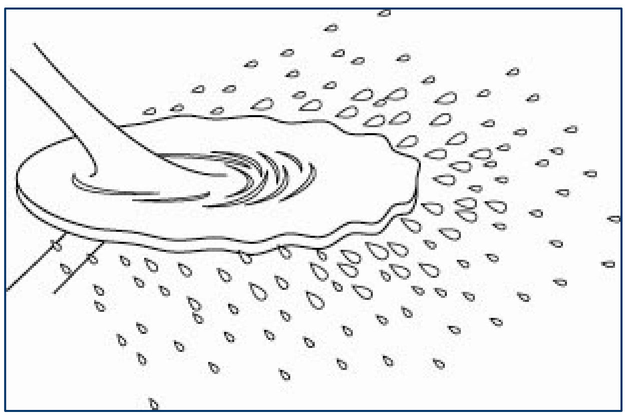

Figure 2.16 Illustration of impinging jet streams (Memmott 2003)

Memmott discusses his attempt to recreate the testing conditions used by Hansen. He encountered similar difficulties in his research "due to the orifice becoming plugged" because of the Al_2O_3 abrasive material settling. Though some of his experiments showed that adding abrasives allowed the water jet to cut up to five times more effectively than a pure water jet, his primary testing to establish the feasibility of two impinging jets could not include abrasives as one of the testing parameters. He concludes that further work concerning abrasives needs to be performed to take this LPWJ technology to market:

The primary study conducted in this research has been done without the addition of abrasive material. A successful method to entrain the abrasive continuously in the fluid has not been determined. This is critical to the success of waterjets as applied to dentistry (Memmott 2003).

Regardless of abrasive entraining difficulties, final testing showed that using [larger] abrasives was the most significant process parameter for the depth of cut on a tooth and ceramic tile plates (which were shown to simulate the material properties of tooth enamel). Within Hansen's testing parameters, he suggests 27 micron Al_2O_3 to achieve the maximum depth of cut for the test apparatus used. He also suggests an orifice diameter of .004-.008 inches and a 5-17% Al_2O_3-H_20 (by weight) slurry concentration.

Realizing that the addition of abrasives is a significant factor for a successful LPWJ system, Hansen concludes his work by stating that an improved system should include the following characteristic: "The ability to meter the feeding of aluminum oxide abrasives, between 10 and 27 micron, directly into the system continuously without the need of batch flows." It would be assumed that "batch flows" would be acceptable if a viable method to homogeneously entrain the abrasives could be developed.

2.10 Relevant Patents

There are several dental systems designs that have similar characteristics and parameters to the low pressure dental abrasive water jet that Brigham Young University intends to design and patent. It is important to know what designs and methods of entraining abrasives are already protected by patent rights to help guide this project to its successful completion. Also, there is no desire to "reinvent the wheel." This is an important step for this literature review.

Though there are several dental tools on the market, it is anticipated that the design presented by BYU is sufficiently unique to merit a patent. In order to prove its "uniqueness" and set its design parameters, pertinent patents on dental jets have been reviewed. A small summary of these relevant patents will be presented. Their similarities and differences will be contrasted to BYU's proposed design that is based on this current work:

U.S. Patent No. 5,934,904 (Elrod et al.) **Filed: 1997; Issued: 1999**

The dental instrument and processes patented by Elrod includes a handpiece having a nozzle from which is ejected a stream of abrasive particles and a microprocessor to regulate the system. The abrasives are entrained by an air supply. The nozzle has an orifice of 0.01-0.03 inch. The stream pressure in the continuous flow ranges from 15-120 psi with an abrasive flow rate of 2-3 grams/minute. It appears that the purpose of this patent is to protect a process of controlling the dental system through a micro processing system. The design does not use water and its parameters are not in the same ranges that BYU's current invention intends to pursue.

U.S. Patent No. 6,164,966 (Turdiu *et al.*) **Filed: 1999; Issued: 2000**

Parid Turdiu *et al*. claim the ability to remove dental caries with a high speed water jet. The system varies its working pressure to allow simple cleaning and also higher pressure caries removal. The patent explicitly states that the method to remove the caries is by adjusting the pressure to "penetrate the soft caries material, but to be deflected by the harder healthy dentin." The stagnation pressures claimed range from 5-30 ksi. The diameter ranges from 0.0004-0.012 inch. This invention is working at much higher pressures and also without abrasives to remove caries. It makes no claims to cutting teeth. It is not the same as BYU's current proposed process.

U.S. Patent No. 3,502,072 (Stillman) **Issued: 1970**

This water jet is designed specifically for "therapeutic oral hygiene implement." It clearly states that it is meant for cleaning the tooth and the gums with no intentions for it being used for a drilling (caries removal) process. As such, it is not a closely-related art.

U.S. Patent No. 3,870,039 (Maret *et al.*) **Filed: 1973; Issued: 1975**

This patent claims to use a water jet as a cleaning and stimulating tool. Its smallest claimed orifice diameter is 0.2 mm (0.0087 inches) which is the largest diameter BYU anticipates using. Also, this patent anticipates ejecting the liquid at a velocity of only 2-7 m/sec, which is far less than the anticipated velocity of BYU's water jet (in the range of 60 m/sec). The most prominent claim for this patent is the fact that it is trying to create droplets by applying a resonance frequency. Consequently, this design is not closely related to BYU's water jet invention.

U.S. Patent No. 5,203,698 (Blake *et al.*) **Filed: 1991; Issued: 1993**

The device, as claimed by Blake *et al.*, is a sandblasting device that uses a chemical that foams and entrains the particles for transport. It is then propelled through a nozzle by gas pressure. It claims "very specific applications in the dental industry."

a. general cleaning of teeth

b. *selectively* abrading away carious enamel

c. cleaning prosthodontic restorations

d. preparation for bonding

e. periodontal pocket cleaning

f. cleaning of occlusal pits and fissures for sealing

The claim continues to list the tool to be used for cleaning jewelry, semiconductor's, automotive and in other industries. There is no specific indication that it will be used to cut and drill teeth. Also, the process of mixing in the abrasive material using a foam is unique for their design. The design is very broad and is believed to not burden BYU's intended invention.

U.S. Patent No. 5,525,058 (Gallant) **Filed: 1994; Issued: 1996**

The dental treatment system designed by Gallant is intended for "treating teeth or associated tooth structure by the use of an abrasive-laden fluid stream." It may be of some concern that this patent is worded such that it encompasses a very broad range of parameters, since no specific values of pressure, abrasives, and "fluid" type, etc. Throughout his claim Gallant's design repeatedly refers to his abrasive slurry as *air* and abrasives. The mixing and transfer of the abrasives will occur via a pressurized stream (similar to sandblasting). It is assumed that this system would not work with H_20 alone. Also, the preferable pressures presented by Gallant for the current system are approximately 80-200 psi. This is below the pressures that will be utilized for BYU's design. It is anticipated that this dental treatment system does not have claim over BYU's current invention.

<u>U.S. Patent No. 6,497,572 (Hood *et al*.) & 6,224,378 (Valdes *et al*.)</u>

Filed: 2001; Issued: 2002, Filed: 1997; Issued: 2001

This water jet apparatus "for dental treatment using high pressure liquid jet" is distinctly a water jet. It is anticipated the system will cover all dental procedures that require tooth material removal: endodontal, periodontal, surgical, and restorative procedures such as gingivectomy, removal of granulation tissue, muco-osseous surgery, caries removal, and scaling and removal of plaque and calculus, and extractions and tissue incisions. To accomplish these tasks the system claims to have working pressures from 500-60,000 psi. This is above the anticipated pressures to be used by BYU's current invention. Also, the jet orifice diameter is "approximately" 10-800 microns. This patent does not appear to impede the anticipated low pressure water jet design by BYU.

A review of relevant patents helps guide the project in two ways:

1. It presents many methods and ideas to solve a need or a want.
2. They help guide our work to avoid infringement on existing patents.

After performing this patent review, it is anticipated that designing BYU's low pressure dental abrasive water jet with the parameters previously mentioned (section 1.6) will be viable for a dental system.

2.11 Water Jet Technology Review

A great deal of time was spent reviewing water jet systems, their history, and their progress and developments. It has taken years to develop methods to entrain and suspend abrasive particles in a high pressure industrial water jet system. It was the opinion of the author that the same entrainment abilities and dilemmas that exist in the high pressure water jets would exist in a low pressure water jet as anticipated by BYU. As a result of this review approach, several concepts have been generated and will be presented in Chapter 3 for further discussion.

3 Research Methodology

This chapter will present the *Product and Design* steps (Ulrich 2000) applied to generate and select possible solutions to entrain abrasives for a low pressure abrasive dental jet, as anticipated by this research at Brigham Young University. The overall objective will be stated and clarified by re-presenting the functional specifications and expected delimitations of this proposed low pressure water jet system. The sub problems will then be identified by performing a functional decomposition of the low pressure abrasive dental jet system.

A list of generated concepts and sub concepts will be presented along with their functions and possible advantages and disadvantages. Thereafter, the concept screening and scoring processes will be presented and discussed. These processes are intended to narrow down the generated concepts to those that appear to be most viable for the anticipated low pressure dental abrasive jet. The process results will be reported in Chapter 4.

3.1 Research Process

Research has been performed on low pressure water jets by Hansen and Memmott at Brigham Young University. They both conclude that the addition of abrasives into the water jet stream for a dental application improves the cutting ability of the water jet sufficiently to merit further investigation. Also, they both insist that it is necessary to find a method to homogeneously and consistently entrain Al_2O_3 abrasives into the water jet stream, probably as close to the exit nozzle orifice as possible. Adding abrasives provides a more appropriate material-removal mechanism and allows lower working pressures and higher cutting rates. It is anticipated that a solution to the entrainment problem for BYU's low pressure abrasive jet will allow the design to be a viable alternative dental system to existing methods.

In order to clearly understand the problem, a list of key functional specifications, delimitations and assumptions are listed here to help facilitate the generation and selection process. These parameters have been narrowed down by the research previously performed by Hansen, Memmott, and by the current research:

- The abrasive jet will have a working pressure range of 0-500 psi.
- The nozzle orifice will be between 0.004-0.008 inches.
- It is anticipated that a range of 5-17% Al_2O_3-H_20 (by weight) slurry concentration will be used.
- The Aluminum Oxide will have a diameter range of 5-27 microns.
- The pressure supply of gas to pressurize the water jet system will likely be a compressed air or nitrogen tank since it is commonly found in dental offices. This approach will eliminate the need of a pump.
- The low pressure dental water jet will have to be comparable to, if not better than, existing dental handpieces in the following categories:
    - Performance (rate and accuracy)

- Cost
- Noise
- Function
- Evades anesthetics for common caries removal
- Minimizes heat and vibration

Understanding these key functional specifications clarifies and simplifies the design generation and selection processes.

3.1.1 Flow Rates and Expected Handpiece Batch Size Volume

Previous work on the low pressure water jet was performed by Scott Hansen of BYU (2000). During his research he determined an expected flow rate under the above noted parameters and conditions. Similar tests using water only were repeated in this research with the intent of comparing data and determining the percent error between the predicted (Bernoulli's) and the actual flow rate values. This data is tabulated in Table 2.

All the tests were performed at the upper pressure limit of 500 psi with a volume of 200 ml. All conversions were made as necessary. Two runs for each factor were performed and then averaged. This average value was then compared to the flow rate value predicted by Bernoulli's equation, which was simplified and is shown in Equation 4:

$$V_2 = \sqrt{\frac{2\Delta P}{\rho_{H_2O}}} \quad \textbf{(4)}$$

where V_2 is the velocity of the water stream exiting the nozzle orifice, ΔP is the change in pressure from inside the vessel to the atmospheric pressure, and ρ_{H2O} is the density of water.

Table 2 Experimental and predicted flow rate values for a pure water jet

Water Jet Flow Rate	**T1**	**T2**	**T3**	**T4**	**T5**	**T6**
Orifice Diameter (in)	0.006	0.006	0.005	0.005	0.004	0.004
Volume H2O (gal)	0.053	0.053	0.053	0.053	0.053	0.053
Pressure (psi)	500	500	500	500	500	500
time (sec)	161	168	239	238	396	404
Flow Rate$_{actual}$ (gal/min)	0.020	0.019	0.013	0.013	0.008	0.008
Flow Rate$_{actual}$ Average	**0.019**		**0.013**		**0.008**	
Flow Rate$_{predicted}$ (gal/min) Bernoulli	**0.058**		**0.040**		**0.026**	
% Error = [pred-act/pred]	66.73%		66.97%		69.22%	
Flow Rate$_{act2}$ (gal/min) This Research	0.019		0.013		0.008	
Flow Rate$_{actual1}$ (gal/min) Hansen	0.023		0.015		0.009	
% difference = [2*(act1-act2)/(act1+act2)]	17.60%		12.08%		12.69%	

The predicted flow rate was calculated by multiplying the predicted exiting velocity, V_2, by the area diameter of the exit orifice. The exit nozzle and orifice design used for these tests have had significant influence on the final velocity of the water jet stream. The orifice used by Hansen and this research is a flat plate which is represented in Figure 5.7 in section 7.1. Correction values have been experimentally calculated for this type of flow restriction, where $Q_{act} = Q_{Bernoulli}*K$, and K is a correction constant. For the type of plate orifice illustrated in Figure 5.7, K = 0.61 (Fox 2004). Note that the "actual" values in Table 2 are the results from experimentation, and the predicted values are those calculated using Bernoulli's equation, which also includes the correction factor.

The percent difference between the actual flow rates for this research and those that were predicted by Bernoulli's equation were consistently around 67%. The flow rates achieved were much lower than predicted by Bernoulli's equation, showing the many inefficiencies of the system. However, when this research's actual results were compared to Hansen's previous results, the percent difference was only about 12%.

Therefore, it is the opinion of the author that the flow rates and the volume removal rates calculated by Hansen provide a good model. It may be desirable to provide a method to entrain and suspend aluminum oxide particles that might be placed near the end of the dental unit hose, close to or a part of the handpiece itself. If these flow rates are pursued, then a given volume of slurry that is sufficient to remove tooth caries must be calculated. Hansen has provided data that predicts the volume removal rate (VRR) on a tooth.

It is suggested by this research that the parameters that currently provides the optimal cutting characteristics are 500 psi, 0.006 in orifice, 27 micron abrasive particle, with 17% abrasive aluminum oxide by weight. A low pressure water jet at these levels will produce a **VRR** of 1.765 E-4 in^3/min.

There are few theories on calculating the amount of dental caries and healthy tooth that needs to be removed to efficiently add a filling. G.V. Black was a pioneer for cavity design who provided much information on this subject; however, as techniques and technology have progressed, the cavity design principles have changed. Though there are guidelines for cavity design, there is no actual dimension that defines an average cavity size. After some review of cavity pictures, it is suggested that a dental caries could be modeled by a cylinder with an estimated volume in the range of:

- **0.05** inches in diameter by 0.02 inches in depth

  [(0.05 in dia. x 0.02 in depth), (1.27 mm dia. x 0.51 mm depth)]

- **0.10** inches in diameter by 0.02 inches in depth

  [(0.10 in dia. x 0.02 in depth), (2.54 mm dia. x 0.51 mm depth)]

These dimensions produce a cylindrical volume in the range of 3.93 E-5 in^3 to 1.57 E-4 in^3 (6.44 E-4 mm^3 to 2.57 E-3 mm^3).

Therefore, the average time (t) to remove a given volume of tooth material would be calculated by the following equation:

$$t = \frac{V}{VRR} \tag{5}$$

where V is the volume of tooth to be removed and VRR is the volume removal rate. For the parameters presented previously, the time range to remove the volumes of tooth material would be in the range of t = 0.22 to 0.89 minutes (13.4 to 53.4 seconds).

According to the experimental data in Table 2, an expected flow rate (Q) with the same diameter, input pressure, and disregarding the abrasives would be about 4.62 in^3/min (0.019 gal/min). Therefore, the necessary volume of water (V_{water}) to remove the presented volume of tooth material would be $V_{water} = t*Q_{water}$. The volume range of water needed would be **1.02 to 4.14 in^3** (1.23 to 4.6 tablespoons; 0.62 to 2.3 oz.) to remove the suggested volume of tooth material.

These values help determine whether or not a concept could be miniaturized and placed at the end of the water jet dental handpiece. It is the opinion of the author that these volumes calculated can be used near the handpiece; however, it should be emphasized that the smaller the volume that is needed, the more feasible the water jet dental drill concept would be as an alternative dental handpiece.

If larger abrasive particles are able to be utilized without causing the exit orifice to clog, then this volume can be reduced greatly according to Scott Hansen's Predictive VRR model. A discussion on the improvement of the current nozzle orifice design being used for this research will be approached in subsequent chapters.

3.2 The Problem at a Macro Level

It is typically easier to narrow down the search for a solution when the entire problem is understood, beyond the specific task at hand. For this application, the low pressure dental abrasive jet will be used in a professional environment and is anticipated to be used on human patients ranging in age from young children to mature adults. The function of the system must be safe and user friendly. Also, just as other dental handpieces are designed to meet the dentist's needs, this water jet system is likely, but not necessarily, to have a similar set-up.

As demonstrated in Figure 3.1 below, a dental system is likely to have the main unit in which input energy is stored and converted when signaled (typically triggered by a switch or button). The unit would probably be located some distance away from where the dentist is performing the dental work on the patient.

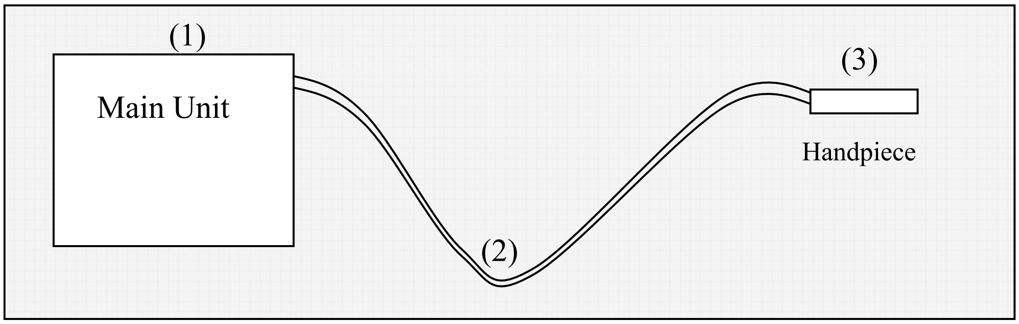

Figure 3.1 Typical dental handpiece system set-up

The actual handpiece would likely be connected by a flexible hose. This enables the converted energy and/or the material in the main unit to be transported to the handpiece. Logically, it would be undesirable to have the main unit of a working machine situated next to the head of the patient.

A problem arises when abrasives are being used. It is anticipated that air and/or water will be the transport medium for the aluminum oxide. Similar to the same predicament encountered in industrial HPWJ's, if the abrasives are passing through a hose when the system is paused or stopped, the particles will begin to settle. Location number (2) in Figure 3.1 shows the lowest point that is likely to occur in the system. If the water flow is slowed or stopped, then the abrasive particles continue to settle to point (2) in the hose due to gravity. This problem is exacerbated for two reasons:

1. The volumetric flow rate of the slurry will be relatively slow in this low pressure dental system.
2. The Al_2O_3 abrasives are small (5-27 microns); therefore, when they settle they tend to adhere or pack together tightly.

Consequently, in the configuration noted in Figure 3.1, the abrasive jet would not be able to maintain a homogeneous slurry over time. After the abrasives have settled, it generally takes an even greater force to re-entrain them back into the water flow. Also, after the Al_2O_3 particles have settled, they tend to stay in small "clumps" when it is re-entrained. These clumps would be prone to clogging the relatively small nozzle orifice. To solve this problem, a mechanism must be designed into the abrasive jet system to keep the particles from settling or have a method to remix the slurry until it is completely homogenized again, whether it is in the main unit, the transfer tube, or the handpiece at the end of the system.

At the macro level, there are really two problems that need to be considered. The first is the need to insert the abrasive material into the water jet system. Due to the water jet system being under pressure during use, the Al_2O_3 particles need to be put into the system in batches or be inserted or fed continuously. If a batch system is chosen, the abrasive material and water could be inserted into the system before pressure is applied. If the system is continuously fed, the abrasives need to be inserted while the system is pressurized. From a mechanical standpoint, a batch system is inherently simpler than continuously feeding the abrasive particles into the pressurized vessel.

The second problem is mixing and suspending the abrasive particles with the water jet stream to produce a homogeneous slurry mixture. Both the first and second problems are considered to be coupled; if one is solved, the other will be directly affected. The focus of this research is to mix and suspend the particles into a homogeneous slurry.

3.3 The Problem Divided into Sub-Components

In order to visualize the problem at a fundamental level, it is necessary to break the desired abrasive jet system into sub-problems. A functional decomposition has been performed. The water jet dental system represented in Figure 3.2 shows its material, energy, and signal flow components as a "black box" (Ulrich 2000). This technique assists in visualizing the overall function of the water jet. After this stage, the water jet functions are broken down further into sub-functions to represent a more specific description of each individual function of the device.

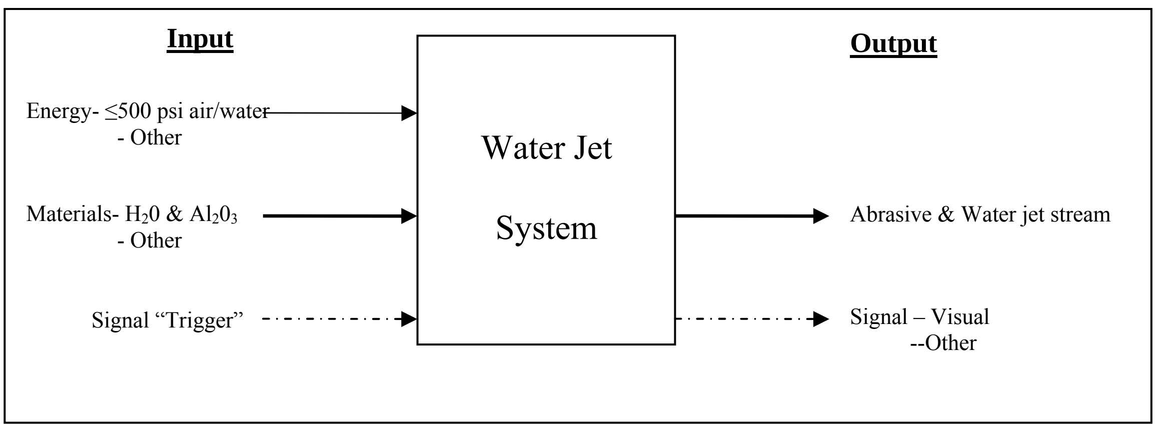

Figure 3.2 Black Box representation of a water jet system

The sub-functions represent each of the variables that can be modified to change the overall function of the water jet. The most critical sub-problem is found in step 2 of the functional decomposition schematic in Figure 3.3. It is the intent of this thesis to investigate several viable methods to convert some type of external energy to entrain and suspend the abrasives in the water solution to achieve a homogeneous abrasive jet stream.

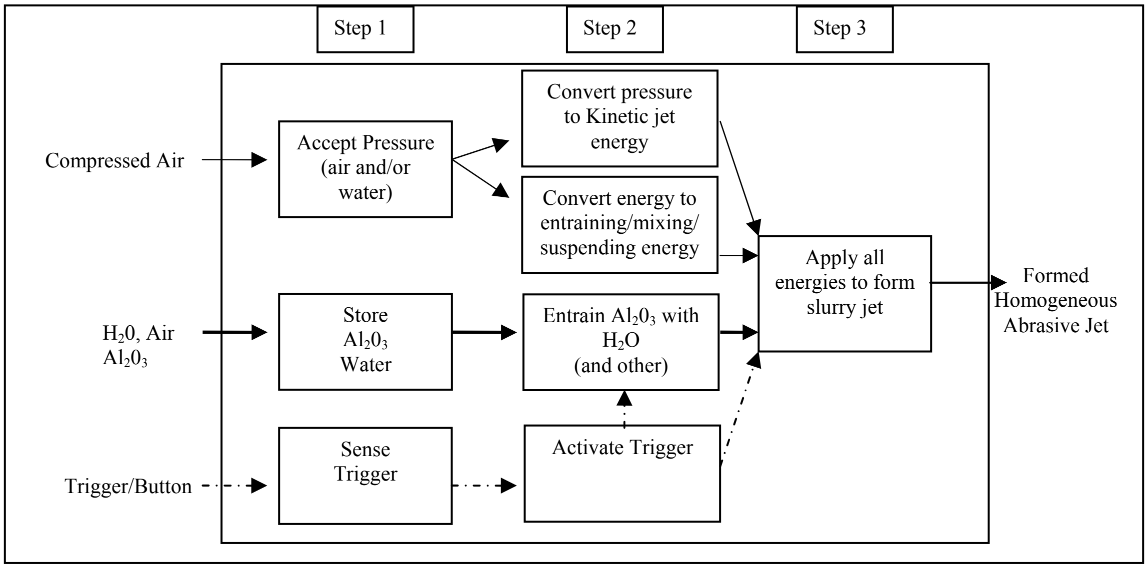

Figure 3.3 Functional decomposition of an abrasive water jet

In a dental office, compressed air or nitrogen, water and electricity are readily available as energy sources; however, there are many other energy forms that might also be implemented to assist in the abrasive entraining processes. A list of possible energy sources are presented here:

a. Gravity
b. Electromagnet
c. Heat
d. Spring (compliant energy storage device)
e. Chemical (reaction, suspension)

This list specifies the energy sources that may be implemented in an abrasive jet for dental applications, but it is not limited to these sources alone.

3.4 Generated Concepts

The next step in the design process is to generate concepts that may solve the entrainment problem, keeping in mind the parameters, delimitations, and functional decomposition sub-functions of the device. The following is a list of possible methods that might be used individually or in combination with each other to produce a homogeneous slurry abrasive jet for a dental water jet system. The following concepts will begin with those that are already on the market for high pressure abrasive jets. Thereafter, a list of possible methods that are from analogous devices and also methods that are new or unique will be presented and discussed.

3.4.1 High Pressure Abrasive Jets

It was emphasized in chapter 2 that the high pressure abrasive jet methods for entraining abrasive particles may be adopted into a low pressure dental system. The post orifice entrainment method designed by Mohammed Hashish for a high pressure water jet system utilizes a low pressure zone in a mixing chamber, which is created from the high velocity jet stream passing through an orifice. Since the anticipated dental jet stream is much smaller in diameter and produces much lower jet stream velocities, the post-orifice method will not be considered for BYU's design. However, the direct and indirect methods of entraining abrasives have many design characteristics which may be useful for the low pressure dental system.

3.4.2 Direct Pumping

The direct pumping method, as shown in Figure 3.4, requires the abrasive slurry to be passed through the pump and then out through the nozzle. Several studies, including that by Scott Hansen, have concluded that Al_2O_3 particles quickly wear the pump components. Also, it is foreseen that a dental office will more likely use compressed air rather than a pumping device. For these reasons, the direct pumping method will not be included for further investigation.

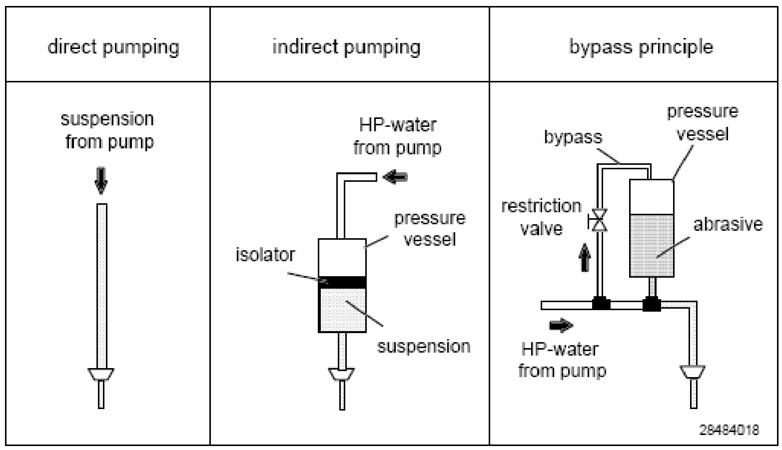

Figure 3.4 Principles of ASJ generation (Brandt & Louis 1999)

3.4.3 Bypass Principle

Much research and literature review was focused on the bypass principle, which is used for the DIAjet system. This design has the advantage of not requiring any secondary energy sources or the need for a moving mechanical device such as a mixer. Some of the input water is bypassed into the pressure vessel. This bypassed water has a slightly higher pressure and velocity. Figure 3.4 shows the basic flow of the bypass method and section 2.2.6 explains this method in greater detail. The water entering into the pressure vessel is manipulated in such a manner that it fluidizes the abrasive slurry. Each design to fluidize the slurry varies from company to company and is considered proprietary.

The disadvantage of this method is the consequence that as more water is used, the less concentrated the abrasive-water slurry becomes. This is due to the fact that water is continuously entering the system and the abrasive particles are entered in batches. In large volume systems the flow can be manipulated to maintain a semi-consistent concentration, which would be difficult for a low volume system. Also, the high pressure system requires a high velocity stream to mix and suspend the slurry. Again, it is anticipated that the proposed low pressure system will have small flow rates; therefore, very small velocities. It is believed that the low velocities would not produce the forces necessary to mix and suspend the 5-17% Al_2O_3-H_20 (by weight) concentration homogeneously in the pressure vessel.

3.4.4 Indirect Pumping

The indirect pumping method has the ability to be employed in a low pressure system. Figure 3.4 shows a basic design that might be utilized. As labeled in the figure, this method generally requires a suspension medium to keep the particles in place without requiring an external force. The input energy may be water or air. One of the disadvantages to this design is the fact that it uses an isolator, which is intended to prevent the suspension medium from mixing with the input water or air pressure.

As reported in chapter 2, this design usually has wear problems around the piston isolator and eventually causes leakage and/or friction, which will cause the isolator to jam. It is possible, however, that the pressure vessel itself could be small enough to make it a single use batch system. This would provide the advantage of disposability, which would eliminate any wear problem concerns, cleaning or maintenance. It is anticipated that the slurry jet would arrive to the dentist as a premixed, disposable, slurry cartridge.

The cartridge would be connected to the existing pressure line, used, and then removed and discarded. This concept relies on the amount of abrasive slurry volume that is required to remove a dental caries as discussed previously.

3.4.5 Polymer Suspension

The manner in which the indirect pumping design is employed is with a suspension medium that keeps the abrasives homogeneously entrained. In high pressure systems, there are many research tests that demonstrate the advantages of using a polymer to suspend abrasives and improve flow performances. It is anticipated that a polymer could be used in this dental jet application; however, the polymer would have to be safe to enter a patient's mouth. When used, it can't obscure the workpiece and it cannot negatively affect the cutting potential of the abrasive jet stream.

The majority of the generated concepts have dealt with adding some type of energy to the system to entrain and suspend the abrasives. As described in chapter 2 of this thesis, it may be feasible to use a medium that is sufficiently viscous to keep the abrasive particles suspended without the need of external forces. It appears that there may be many benefits to using this method in a low pressure water jet system. Firstly, if the water jet performance is maintained or even enhanced while employing a polymer, it would simplify the overall design tremendously by avoiding the need of extra mechanical parts. There would be no need to use any secondary mixing mechanism, since the suspension medium would keep the particles suspended. With the right concentration of polymer additive, the H_2O-Al_2O_3 slurry solution could be premixed and ready to use upon request.

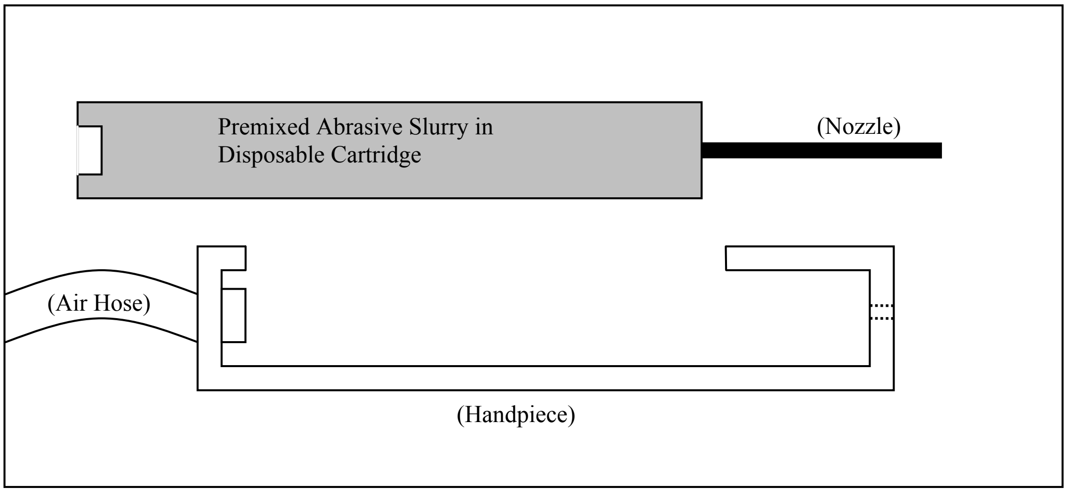

Figure 3.5 Simplified design for a premixed batch polymer suspension method

The basic design to be considered would utilize a single-use batch method. A cartridge holding the pre-manufactured solution would carry enough slurry to perform a dental cutting surgical treatment. This would enable the cartridge to be sufficiently small to be located at the point-of-use, which is at the handpiece. Consequently, the supply energy could be air instead of water. If this were the case, then the water jet could be designed to connect directly to existing dental pressure supply equipment. This would greatly reduce the need for extra equipment and costs. Using this approach, the dentist could simply add a new cartridge to the handpiece attachment and discard it when he was finished. There would be no need to clean or refill containers with abrasive material and water.

There are two possible disadvantages of the polymer suspension method: it is possible that the polymer medium will 1) cloud the work site and 2) decrease the water jet performance due to the increased viscosity of the medium.

Previous studies performed by Hanson demonstrate the consequences of decreasing the visibility of the work piece when baking soda and other materials are used. Simply put, any obscurity of the caries being treated during surgery would be unacceptable. It is necessary that the dentist be able to clearly see the caries material to be cut away.

In high pressure water jets, polymers have been shown to increase cutting performance. It is unclear, however, if the lower pressures and velocities of the water jet parameters considered for this research would produce similar cutting results when combined with a polymer. It is assumed that there exists an optimal point of polymer concentration which would provide sufficient suspension characteristics and minimal viscosity resistance. The greater the polymer concentration used, the better the suspension ability; however, this also increases the viscosity of the solution.

As discussed in section 2.4.5, xanthan may be a suitable suspension medium for a low pressure water jet system. There are several companies that pre-process this carbohydrate so that it is transparent. In order to determine whether it is a viable suspension medium for this application, several tests will need to be performed.

There are many possible advantages of using a polymer to suspend abrasives for a dental application. No external energy or forces would be required to maintain a homogeneous slurry. As discussed, it is feasible that a dentist could insert a pre-filled slurry cartridge, use it, and then discard it after each patient. This would provide a convenient and clean method to remove dental caries.

3.5 Analogous and Unique Solutions

Throughout the literature review and general research on entraining, mixing, and suspension systems, a list of concepts was generated. The following ideas are in no particular order. These generated concepts are only a few of the most practical methods that may be able to accomplish the desired entrainment. It should be emphasized that these are possible methods that could solve the entrainment problem but are not yet completed designs ready to be manufactured. It is anticipated that a more developed design(s) would be produced after the list of generated concepts is narrowed down to the one or two methods that could be the most viable for a dental handpiece system.

3.5.1 Stirring Mechanisms

A stirring mechanism may consist of one of the following:

- Propeller
- Impeller
- Blade
- Wisk

These mechanisms may be agitated or rotated by an electric, electromagnetic, or pneumatic motor. It is also feasible that they may be manually activated by winding or compressing an energy storing device such as a spring or other compliant mechanism. Difficulty lies in the ability to achieve a mixing motion under the previously-explained dental environment and water jet delimitations. These mechanisms could be placed in many different locations in the pressure vessel. If a stirring mechanism is chosen as a final method, it is anticipated that a more detailed design would be pursued.

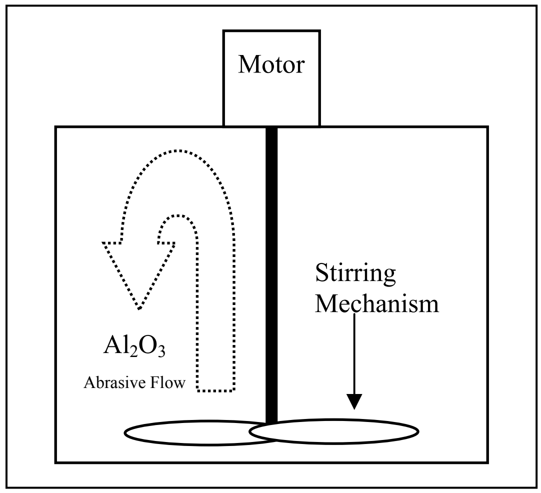

Figure 3.6 Stirring mechanism using a propeller to suspend abrasive particles

Electric Motor:

An electric motor may be implemented, either internally or externally, within the mixing tank. Placing the motor internally is possible, but it would require an expensive waterproof motor that would need to withstand a constant working pressure of up to 500 psi. In order to power the motor, the wires would have to enter the high pressure tank. Though this is not critical, it is undesirable to have holes through a pressurized tank, which would decrease the integrity of the tank structure. Also, the types of motors for this situation are generally large and expensive. If a key goal of the abrasive dental jet is to be cost competitive with current dental systems, an internal motor is likely not the best option.

The motor could be placed outside the mixing tank. In this case, the motor shaft would have to pass through the wall of the high pressure tank. This would require high pressure seals that would allow the shaft to spin freely. It is assumed that this method could have a greater risk of failure over time due to water or air leaks through the seal; however, placing the motor on the outside of the tank would permit a larger and more powerful motor at a fraction of the cost of an internal motor.

Electromagnetic Motor:

To avoid having any parts passing through the pressurized tank's wall, an electromagnetic motor may be used. This may be achieved by having the magnetic "guts" of a motor inside the tank and the electric windings on the outside of the tank. This would be an inventive idea and its capabilities are unknown.

Figure 3.7 represents a potential design. It should be noted that the propeller may be placed in many different locations within the pressure vessel. It is assumed that if any one of these entrainment designs are chosen for further investigation, finding the optimal location for the mechanisms would need to be pursued.

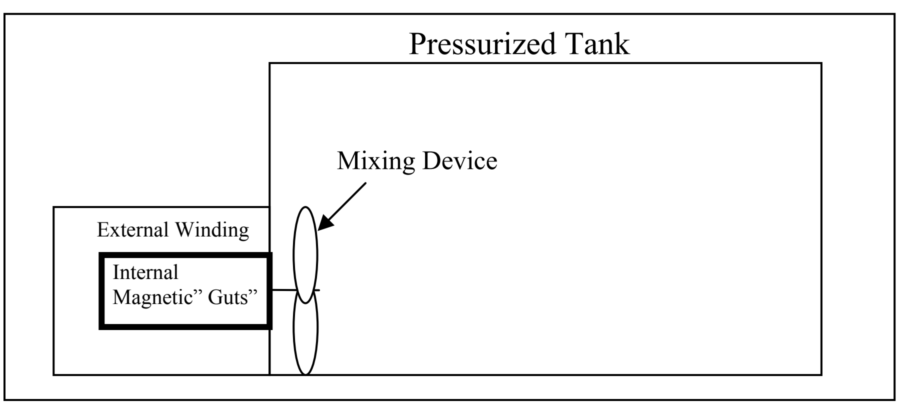

Figure 3.7 Electromagnetic motor schematic

Pneumatic Motor:

It is feasible that a pneumatic motor may be employed, since it is assumed that compressed air will be readily available in the dental office. This has the advantage of avoiding any additional energy source, but it would still have the same disadvantages of having more parts passing through the pressure vessel. One of the weaknesses of the current handpiece bur tool is the notorious “whine” that it creates because of the air-driven motor. It is possible that a pneumatic motor for this method could produce similar noises that would cause patient discomfort.

If these motors or any other method to entrain abrasives is designed to occur in the main unit (1) as shown in Figure 3.1, the settling abrasive dilemma would still remain. Anytime the system is at rest the abrasives that are not near the stirring device will settle to the lowest energy point, such as the bottom of the transport hose as demonstrated in the same figure.

A secondary solution to the settling problem in the transport hose may be a twisted cable that is also connected to the motor. This cable would pass through the tank and continue up the transport tube until it reached the handpiece. The cable would continue to rotate in the tube, agitating the abrasives and obstructing them from settling into any single location. This design is not necessarily recommended, but it is a possible accommodating solution if a motor is designed to be in the main dental unit.

It is possible to design the motor to be near or part of the handpiece. This would avoid passing abrasives through the transport tube. However, it is assumed that the shape of an abrasive dental jet would need to be similar to currently employed dental handpieces. Adding any mechanism to the handpiece would need to be small and non-intrusive.

These methods for suspending the particles to form homogeneous slurry do not solve the problem of initially entraining/inserting abrasives into the system. The Al_2O_3 can be inserted continuously or in batches as previously explained. If a batch system is chosen, these mixing methods could be possible. If a continuous abrasive feed system is desired, it is still necessary to determine how and where to insert the abrasive particles.

3.5.2 Vibration Mixing

It may be possible to utilize vibration to suspend abrasive particles. This may be achieved by mechanically shaking the vessel, using piezoelectric motors to transport the particles, or by using acoustic waves to create a mixing action. From previous experience, it is known that vibration at certain frequencies may cause the particles to settle and become more compact, making it even more difficult to re-suspend the abrasive material. It is therefore important to employ a design that would achieve the desired function with Al_2O_3 abrasive particles. There are several designs that could be considered:

Magnetic Shaft

As explained in the electromagnetic section, it might be beneficial to use magnets to avoid having a mechanical stirring device pass through the high pressure vessel. Similar to hair clippers or a Sonicare® toothbrush, a magnet could be placed in the vessel. An electric winding would be located just outside the vessel, around the internal magnets and would produce an alternating current (A/C). This would force the magnet to translate back-and-forth, resulting in a vibrating motion. A key element of this concept would be to design a mechanism that could be attached to the magnet inside the pressure vessel which would stir or mix the abrasive in the water.

It is proposed that it would be possible to design such a mechanism that would produce a swirling motion in the vessel, which would mix and suspend the particles. Hair clippers have the advantage of producing relatively high forces with no actual physical shaft (like for a motor) contacting the mechanism. The forces are created through electrical current and magnetic field interactions. Noise could be a possible negative consequence. It is anticipated that much lower forces than those used for hair clippers would be needed, which could also decrease the noise levels and intensity. If this method is pursued, further investigation of the noise levels would need to be considered.

Piezoelectric Motors

Another possible design may employ piezoelectric motors. Some of these motors are designed to carry/transport objects at the micro and nano level. It is suggested that an array of piezoelectric motors on a board could act as escalating stairs for the abrasives. A general design is demonstrated in Figure 3.8. These motors are capable of moving objects at great speeds. It is hypothesized that they could generate enough energy to the abrasive particles to virtually mix them into the water and keep the slurry continually stirred.

The aluminum oxide would be stored at the bottom of the pressure vessel. When in process, the abrasives would begin to travel up the board which would be arrayed with piezoelectric motors. Its transfer action would be very similar to a vibratory bowl feeder in a manufacturing assembly line. With enough momentum the particles would mix into the water. It is hypothesized that with enough strategically placed motors, a whirlpool action may be produced, which would keep the abrasives in a suspended state. With the appropriate final design, the slurry would be homogeneous and the slurry could be pressurized and forced through a hose for transport to the handpiece. Piezoelectric motors can be very small, with some motors even at the nano size.

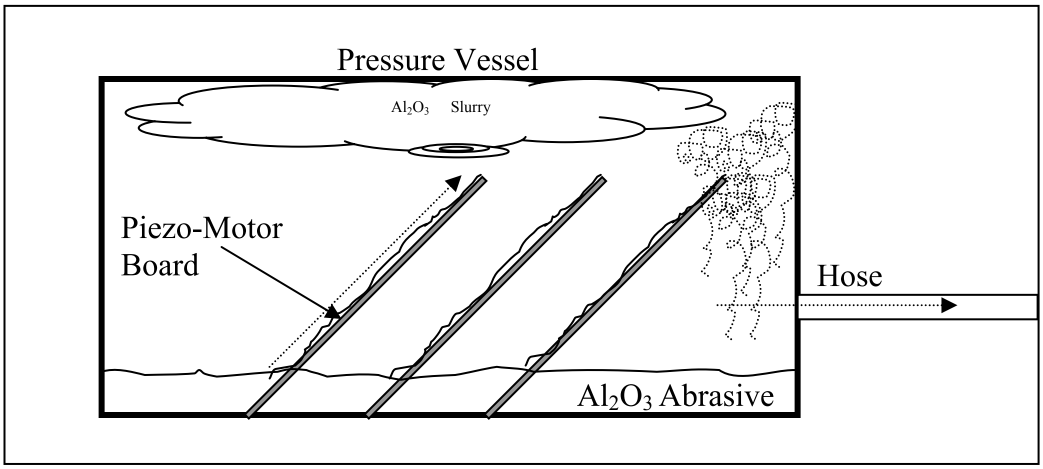

Figure 3.8 Piezoelectric-motor boards

This method has its obvious disadvantages. Finding the right motors for this application and water jet parameters would be entering uncharted areas of any known research. A general literature search for waterproof piezoelectric motors provided no results. Also, it is only hypothesized that a stirring and suspending motion could be achieved with this type of motor. It is assumed that the abrasives would have to be inserted directly into the vessel in batches, which could be stored in pre-manufactured cartridges. Though the method seems novel, the design would probably be rather complicated and contains many unknowns and uncertainties.

3.5.3 Ultrasonic Characteristics

It has also been suggested that ultrasonic waves may produce sufficient energy to suspend abrasive particles. Ultrasonic sound waves can use frequencies that are above human hearing, which is above 20 kHz. The most used frequencies for ultrasonic's in water are from 20 kHz to 1 MHz and also 1 MHz to 100 MHz, which is referred to as the megasonics range. In this range, the sound velocity is about 1500 m/s with wavelengths on the order of 30 μm to 3 mm.

Ultrasonic processing is the application of high frequency sound to liquids, which causes the fluid to flow. The intense waves produce a mixing effect through physical reactions in the water. When the wave intensity is increased sufficiently, cavitation might also be produced. Ultrasound is currently used in areas such as chemical mixing, in hospitals for removing kidney stones and treating cartilage, emulsifying cosmetics and foods, welding plastics, cutting alloys, and even cleaning jewelry (Cheeke 2002).

Ultrasonic waves have the ability to accelerate reactions, improve the flotation of minerals through benefaction, disperse fine particles, and homogenize fine particles (Berliner 2006). Some research performed as part of this study suggests that ultrasonic waves may be utilized to stir and suspend particles such as aluminum oxide in water.

Dr. Ronald Feke of the Chemical Engineering department at Case Western University has performed research that involves the suspension of micron and sub-micron particles using this approach (Feke 2006). He anticipates that a frequency that is below or above cavitation frequencies might be utilized to make the abrasives "dance" and become suspended in a water solution without destroying the particles. Several others have performed research in various areas of ultrasonic mixing and have provided helpful insight (Hamilton 2006, Holt 2006, Busnaina 2006).

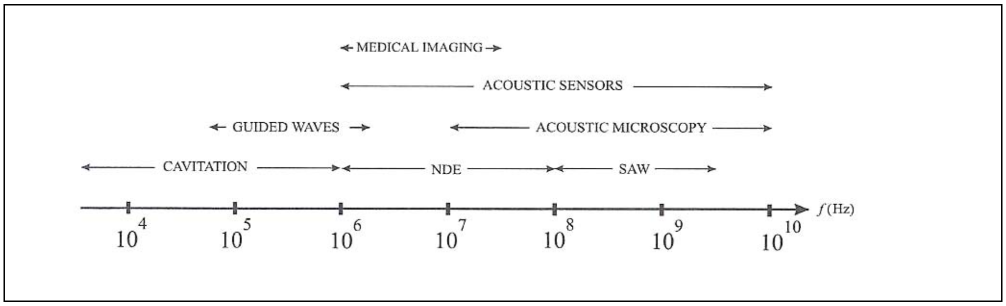

Figure 3.9 Most common frequency ranges for ultrasonic processes

Ultrasonic Theory

The source of an ultrasonic wave is a plane surface that typically oscillates at a single frequency, which produces a longitudinal wave. The physical oscillation transmits vibrational energy which propagates through a given fluid. Since the oscillation is produced in a finite period of time and follows a sinusoidal function, pressure and velocity will be different at each finite distance along the axis perpendicular to the source. At room temperature and in water, the following functions hold (Ahmed 1994):

- Angular frequency = $2\pi f$ where f is the frequency in Hz
- Wave Period $T = 1/f$
- Wave Length $\lambda = c\,T$
- Absorption Coefficient, α (Loss of Energy in a Medium)

When considering ultrasonic's, it is important to know what reaction forces are desired. There are several phenomena that are produced by ultrasonic waves: cavitation, streaming (quartz wind), and levitation. Each of these phenomena will be discussed and then related to the suspension of aluminum oxide in a low pressure water jet for this research.

Cavitation

The production of vacuous cavities in a liquid medium due to extreme pressure changes is called cavitation. It is most notorious for occurring on areas such as found around a ship's propeller. Though less commonly known, it has also been studied for use in ultrasonic applications. The steps for the development of a cavitation bubble are listed (Busnaina *et al* 1994, Willard 1953):

1. There exists a pre-initiation condition that requires the presence of weak spots or "nuclei" in the fluid. The nuclei must be in the vicinity of the focal region of the applied ultrasonic wave. The number of weak spots present will influence the repetition rate of the initiation phase of the cavitation bubble.

2. The initiation phase will occur wherever a weak nucleus enters the intense core of the sonic field. Here the amplitude pressure increases from about zero at the edge of the core to about seventy atmospheres near the center of the core. The nuclei volume oscillates with the applied forces in a sinusoidal manner and gradually

grows larger. Eventually, depending on the frequency and amplitude of the wave, the catastrophic phase begins.

Approximations have been developed through experimental data which help determine when cavitation generally begins. The mechanical index (MI) is defined as the peak negative pressure (P^-) in MPa divided by the square root of frequency in MHz:

$$MI = \frac{P^- / MPa}{\sqrt{f / MHz}} \tag{6}$$

If the $MI \geq 3.0$, then cavitation will be present. The peak negative pressure for a sine wave of ultrasound is the pressure amplitude of the sine wave. In Doppler ultrasound and other imaging modes, the waves are not symmetrical sine waves, so it is the value of the pressure drop (below atmospheric) in the wave. For a sine wave, the peak negative pressure is related to the average intensity by:

$$I = \frac{(P^-)^2}{2Z} \quad \text{W/m}^2 \tag{7}$$

where Z is the acoustic impedance (1.5 x 10^6 kg/m2/s Rayls for water). The intensity value, I, is the power per unit area (W/m^2) and is usually designed by the manufacture of the sonicating machine. Therefore, the equation could be solved for P^- and then plugged into equation 6. If a larger diameter ultrasound generator is used, such as a sonicating tip, then the intensity will be decreased proportionally.

3. The catastrophic phase begins only after the initiation phase in completed. True cavitation occurs if the pressure on the nuclei bubble is reduced to the vapor pressure. This occurrence is analogous to tensile failure in solids. When the tensile strength of a liquid is exceeded, cavities form. When a high enough pressure amplitude is reached, the nucleus becomes unstable and grows into a vapor-filled bubble or transient cavity.

4. The collapse of the nucleus is rapid and radiates a shock wave with an amplitude exceeding the amplitude of the driving sonic waves. The radiated spherical shock waves, combined with the input ultrasonic waves, produces sufficient magnitude to open up many other micro-cavities in the contiguous water volume. These secondary cavities are minute and indistinguishable, but they are numerous and very close together, which gives the cloud-like appearance during the cavitation bursts. This effect occurs as the nucleus is being transported by the streaming effect of the ultrasonic waves until the forces of the ultrasonic waves are no longer sufficient to create the cavitation.

5. The shock waves produced by the collapsing bubbles create extremely high pressures and temperatures that permeate through the water volume. These extreme pressures result in a rapid mixing and stirring of the water.

Figure 3.10 represents the induced flow caused by the collapse of a nucleus. The velocity of the flow increases with the proximity of the contours, which approaches its maximum along the core. This flow produces a streaming affect that is rapid and intense.

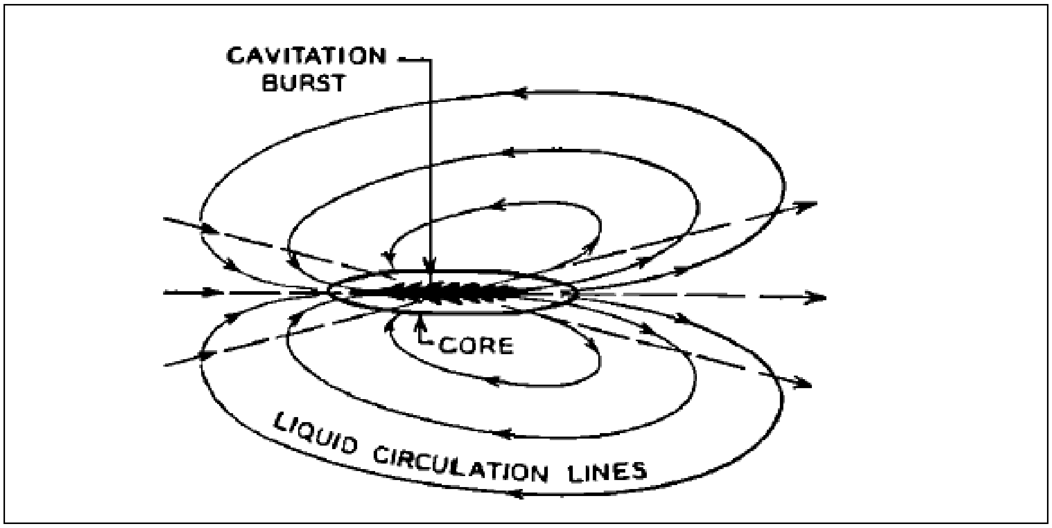

Figure 3.10 Radiation-pressure induced flow and circulation (Willard 1953)

It has been discussed whether or not the extreme effects of the cavitation shock waves would be too detrimental to the aluminum oxide particles. Also, the high temperatures produced by the cavitation may create too much heat in the water and, consequently, for the patient. As stated by G. W. Willard (1953):

The mathematical treatment of cavity growth and collapse is extremely complicated due to the many factors involved: surface tension, viscosity, liquid compressibility, thermal transfers, gas and vapor transfer and diffusion, and time variations of the ambient pressure surrounding the cavities. Solution of formulas which involve too many factors become tedious and hopeless. For this reason experimental studies have often been of great help in determining which of the many factors involved are of importance and which may be neglected.

If this method is considered for further investigation, experiments would need to be performed to determine whether ultrasonic cavitation may be suitable for the application of this research.

Acoustic Streaming

As ultrasound propagates through a fluid, flow is generated along the acoustic axis in the medium. This is referred to as acoustic streaming. This flow is created by the radiation pressure gradient due to the absorption of the acoustic wave into the medium (attenuation). The velocity generally increases with higher frequencies because of the increased absorption of the waves. It should be noted that streaming occurs at virtually all frequencies; however, cavitation can be prevented if frequencies of 1 MHz and above are used. This avoids the destructive affect on the particles due to the shock waves. This phenomenon has already been utilized in such areas as chemical mixing (Murata *et al.* 1997). This has the advantage of stirring the solution without any mechanical stirrer.

It has been shown that for a plane sound beam in a tube, the streaming velocity, ν, is proportional to the amplitude absorption coefficient, α, of the fluid and inversely proportional to its kinematic viscosity, υ, as shown below in Equation 8:

$$\nu = \frac{\alpha \ell^2 \mathrm{I}}{c\upsilon} G \quad \textbf{(8)}$$

where, I is the intensity in the beam and ℓ is the beam diameter, c is the velocity of sound in the fluid medium, and G is a geometric factor which depends of the size of the acoustic beam relative to the tube (Zauhar *et al* 1998).

A study on the generation of enhanced acoustic streaming has been performed by Murata (1997). A piezoelectric ceramic transducer with a diameter of 15 mm was used at 1.1 MHz. Both continuous and bust (pulse) waves were generated. A cell (transparent glass cylinder) with a height and diameter of 150 mm and 70 mm respectively was used. The setup is illustrated in Figure 3.11.

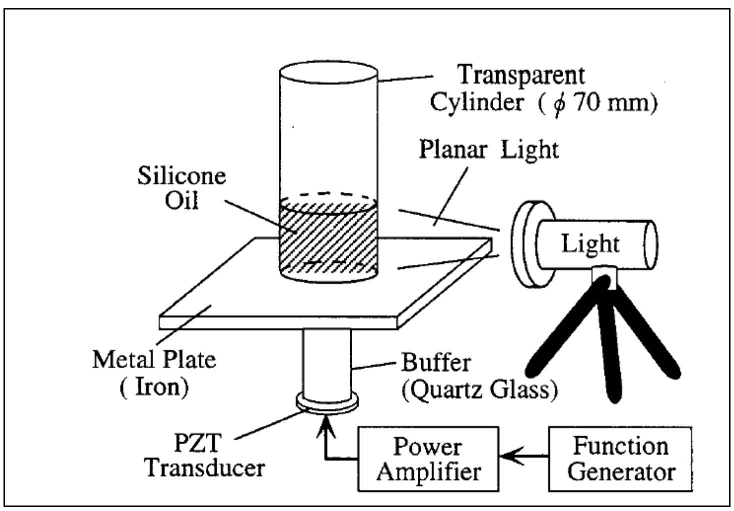

Figure 3.11 Experimental system for visualizing acoustic streaming (Murata *et al* 1997).

The acoustic streaming was allowed to achieve steady state and then *pictures* were taken. The streaming velocities along the acoustic axis were measured by recording the high density polyethylene particle movements with a video camera. The results are represented in Figure 3.12. The figure shows three pictures and their related sketches. The particle flow in photo (a) is produced with no radiation pressure. The particle flow in photo (b) is produced by continuous ultrasound, while the particle flow in (c) is produced by ultrasonic tonal bursts. It is obvious in the photo and sketches that the tone bursts produced greater acoustic streaming and particle mixing.

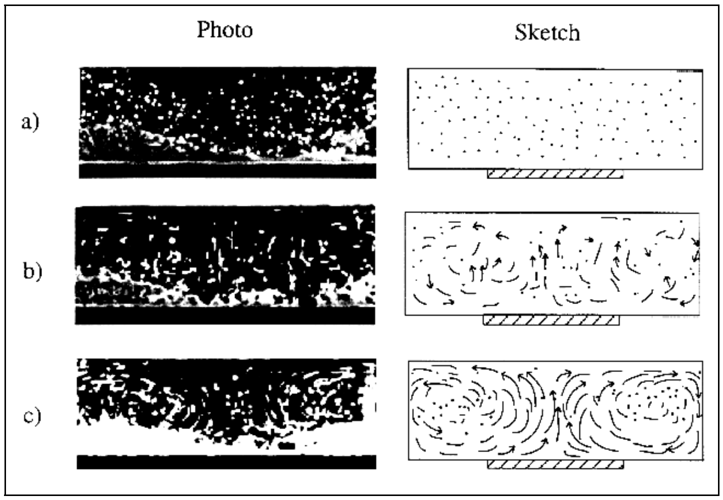

Figure 3.12 Acoustic streaming (a) no radiation pressure (b) under continuous ultrasound (c) under tone bursts (Murata *et al* 1997)

There are many theories for calculating steady streaming which are associated with sound fields (Nyborg 1953, Nowicki *et al* 1997, Hill *et al* 2004, Brereton & Bruno 1994). Most of the calculations are "tedious" and are usually difficult to apply to each individual application. After much review and conversation with researchers in the ultrasonic cavitation and streaming field, it became obvious that a series of experiments specific to the low pressure water jet would need to be performed to determine whether or not this approach might be a viable concept for entraining the Al_2O_3 particles in water for a dental application.

Acoustic Levitation

Levitation of particles may be achieved by producing a standing wave. The levitation of the particles is the net balance between an acoustic force and gravity (or gravitation field). This is accomplished by producing "radiation forces" that drive the particles towards pressure nodes or antinodes. An equation for radiation force, F_r, on a spherical particle of volume V, density ρ_p, and compressibility β_p, suspended in a fluid of density ρ_f, and compressibility β_f, is given by (Coakly 1997):

$$F_r = \left(\frac{\pi P_o^2 V \beta_f}{2\pi} \right) \Phi(\beta, \rho) \sin\left(\frac{4\rho_p}{\lambda} z \right) \quad \textbf{(9)}$$

where P_o is the acoustic pressure amplitude of the acoustic field, λ is the wavelength in the suspending fluid and z is the distance from a pressure node. The acoustic contrast factor $\Phi(\beta, \rho)$ is given by:

$$\Phi(\beta, \rho) = \frac{5\rho_p - 2\rho_f}{2\rho_p + \rho_f} - \frac{\beta_p}{\beta_f} \quad \textbf{(10)}$$

Most particles have a positive contrast factor and tend to be driven towards the pressure nodal plane. It is important to remember that streaming would still have an effect and would redistribute the particles to some extent. The standing wave is induced by constructing a fluid cavity that is a half-wavelength in depth. The result is a classic rigid-body boundary model with the maximum pressure amplitude at the boundaries which concentrates particles at the center of the fluid. Recent developments have allowed designs to have nodes at other positions in the fluid. This technique has been widely utilized for forcing particles into a specific area as demonstrated in Figure 3.13.

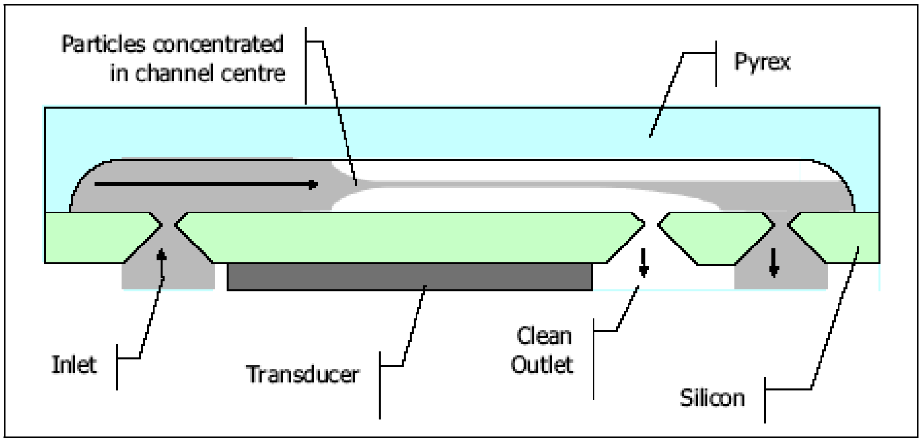

Figure 3.13 Representation of a micro-fluidic filter (Hill *et al* 2004)

For this situation, the particles needed to be separated from the fluid. To achieve separation, a standing wave was generated which forces the particles to a nodal plane. This is the opposite effect that this research desires; however, the ability to suspend the particles in a particular area may have some benefits that could be considered. It is anticipated that mixing by cavitation or streaming will be more advantageous for the low pressure abrasive jet design than levitation.

3.5.4 Rotating Pressure Vessel

Another possible method to mix the abrasives into a slurry mixture is by rotating the entire vessel. This may be accomplished by using a motor or a simple wind-up mechanism.

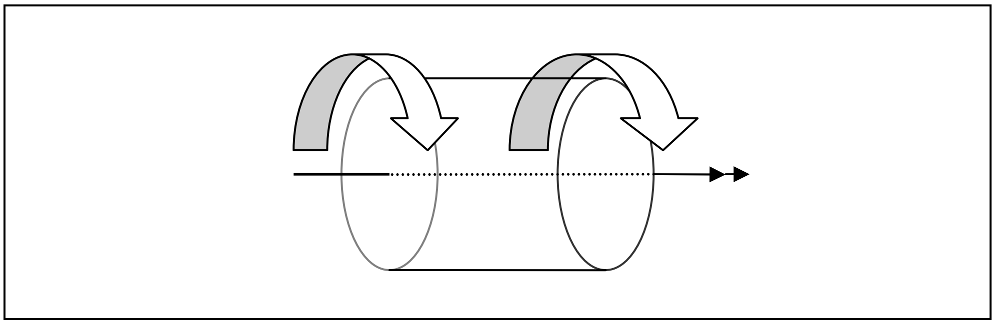

Figure 3.14 Rotating Mixing Barrel

The basic concept is represented in Figure 3.14. Simple experiments show that successful mixing occurs if the vessel is rotated at the appropriate speed. If it rotates too quickly, then the particles stay forced against the wall of the vessel due to centrifugal acceleration. If it rotates too slowly, then the abrasives remain at the bottom of the vessel and insufficient mixing occurs. This design may be more feasibly incorporated with the batch method rather than a continuous feed system.

The rotating vessel concept does present a few design challenges. If the vessel is rotating, then anything connected to it must rotate or have a connection that swivels. For example, the input pressure hose would have to have a high pressure fitting when connected to the vessel that could rotate, such as a rotary union. A more critical component would be the hose/nozzle. It is presumed that a rotating tube or nozzle near the handpiece would be unacceptable. The dentist would need something to grasp and to direct the water jet stream towards the target area.

A possible solution could be a hose that rotates inside another hose so the dentist could grasp a non-moving part. However, this would add to an already complicated system. This design could be utilized in the main dental unit or in a smaller batch-size version at the handpiece.

3.5.5 Mixing Recirculation Pump

There are several pumping methods available. A pump could be located inside or outside of the pressure vessel. However, it has been determined that submersible pumps that could withstand the pressures that are expected to be used for this application are expensive. A pump's design would have many of the same disadvantages as using a motor, such as requiring components to enter the pressurized vessel.

One alternative solution may, once again, be to use magnets. Many of the pumps used for fish aquariums use shafts with magnets to generate rotation and, as a result, a pumping action. Fish pumps use an alternating current winding, which is sealed inside a plastic casing that surrounds the shaft with magnets. Through this approach, the electric windings would always be dry and protected, but would still be able to produce an alternating magnetic field to turn the shaft on the other side of the plastic wall.

There are many different types of high pressure pumps; however, none of them are necessarily designed to handle abrasive particle flows. As discussed in chapter two, pumping abrasives and slurries cause extreme wear on component parts of pumps. *Depco Pumps* highly recommends that a pump be avoided altogether for the parameters of this water jet application (Depco Pumps 2006). It was made clear that special silicon carbide (or other hard non-corrosive seals) would be required due to the high pressures. In order for these seals to function properly, they would also have to be pressurized on both sides. It was explained that this design would become expensive and that the seals would require significant long-term maintenance.

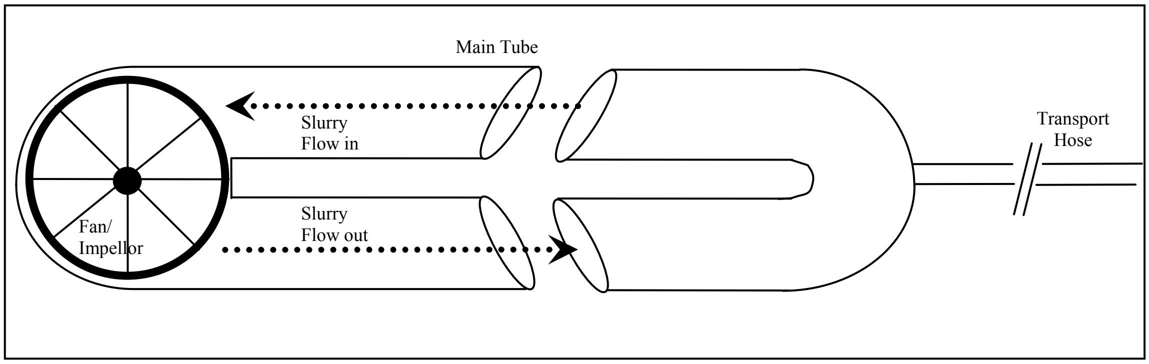

Figure 3.15 Schematic of a recirculation slurry method

It is feasible that a pump-action method might be more suitable for the application of this research. The initial generated concept is depicted in Figure 3.15. After speaking with a mechanical design engineer at *Depco Pumps*, it is believed that this design may be considered more of a mixer that has some "pumping" action. It was suggested that a real pump be avoided because of the tight seals and tolerances that would be required. Alternatively, mixers have more robust seals that may be less problematic with regards to abrasive slurries.

For the method represented in Figure 3.15, a shaft would pass through the high pressure vessel and connect to the hub of an impellor. This design would push the water out on one side of the main tube and pull it back in on the other side. There are no tight tolerances which would help avoid abrasive wear or erosion. The pressure in this system would come from the compressed air or nitrogen supply and not the re-circulating device. This mixer design with a "circulation" or "pumping-action" would only be re-circulating the abrasive slurry at a speed necessary to keep the abrasive particles homogeneously mixed and suspended. It is anticipated that abrasives and water could be added into the tank area near the mixing fan in batches. The tubes that the slurry would travel through could be designed for the slurry to flow in any direction. At the end of the main recirculation tube, a transport hose would be attached to continue transport of the slurry to the patient. This transport hose would have the orifice nozzle at the end, which could be disposable.

This method has several disadvantages that need to be considered. If the slurry flow is circulated in a continuous circle, then the abrasives would be forced to the outside of the tube and against the wall due to centrifugal forces. To avoid this dilemma, a group of “inner-tubes” could be placed inside the main tube that could be placed in a crisscrossed manner and which could continuously change direction, as shown in Figure 3.16. By changing the direction and placement the inner-tubes the abrasive particles would also be forced to change directions inside of the tube. Consequently, the irregular flow would produce a mixing effect that might create the homogeneous slurry desired.

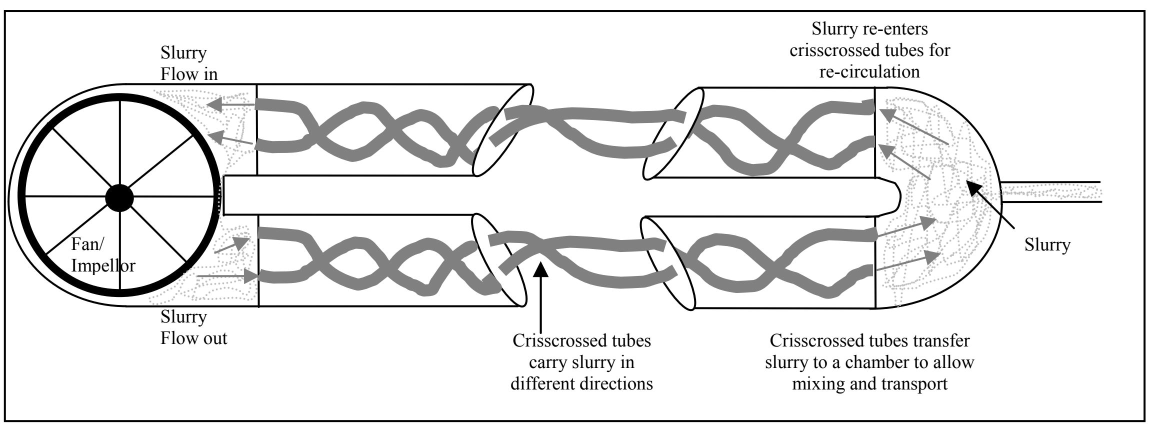

Figure 3.16 Re-circulation pump with inner-tubes to assist mixing

Another disadvantage with the recirculation method is the fact that the circulation would only occur in the main tube where the flow is continuous. Eventually, the slurry would be directed into the transport hose which is diverted towards the nozzle orifice (and patient). There is no mechanism, except the flow momentum of the exiting slurry, which would keep the particles suspended.

As explained before, if a dentist stops the cutting process for any extended period of time, the abrasive particles would settle in the transport hose, even though the slurry in the recirculation tube would continue to recirculate. If the particles settled in the transport hose, there would be no mechanism except the exiting flow to re-accelerate the settled abrasive particles. This would result in a non-homogeneous and inefficient cutting water jet.

One possible solution could be to run the recirculation tube as close to the patient as possible. This would allow the transport hose to be shorter in length, which would result in less slurry needing to be suspended. The transport tube could have a relatively small diameter so that the velocity of the water stream is higher. A second option might be the use of a polymer. The suspension characteristics of polymerized water might prevent the abrasive material from settling for extended periods of time.

After reviewing pumps that are on the market and speaking with professionals in the pump industry, it is clear that there are no current pumps made specifically for this slurry scenario. Using a recirculation method may, however, offer a viable solution to the dental entrainment and slurry application for BYU's anticipated low pressure water jet.

3.5.6 Bubble Mixing System

Using air to mix a variety of substances has been utilized for years. It has been used in the sewer-treatment industry to mix waste and chemicals, which increases the decomposition rate. A company named Pulsair ™ Systems Inc. has developed a method of using pulsed air bubbles to create a mixing action for petroleum, winemaking, paint and coatings, foods, chemicals, and paper pulp. The system is illustrated in Figure 3.17. The principle of bubble mixing is straightforward. Pulses of air are released at the bottom of a water-filled tank causing bubbles to form, which begin to rise to the top of the tank due to buoyant forces. The air-water interaction forces, created by the rising bubbles, displace and carry the abrasive particles upwards in the center of the vessel.

As the abrasives reach the top and the air bubble disperses, they begin to fall down through the water along the sides of the vessel and return to the bottom, where the process is repeated. The mixing occurs throughout the process due to the fluid dynamic interactions. Figure 3.17 demonstrates this process at a macro bubble level. It is suggested that many small bubbles would be created and that a vertical mixing action would be produced by displacing both the abrasive particles and the water.

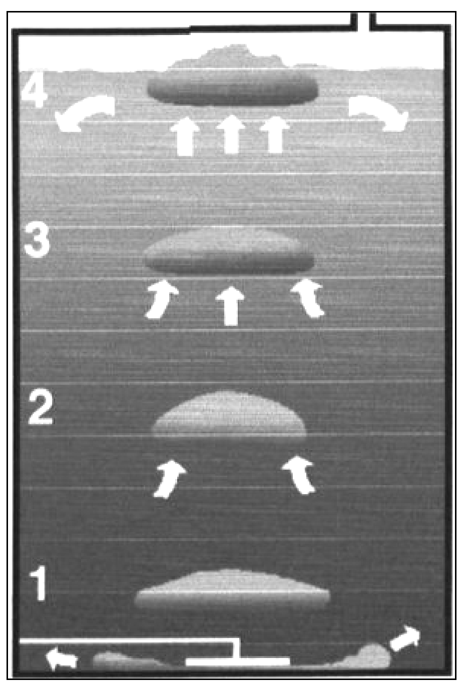

Figure 3.17 Mixing abrasives by pulse/bubbles of air (Pulsair ™)

In order to utilize this particular system design in a pressurized vessel, one of two options could be employed. The amount of air that is used to create the bubbles would need to either be exhausted or recycled.

The exhaust design would allow the air to be released after it is used. In the schematic above, a pressure valve would be place in the exiting exhaust pipe. The valve would be set to open at a specific pressure (500 psi). The air would enter the system from a compressed air or nitrogen tank, perform its suspension and mixing cycle, and then exhaust out of the valve. The advantage of this design is that there are very few mechanical moving parts. The disadvantage is the fact that a constant supply of air would be needed to create the bubbles. The air or nitrogen gas would only be used once.

The Recycle design would simply reuse the bubbled air continuously. This may be achieved by inserting a pump inside the vessel system. The pump would take the air that has risen to the top of the tank and cycle it back down to the bottom. The location of the pump would be designed such that it only needed to pump air and not water. In order for this concept to be possible, the air would have to accumulate to a single area (the top of the pressure vessel). This would decrease pump costs and maintenance substantially because it would not be passing abrasive particles through the pump. The disadvantage of this design is the fact that it would require more components and that wires to power the pump would need to enter the pressurized vessel at some location.

Chapter 2 discussed some of the negative consequences of having air entrained in the water stream. The air is compressed as it is pressurized and as it leaves the exit nozzle it begins to expand. The transport hose would have to be connected to the system in a location that would not allow the air to be transported with the slurry. Also, this method of suspension would have no ability to maintain the slurry suspended in the transport hose.

3.5.7 Abrasive Ice Cube

One of the most prominent problems for this low pressure abrasive jet is the difficulty in keeping the abrasives in a suspended and homogeneous state because of the density differences of the AL_2O_3 and H_2O as described in Chapter 1. It may be feasible to freeze the abrasives into a piece of ice in any desired shape. This method provides exact concentration and suspension of the abrasives that would be secured until it is called (signaled) for. A simple heating element would then be pressed up against the ice. As the water jet signal is triggered, the element would melt the ice and the melted slurry mixture would be forced by compressed air to the handpiece to be used immediately. The rate of melting the abrasive-filled ice could be easily adjusted by simply passing more current through the wire mesh to increase the heat. There are some obvious disadvantages.

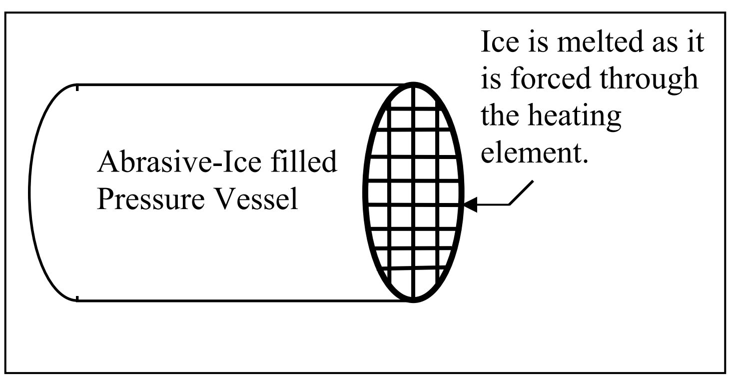

Figure 3.18 Abrasive filled ice with heating element.

Again, if this method is performed at the main unit, then settling may occur in the transport hose. Also, it may be difficult to get the water to a proper temperature to be able to safely contact different parts of the mouth. The system would have to be well-insulated for longer sessions. If the office ambient temperature were warm, the ice might melt before it is utilized. It is also wise to avoid having any type of electrical current passing through water that would also come in direct contact with a patient.

3.5.8 Pulsing Bladder

A pulsing bladder may be utilized to suspend abrasive particles, which would be similar to squeezing a compliant bag, such as a water balloon. It is more easily visualized by imagining grasping a balloon with both hands. To achieve a continuous flow, one hand would squeeze half the balloon, forcing the fluid to the other half. When the fluid is finished transferring to one side, the other hand would begin to squeeze, forcing the fluid in a continuous back-and-forth motion. This design is represented in Figure 3.19. If the cross-sectional area in the center of the balloon is smaller, the velocity and turbulence is increased greatly as the slurry passes through that point. This would create a mixing action, keeping the abrasive particles suspended.

This offers a possible solution to achieve a homogeneous slurry mixture, but it still needs a method to perform the squeezing action. It has an obvious difficulty because the entire bladder will be pressurized, inside and/or out, up to 500 psi. It may be feasible to have the entire bladder enclosed in a hydraulic fluid that would be pressurized by a pump or a piston. To understand this concept, follow the arrows in the figure. Starting at the bottom of the schematic, a piston is pushed to the left. This motion both pulls fluid in from the right side of the hydraulic reservoir and pushes hydraulic fluid into the left side of the reservoir. As the piston cycles back and forth, the transferring of hydraulic fluid from one side of the reservoir to the other would create a pulsing action with the compliant bladder.

The bladder design has the disadvantage of requiring a more advanced set-up; however, hydraulics are well understood and they are already designed for much higher pressures than the proposed low pressure dental water jet application. The abrasive material and water would have to be added manually in batch sizes. This type of design might require a flush-cleaning system to clean out the bladder over time. Since the system is enclosed, left over slurry may result in build-up which could lead to a clogged nozzle. The nozzle for the water jet may be placed anywhere, but it appears it would be most logically connected to the tube between the bladders. This would help minimize clogging, since it is unlikely that particles would settle in the smaller high velocity region of this device.

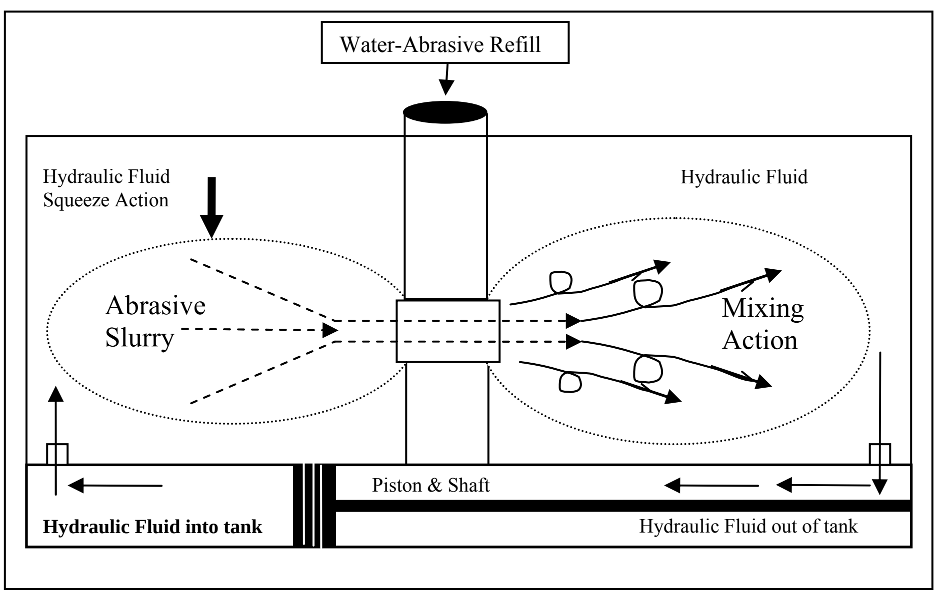

Figure 3.19 Abrasive slurry mixed by a pulsing action on a bladder

3.5.9 Magnetic Stirrer

It is common to stir chemicals and fluids for extended periods of time. One method to achieve a constant stirring action without introducing any contaminating matter, complicated mechanism, or costing large amounts of money is through the application of magnetic fields. For example, if a solution is located in a non-ferrous beaker and the solution needs to be continuously mixed, it could be set on a magnetic table. Several magnetic or ferrous rods (or other shapes) would be inserted in the solution inside the beaker. The magnetic table creates a moving magnetic field causing the stirrer inside the beaker to rotate. This motion stirs the solution, keeping the abrasive particles suspended and homogeneous.

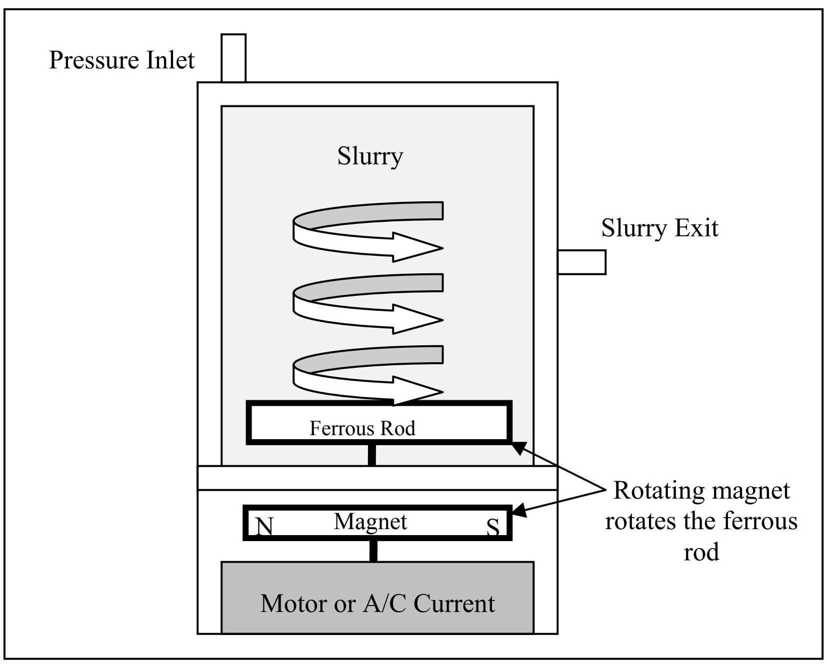

Figure 3.20 Rotating magnet rod forces the ferrous rod to rotate

This method of mixing could be employed in a low pressure water jet to keep the Al_2O_3 mixed and suspended as illustrated in Figure 3.20. It is also presumed to be easy to employ and relatively inexpensive. There are many possible designs that could be used to implement this concept. A weakness of this method is the fact that magnets inherently interact with ferrous materials. Consequently, the materials chosen to manufacture the dental unit would have to correlate with the magnetic design. This may or may not be a serious limitation. If this concept were chosen for further investigation, a more detailed design would need to be pursued.

3.6 Selection Methods

In order to methodically rate the generated methods or concepts described here in Chapter 3, which may or may not be viable solutions to entrain and suspend abrasives in a low pressure dental water jet, both concept screening and scoring processes will be employed (Ulrich 2000). This design approach will provide a means of ranking each concept from the highest (best) score to the lowest (worst) score. After ranking the concepts, they can be narrowed down to the most promising methods for this application. It should be clearly noted that the scoring of each concept using the proposed criteria is based on engineering judgment and advisor counsel, cultivated through a significant amount of literature review.

Chapter 3 of this thesis presented a number of possible concepts with each of their noted advantages and disadvantages. It also has set forth the functional specifications, delimitations and necessary characteristics for a low pressure dental water jet. The functional specifications will be used to establish the *selection criteria* for the process selection screening and scoring matrices. A list of these criteria, developed from the functional specifications, is noted below:

- Overall Functionality
- Cost
- Reliability
- Performance (Homogeneity)
- Performance (Entrainment)
- Performance (Water jet stream)
- Safety
- External energy
- Manufacturability
- Placement Ability (Any location)
- Visibility for Dentist
- Noise

Each of the concepts will be given a score for each of the selection criteria. The concept that receives the highest summed score will be considered the most viable concept to entrain and suspend the abrasives in a low pressure dental water jet system. This process will be explained in detail and reported in Chapter 4.

3.7 Review of Research Methodology

In order to methodically generate, discuss, and narrow down the concepts that have been presented as possible entrainment and suspension methods for a low pressure water jet, a *Product and Design Process* has been employed. In this chapter, the basic water jet design was broken down into its most basic components and sub-problems.

A list of concepts suggested by the author was presented and their potential advantages and disadvantages were discussed and summarized. The next step in the design process is to narrow down the concepts to the most viable methods for the low pressure water jet system by employing screening and scoring processes, which will be presented in Chapter 4.

4 Concept Selection

This chapter will perform screening and scoring processes, which will be used to narrow down the suggested generated concepts presented in Chapter 3. A summary table of the concepts will be included in order to simplify and justify the score given to each concept for every selection criterion. The concepts that receive the highest scores will be considered further. After the list of concepts is narrowed down to a select few, some tests will be performed to validate their entrainment and suspension abilities. The results will be reported in Chapter 5.

4.1 Concept Summary

In order to help substantiate the screening scores of the selection criteria for each of the concepts, a table has been prepared which summarizes many of the advantages and disadvantages for each of the generated concepts. It is suggested that the summary for each of the concepts and their diagrams found in Chapter 3 be reviewed to help grasp a better understanding of the decisions made during the selection process. As previously stated, the scores attributed to each generated concept or method is based on the literature review, concept generation process, and the authors engineering judgment.

Table 3 Summary table of the possible advantages and disadvantages of the generated concepts

Concept	Advantages	Disadvantages
Post-Orifice Entrainment (Hashish)	• Adds abrasives after the water jet exits the orifice. • Avoids pump and internal system wear	• Low pressure velocities too slow to create sufficient low pressure zone to pull in abrasive particles • Abrasives damage mixing/focusing tube • Manufacturing and components likely to be expensive
Direct Pumping	• Abrasives can be added before the water is pressurized	• Abrasives have proven to be detrimental to the pump • Requires a polymer additive if system is ever at rest to prevent particle settling
Traditional DIAjet System (Bypass Principle)	• Does not require a secondary external force to entrain and suspend particles (in high pressure systems) • The design and experience is available and has been improved upon for years (since early 1980's) • Appears to be safe • Believed to not create any noise	• Requires higher velocities and slow rates to create the slurry and suspend it sufficiently • Requires complex design to create the appropriate slurry inside the pressure vessel • Requires several valves and regulators to keep system at the proper pressures • The slurry becomes less concentrated with abrasive materials during the process • Miniaturization may be difficult
Indirect Method w/Polymer	• Avoids passing abrasives through the pump • Does not require secondary energy source • Polymer suspends the slurry homogeneously and consistently • Can be easily miniaturized and pre-manufactured in a disposable cartridge	• Requires a batch system design • Must use a separator or a cartridge to prevent water or air from mixing with the slurry • Polymer obscures worksite for dentist • Tested xanthan may decrease cutting ability (unknown)
Mechanical Stirring	• Has several potential design possibilities • High mechanical and mixing power easily suspend the abrasive particles • Virtually instant mixing and slurry suspension • May possibly be miniaturized	• Requires secondary energy source to mix and suspend particles • If motor is places outside of the pressure vessel, a high pressure rotating seal is required • If the motor is placed inside the pressure vessel, durability and high prices become an issue • If placed in the main unit, settling will still occur in the transport hose • Extra components become expensive and possibly unreliable

Table 3 continued

Vibration (magnetic clippers)	• Strong vibrational forces • Magnets allow the electrical components to be located outside the pressure vessel • No physical parts would need to cross through the vessel • Components common and possibly inexpensive • Believed to have sufficiently strong forces to entrain	• The vibrational forces may be unsuitable for dentist • May produce unwanted sound • Requires secondary energy source • Design may be difficult to efficiently manufacture • Homogeneity of the slurry unknown
Vibration (piezoelectric motors)	• Small and relatively efficient with translational forces • Several design possibilities • May be miniaturized	• Would have to be water proofed • Actual mixing abilities with abrasives is unknown • May be noisy • May produce significant and intolerable vibrational forces • Requires secondary energy source
Ultrasonic's: Cavitation, Streaming, and Levitation	• High frequency sound waves create strong stirring and mixing reactions and generate a homogeneous slurry • Waves are above audible region • Cavitation separates individual particles • Somewhat understood technology	• Produced waves are not audible but the piezoelectric motors produce high pitched shrills • Cavitation may destroy particles • Cavitation increases temperature of the mixture • Requires secondary energy source • Equipment tested was large • Levitation focuses abrasives to a point (node) rather that homogenizing
Rotation Pressure Vessel	• Principle is simple • No mechanical parts pass through the vessel while under pressure	• The input and output hoses would have to be connected to seals that rotate/swivels • The vessel would be in motion • Mixing effect does not appear to create the homogeneous slurry desired which will affect the cutting ability of the water jet stream
Recirculation Pump	• Circulates slurry without a pump, avoiding severe wear damage • Can be designed to have slurry flow from the main unit all the way to the handpiece (hypothetically) • Relatively inexpensive	• Requires a mechanical shaft to pass through the pressure vessel • True suspension characteristics unknown • Erosion of impellor still a possible problem • Requires secondary energy source

Table 3 continued

Bubble Mixing	• Principle is simple and likely to be safe • Air is readily available • Deemed easy to manufacture	• Air entrainment may decrease efficiency of the water jet • System must stay in the general upright position to produce homogeneous entrainment • Requires an air pump or exhaust • Bubbling may produce undesired noise
Abrasive Ice Cube	• Particles pre-entrained and homogeneously mixed • Likely to not create a noise issue	• Requires elaborate design • Heating element may not be safe • Extreme temperatures may cause patient discomfort • Warm ambient temperatures may promote premature ice melting • Likely to produce inconsistent melting • If not performed near exit nozzle, abrasives may settle when jet stream is paused • Requires secondary energy source
Pulsing Bladder	• Good mixing potential • Components and principles are generally well understood (hydraulics)	• Complicated design and parts which would likely be unreliable • Requires seals and hydraulic fluids • Volume size change during use will affect pressures • Likely too complex to miniaturize • Difficult to clean out • Pulsing may be noisy
Magnetic Stirrer	• Design and principle is simple • Lower costs in comparison to other generated concepts • Magnetic forces more than sufficiently strong to mix slurry homogeneously • Can be miniaturized • No mechanical component passing through the pressure vessel	• Requires secondary energy source • Magnetic forces will interact with any ferrous metal present • If abrasives settle compactly together around the stirring rod, the rod may become stuck • Stirring rod in vessel must be coated to prevent rusting

4.2 Screening as a Means of Process Selection

The screening process, or *Pugh concept selection*, will be applied to quickly narrow down the number of concepts considered (Ulrich 2000). The screening matrix is prepared by creating a table and listing the concepts across the top and the selection criteria along the left side, as illustrated in Table 4. Recall that the selection criteria are based on the functional specifications outlined in Chapter 1.

The next step in the design of the screening matrix is choosing a benchmark, or reference concept, against which all the other concepts will be rated. This reference concept is generally one that is straightforward or best understood and is generally placed as the first concept in the matrix. A relative score of “better than” 1, “same as” 0, or “worse than” -1 value will be applied to every generated concept, evaluated against the reference concept, for each of the given selection criteria. The reference concept will typically have a zero (0) score for each of the criteria. It is suggested that the scoring sequence start with an individual selection criterion for the reference concept and then score every generated concept for that same criterion. The same process is repeated for each of the other selection criteria.

Again, each concept will receive a 1, 0, or -1 in the screening matrix for each of the selection criteria. After rating all of the generated concepts, the scores will be summed up. After the concept score summation is completed, they can be ranked. The highest score is considered a more likely viable candidate and the lowest score is a less-likely candidate as a method to entrain and suspend abrasive particles in a low pressure abrasive dental jet.

Table 4 Screening matrix for generated concepts

	Generated Concepts										
	A	B	C	D	E	F	G	H	I	J	E
Specification Criteria	**(Reference)** Stirring Mechanism (ex impellor)	Polymer Suspension	Melting Abrasive Ice	Vibration (ultrasonic)	Vibration (magnetic mechanism)	Mixer (Recirculation Mixer/Pump)	Magnetic Stirrer	Pulsing Bladder	Bubble System	Traditional DIAjet System	Rotating Vessel
Overall Functionality	0	0	-1	1	0	1	1	-1	-1	0	-1
Cost	0	1	0	0	1	1	1	-1	1	0	0
Reliability (overall design)	0	1	-1	0	0	0	0	0	0	0	-1
Performance (Homogeneity)	0	1	0	1	0	0	0	0	-1	0	0
Performance (Entrainment)	0	1	1	1	0	0	0	1	-1	0	1
Performance (Water Jet steam)	0	-1	0	1	1	1	1	0	0	0	1
Safety	0	-1	-1	1	1	1	1	0	1	1	0
External Energy	0	1	-1	0	0	0	0	-1	0	0	-1
Manufacturability	0	0	-1	-1	-1	-1	0	-1	1	-1	-1
Location (miniaturization)	0	1	1	0	0	not required	0	-1	1	-1	-1
Visibility for Dentist	0	-1	0	0	0	0	0	0	0	0	0
Noise	0	1	1	-1	-1	0	0	-1	0	1	0
Total	**0**	**4**	**-2**	**3**	**1**	**3**	**4**	**-5**	**1**	**0**	**-3**

4.2.1 Screening Process Results

After considering the advantages and disadvantages of the presented concepts, the screening process was performed and the results are reported in Table 4. The list of generated concepts was narrowed down to the most viable concepts that may possibly be employed to entrain and homogeneously suspend abrasive particles in a low pressure dental jet. The methods with the highest score, which will continue to be considered as viable candidates for the low pressure abrasive dental jet, are concepts B, D, F, and G; which are polymer suspension, ultrasonic vibration, continuous recirculation mixing, and magnetic stirring, respectively.

It is important to note that the other listed concepts that received a lower score may still merit consideration. Each generated concept offers some value and creativity; however, for this study and its list of screening selection criteria, the concepts that received the highest score appear to be the most viable methods to entrain and suspend abrasive particles in a low pressure dental abrasive jet.

In order to narrow down the list of concepts further, another process with increased resolution must be employed. An inherent weakness of the screening process is the fact that every selection criterion is considered equal in importance. This is not necessarily the case. A scoring process may be performed, which increases resolution by using a weighting system for the criteria.

4.3 Scoring as a Means of Process Selection

Following the screening matrix, the concepts chosen to continue will be analyzed and ranked further in a scoring process. The scoring process is similar to the screening process; however, its purpose is to increase the scoring resolution. This is accomplished by weighing the importance of each selection criterion, the total weight being 100%. Each criterion receives a portion of the total percentage, a higher percentage to the more important criteria, and a lower percentage to the less important criteria, as shown in Table 5. The weight given to each of the selection criteria is determined by engineering judgment.

In the scoring process, a 1, 2, 3, 4, 5 point score system will be used. Again, a concept is chosen to be a benchmark reference. This reference will receive a 3 as its value. Each of the other concepts will be compared to this reference concept and receive a score accordingly, 1 being "much worse than" and 5 being "much better than." At times, a reference value will be given to a different concept other than the reference concept to permit a more accurate comparison. The reference value will still be "3" and should be in bold print in the matrix.

After the scoring of each generated concept is completed, the scores will be summed up. As in the screening process, the highest score is ranked first, the next score is second, and so on. According to the design process performed, the generated concept that ranks first should be considered as the most viable method to entrain and suspend abrasives in BYU's low pressure abrasive dental jet.

Four of the concepts with the highest screening score, which were narrowed down by the screening process, will be considered in the scoring process. It is the opinion of the author that the polymer suspension, recirculation, ultrasonic vibration and magnetic stirring concepts have the most potential to be successfully employed in a low pressure dental jet. Each of these concepts has their advantages and disadvantages, which have been presented and discussed

The benefit of the scoring process is its ability to allot more scoring significance on certain criterion over others. Since this research is making judgments on criteria that are not considered to be as significant, or that would not differ substantially, it was decided that certain criteria could not be included in the scoring matrix. The criteria that were excluded are cost, reliability, and safety. Once the final concepts are selected through the scoring process, these omitted criteria should still need to be considered.

4.3.1 Scoring Process Results

The scoring process was performed and its results are presented in Table 5. According to the specification criteria and the weighted scores, the magnetic stirring ranked first as a method which may be the most viable to entrain and suspend abrasive particles in a low pressure abrasive dental jet. Polymer suspension, ultrasonic propagation, and recirculation methods rank second, third, and fourth respectively. It is the opinion of the author that the concepts that ranked first and second will be the most promising methods to entrain and suspend abrasive particles.

Up to this point, it has been presumed that the selected concepts have the ability to entrain and suspend the aluminum oxide abrasive particles. Though the assumptions appear valid, it is important to test each of their basic entraining and suspending capabilities with proof of concept hardware. This will provide a level of confidence to the generated concepts chosen.

The next step in this research is to perform experimentation with each of the final concepts. The ultrasonic streaming concept will also be tested. This concept was considered late in this research; however, it appears to be a strong candidate and a novel idea. The results of the experiments will provide a starting point from which future work may be performed. The research process and test results will be reported in the following chapters.

Table 5 Scoring and ranking matrix for the screened generated concepts

Specifications Criteria		**F** (Reference) Mixer (Recirculation Mixer/Pump)		**B** Polymer Suspension		**G** Magnetic Stirrer		**G** Ultrasonic Cavitation/Streaming	
	Weight	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Functionality	10%	**3**	0.3	3	0.3	5	0.5	4	0.4
Performance (Homogeneity)	15%	**3**	0.45	4	0.6	3	0.45	4	0.6
Performance (Entrainment)	15%	**3**	0.45	5	0.75	5	0.75	5	0.75
Performance (Cutting Ability)	15%	5	0.75	**3**	0.45	5	0.75	5	0.75
External Energy	10%	**3**	0.3	5	0.5	4	0.4	3	0.3
Manufacturability	5%	2	0.1	4	0.2	**3**	0.15	3	0.15
Placement (any location)	15%	**3**	0.45	5	0.75	4	0.6	3	0.45
Decrease Cutting Visibility	10%	5	0.5	**3**	0.3	5	0.5	5	0.5
Noise	5%	1	0.05	**3**	0.15	1	0.05	1	0.05
Total Weighted Score		**3.35**		**4.00**		**4.15**		**3.95**	
Rank		**4**		**2**		**1**		**3**	

Relative Performance	Rating
(Reference number in bold)	
Much worse than reference	1
Worse than reference	2
Same as reference	3
Better than reference	4
Much better than reference	5

5 Concept Validation and Results

The objective of this chapter is to report on the results obtained from tests performed on the magnetic stirring, polymer suspension, and ultrasonic streaming concepts.

A list of concepts was generated and explained in chapter 3 and their strengths and weaknesses were presented. In order to narrow down the generated concepts to those which could most viably entrain and suspend aluminum oxide particles in a low pressure abrasive dental jet system, both a screening and scoring process has been performed as reported in Chapter 4. After careful consideration of each of the generated concepts, the list was narrowed down to two concept designs that currently appear to be most viable for a low pressure dental abrasive jet. These are the magnetic stirring and polymer suspension concepts.

In order to better understand the magnetic stirring and polymer suspension concepts, tests will be performed. It is the intent of these tests to validate the chosen concepts and to provide further insight to their entrainment and suspension abilities, which is a key requirement of this research.

Tests will also be conducted on the ultrasonic cavitation and streaming method. The concept of applying sound waves arrived late during this research. The concept may or may not merit more consideration; therefore, several experiments will also be performed for this method to provide further information.

As described by the delimitations of this research, the optimal particle size should be 25 microns and makes up 11.0% of the Al_2O_3-H_2O slurry by weight. It is anticipated that the suspension capabilities of each of the three concepts will be the same whether or not the system is under pressure; therefore, pressure will not be used for all the tests.

5.1 Polymer Suspension, Xanthan

Xanthan and other polymer suspension characteristics have been discussed in detail in section 2.7 and 3.4.1 (polymer suspension). This concept potentially offers many desired characteristics for a low pressure abrasive dental jet system. Suspension mediums have the ability to maintain a pre-entrained and near permanent homogeneous slurry, whereas most other offered concepts require a mechanism to continuously mix and suspend the particles. The polymer suspension method provides the possibility of pre-manufacturing the slurry, which negates the need of refilling the water jet unit with abrasives and water by dental office staff. However, there are several potential disadvantages of using polymer suspensions in low pressure system that need to be considered further.

Section 3.4.1 of this thesis discusses the tradeoff between increasing viscosity to suspend particles and decreasing the performance of the water stream's rheology. By increasing polymer concentration, the ability to suspend abrasive particles is improved; however, the increased amount of polymer also increases the viscosity of the solution. Too much viscosity will decrease the velocity of the water jet stream's momentum.

Consequently, the jet's cutting ability will also decrease. It is believed that there exists an optimal polymer concentration that will provide the best level of viscosity to suspend aluminum oxide particle with a diameter of 25 microns, but would also sufficiently maintain the performance of the water jet stream for a low pressure system.

Since xanthan is a carbohydrate, it will begin to ferment if not preserved; therefore, it requires a chemical preservative. Tic gums® suggests that potassium sorbate or sodium benzoate at a 0.01% concentration by weight be used. Both are used as food preservatives and are FDA approved. This, along with refrigeration, will help prolong the life of the xanthan slurry (Tic Gums 2006). The xanthan slurry would have a shelf life, which would have to be considered for the usability of this concept.

To determine whether a suspension medium could be used for the low pressure system, a series of experiments were performed. As discussed previously, xanthan is a carbohydrate that is FDA-approved and considered a good candidate for this application. A sample supply of xanthan has been donated by Tic Gum for testing. This sample was specifically chosen due to its preconditioned state; it is preconditioned so that it is transparent. Preconditioning also helps prevent clumping problems during the mixing stage. Hansen's research concluded that using baking soda obscured the work area and target material during testing. It was assumed that using a polymer that was opaque would produce similar results. It is suggested that the clear xanthan sample may minimize the obscurity problem.

5.1.1 Validation and Test Results of Xanthan

A comparative performance study on xanthan determined which concentration levels may provide the desired characteristics for a high pressure water jet system

(Chacko *et al* 2003). The study concluded that xanthan concentrations of around 1.0% by weight offered the best cutting and suspension results when garnet particles were used. For this experiment, Al_2O_3 particles with a diameter of 25 microns will be used. These particles are much smaller than garnet, which is most often used in high pressure industrial water jet systems. It is assumed that a smaller concentration of xanthan will provide better results for the smaller abrasive particles in this experiment.

To obtain a general idea of the viscosity with 1.0% concentration of xanthan, an intermediate test was conducted. A small clear 75-ml container was filled with water, 1.0% by weight of xanthan, 11.0% by weight of aluminum oxide material, and the rest was water. The slurry was allowed to sit for 24 hours and then remixed to ensure that the polymer was completely homogeneous and saturated in the water. The intermediate test showed that the 1.0% xanthan viscosity was more than adequate to suspend the 25 micron particles for this application. The slurry appeared to be very "thick" and kept the abrasive particles completely suspended. These results provided the upper limit of xanthan polymer concentration for the subsequent experiments.

It was decided that several concentration samples ranging from 0.10%, 0.30%, 0.50%, 0.70%, and 0.90% of xanthan by weight would be tested. This range of concentrations would allow us to find the best interval of concentrations that may work for the low pressure abrasive jet. For example, if 0.30% xanthan proved to be sufficiently viscous to suspend particles and 0.10% xanthan allowed particles to settle, then the optimal xanthan concentration would then lie somewhere in between these two concentration limits.

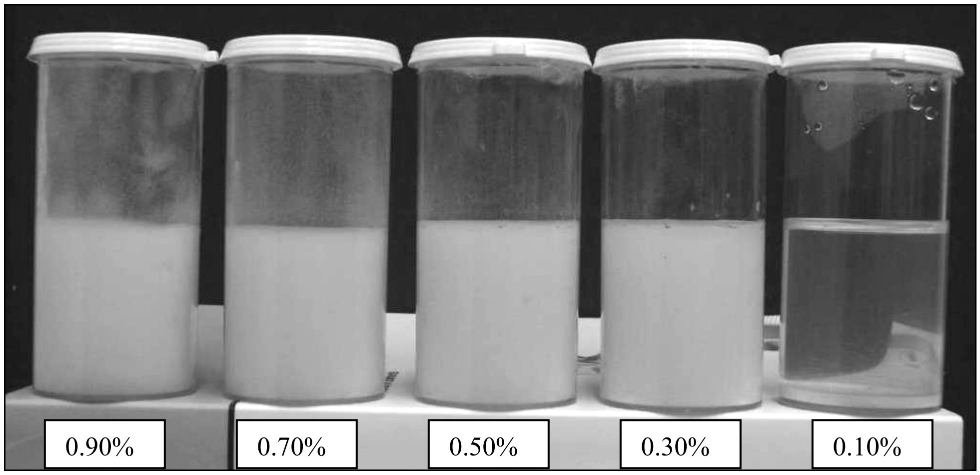

Figure 5.1 Test 1 of xanthan concentrations after 24 hours: 0.90%, 0.70%, 0.50%, 0.30%, 0.10%

The test results demonstrated the viscous suspension ability of the xanthan slurry at different concentrations. There was a very obvious increase in suspension ability from 0.10% to 0.30% concentrations. The 0.30% xanthan (second from the right in Figure 5.1) appears to be suspending the Al_2O_3 particles well; however, upon close inspection of the bottom of the container, there is obvious settling of the particles within 24 hours. The 0.50% xanthan slurry had virtually no settling effects. Therefore, it is deduced that the optimal suspension characteristics for the low pressure abrasive dental jet may be between 0.30-0.50% xanthan by weight with a concentration of 11.0% Al_2O_3.

During the mixing stages of the experiment, the containers were mixed with a whisk and also shaken rapidly. It is difficult to see a difference in suspension abilities from the 0.30%-0.90% concentration. However, the xanthan film thickness covering the upper side of the walls of each container easily distinguishes which slurry is more viscous. The mixtures with higher concentrations of xanthan appeared to “coat” the walls of the clear containers.

To increase the confidence level of the experiment, a second series of tests was performed. With the new concentration limits defined, five more slurry samples were prepared: 0.10%, 0.20%, 0.30%, 0.40%, and 0.50% of xanthan, each with 11.0% aluminum oxide by weight. The second test would provide a comparison of the concentrations (0.10%, 0.30%, and 0.50%) against test 1, which would confirm or confute the previous conclusions. Also, testing the center points of 0.20% and 0.40% concentration would help narrow down the optimal concentration levels of xanthan.

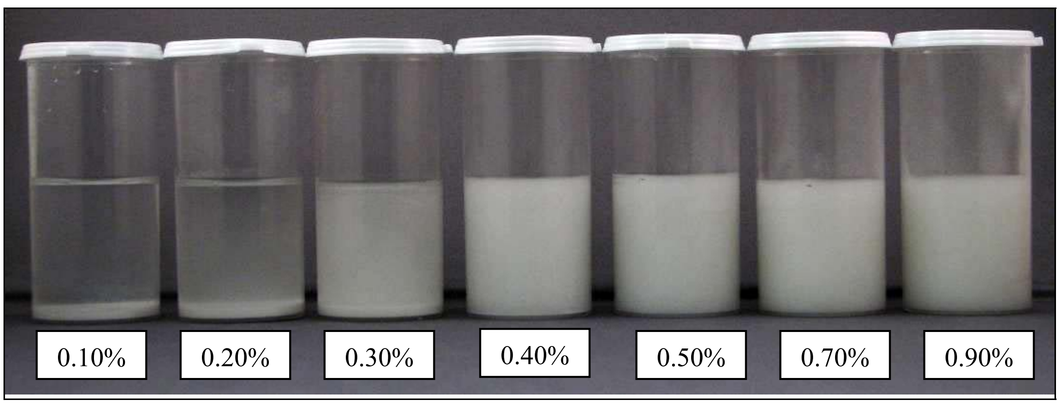

Figure 5.2 Test 2 of xanthan concentrations after 1 week

Test 2 validated the conclusions drawn from test 1. The xanthan slurry concentration of 0.30% by weight has obvious settling. The 0.40% xanthan concentration appears to sufficiently suspend the aluminum oxide particles and 0.50% shows no settling of the particles. Several close-up pictures were taken to better show the settling that occurred. It was obvious that the majority of abrasive material settled down to the bottom of the container for the 0.30% xanthan concentration. However, there are very little trace amounts of abrasive that settled for the 0.40% xanthan concentration. The arrow in

Figure 5.3 points to the small amounts of aluminum oxide (though difficult to see) that have settled around the edges of the container with the 0.40% xanthan concentration.

The 0.10%-0.90% xanthan concentration slurries were allowed to sit in a refrigerator for 2 more weeks. It was apparent that the abrasives had continued to settle in the lower concentration slurries. Previously, it was believed that 0.40% xanthan might be a candidate for the slurry concentration; however, after 2 weeks of sitting it was obvious that come of the abrasive particles for this concentration had settled. Providentially, the 0.50% has continued to show no signs of settling and will continue to be considered as the best concentration level candidate. If the xanthan method is chosen for future research, long term tests should be performed to determine the length of time that the desired concentration of xanthan slurry would keep the particles suspended.

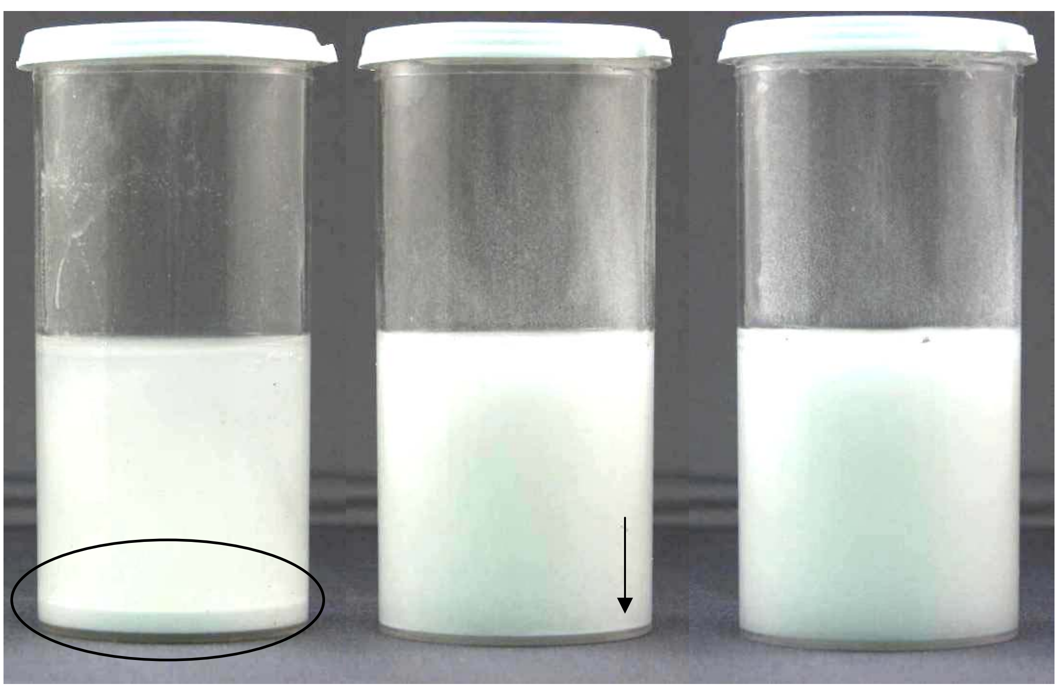

Figure 5.3 Xanthan particle settling results from left to right: 0.30%, 0.40%, 0.50%

Previously, it was explained that baking soda created a cloudy mist which left an obscure layer on everything around the worksite. It has been shown in previous figures that the suspended-particle xanthan slurry solutions are not transparent. This is to be expected while the water and abrasive materials are suspended together. If no polymer is added to the slurry, the abrasives quickly settle. Therefore, after the non-polymer slurry is directed out the exit nozzle and makes contact with the target workpiece, the water and abrasive particles separate. The abrasives settle and the water returns to a more transparent medium. This separation enables the operator to see the workpiece being cut.

Since the xanthan polymer continually suspends the abrasive material even after being jetted out of the exit nozzle, it may leave a layer of obscure slurry, which would block the operator's vision of the target workpiece. The consequence may be similar to that of the film left on the inside walls of the test containers shown in Figure 5.1. It is shown that the greater concentration of xanthan slurry results in a thicker slurry film that will be produced. It is easy to see through the slurry film in the container of 0.10% xanthan, while it is difficult and obscure for the 0.90% xanthan concentration.

In order to determine the functionality and capabilities of the xanthan polymer suspension method, a series of low pressure water jet tests were performed. Batch sizes of 400-gram slurry solution with 0.30%, 0.40%, and 0.5% xanthan concentration were prepared. The nozzle sizes available were 0.004 and 0.006 inches in diameter. The basic schematic of the water jet system is in Figure 5.4.

Previous intermediate experimentation with xanthan provided crucial knowledge for determining which steps for mixing the ingredients together are considered optimal. Listed below are the steps for mixing the xanthan slurry:

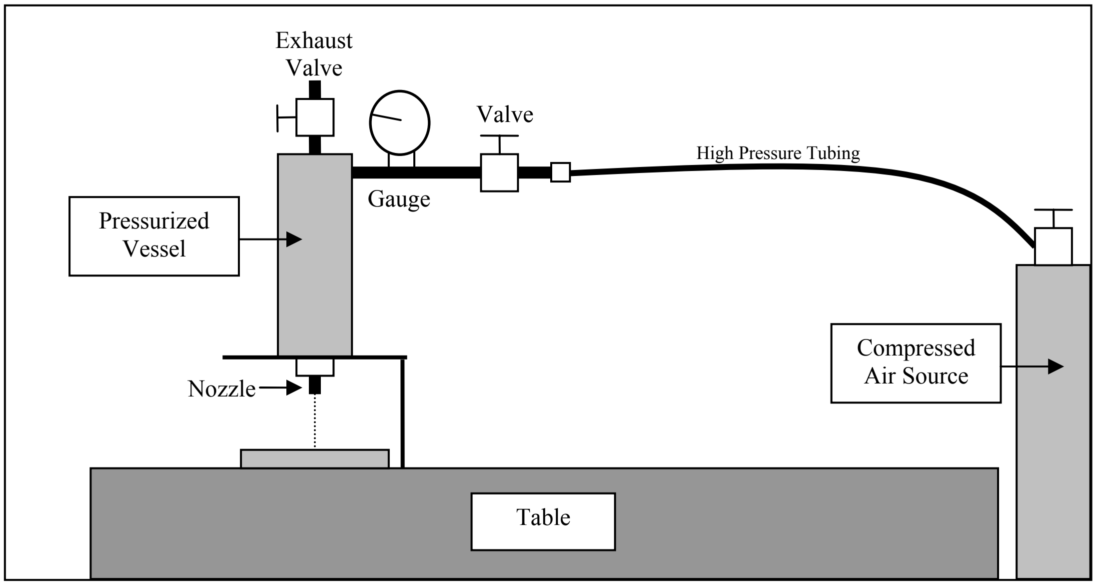

Figure 5.4 Schematic of water jet test apparatis.

1. Add water to a container
2. Add needed preservative (Potassium Sorbate, 0.01%)
3. Commence stirring the water and add the abrasive material
4. Continue to mix rapidly and slowly add the xanthan polymer

It is crucial that theses steps are performed in order. To achieve the most homogeneous slurry possible, the water and abrasive mixture needs to be stirred in such a manner that the slurry is homogeneous before/while the xanthan polymer is being added.

Experience has revealed that if the water and xanthan powder are mixed together first, before the abrasive material is added, then the abrasive particles will clump-up inside the viscous solution. Even rigorous mixing after the fact will not sufficiently break apart the "clumps" into the desired homogeneous slurry. These clumps are much greater in size than the exit nozzle orifice diameter and have proved to be a source of clogging.

The slurry concentrations were prepared, allowed to sit for 24 hours, and then re-mixed to verify that the xanthan was completely saturated and that the particles were homogeneously entrained. Since clogging of the exit orifice had been a problem in previous testing, it was necessary to clean out the water jet system well before testing began. All the system components were washed and rinsed thoroughly, as any unwanted contaminants could potentially clog the nozzle orifice and interrupt testing. It was decided that pure water (no slurry or particles) would be passed through the system after each slurry test with and without the orifice, which would clean out the system and the nozzle orifice after each test run.

The initial tests were performed with only water to verify that the system was working as designed. The system appeared to be in working order and the slurry tests began with the following run order shown in Table 6:

Table 6 Xanthan test run order

Run	Orifice Diameter (in)	Xanthan Concentration	Pressure (psi)
1	0.008	0.50%	400-500
2	0.008	0.40%	400-500
3	0.008	0.30%	400-500
4	0.004	0.50%	400-500
5	0.004	0.40%	400-500
6	0.004	0.30%	400-500

The results of the tests were strictly observational. The goals of the experiment were to determine whether or not the polymer slurry would effectively exit the orifice nozzle while maintaining the abrasive particles homogeneously suspended. Also, it was important to determine whether or not the slurry would leave an obscure covering around the work area similar to that of the baking soda experiments performed by Hansen.

It was desired to determine whether the xanthan slurry jet provided some cutting ability. Though the cuts would not be measured for depth or rate, they could be compared to the photographic results recorded by the previous work performed by Hansen and Memmott.

To compare the cutting ability to the previous work, the xanthan slurry jet stream was directed towards the same ceramic tile plates used by Hansen and Memmott, which have material and strength characteristics similar to the enamel of human teeth. Observing that the xanthan slurry jet would be able to cut the tile, would demonstrate that the xanthan viscosity might not be interfering with the abrasives particles' ability to remove material.

All of the test runs were performed to some extent; however, most of them were inconclusive. From the beginning of the experiment, there were orifice-clogging interruptions, just as previous researchers found in the past. It is strongly believed that the polymer slurry was performing as expected and that there was a secondary and unanticipated factor that had not been previously considered, which was plugging the exit orifice. The clogging seemed to be random, but it was found to be more prominent with the 0.004 inch diameter nozzle. The clogging occurred more often when the pressure was initially applied (no particular pressure value), but it sometimes randomly occurred toward the middle or end of the test run. Fortunately, some of the tests were completed and performed well with both orifice sizes. This allowed general conclusions to be made about the performance of the xanthan concept.

The cutting ability of the xanthan slurry jet was shown to have similar results as those presented by Hansen and Memmott. The jet stream cut the ceramic tile, but appeared to require more time than recorded by Hansen. Also, when clogging was not an issue, the xanthan slurry jet stream appeared to be more cohesive than that of a pure water jet stream. This might increase the jet's cutting ability, which would be similar to the results found for high pressure industrial jets. If the xanthan slurry suspension method is considered further for use in the anticipated low pressure dental jet, more tests will need to be performed in order to determine whether the xanthan polymer increases or decreases the water jet stream cutting performance. This can only be accomplished if the factors causing the nozzle orifice to clog are determined and solved.

Unfortunately, there is a negative consequence of the xanthan slurry being much more cohesive than water alone. It was very apparent that a thick layer of obscure slurry often made it difficult to see the cutting target. This may be a serious concern for this low pressure abrasive dental jet concept. In order to determine whether the obscure slurry layer could be manipulated, a series of simple experiments was performed.

While the slurry jet was cutting a tile sample, air or water was directed toward the cutting area to "wash-away" the slurry. This proved to be helpful in removing the undesired leftover slurry, which improved the ability to see the target. If this method is considered for further research, more tests should be performed to determine the methods and parameters which would wash away the xanthan build-up.

5.1.2 Orifice Clogging Tests

After careful discussion with Dr. Todd of the mechanical engineering department at BYU, it was decided that a second run of tests should be run to determine what other factors could be contributing to the clogging dilemma. Figure 5.4 shows the schematic of the water jet apparatus that was initially used for testing. The manner in which the test apparatus is setup could permit abrasive particles to settle when the system is in progress or at rest. To test whether or not clogging is caused by settling abrasives, a simple component could be added to the test apparatus.

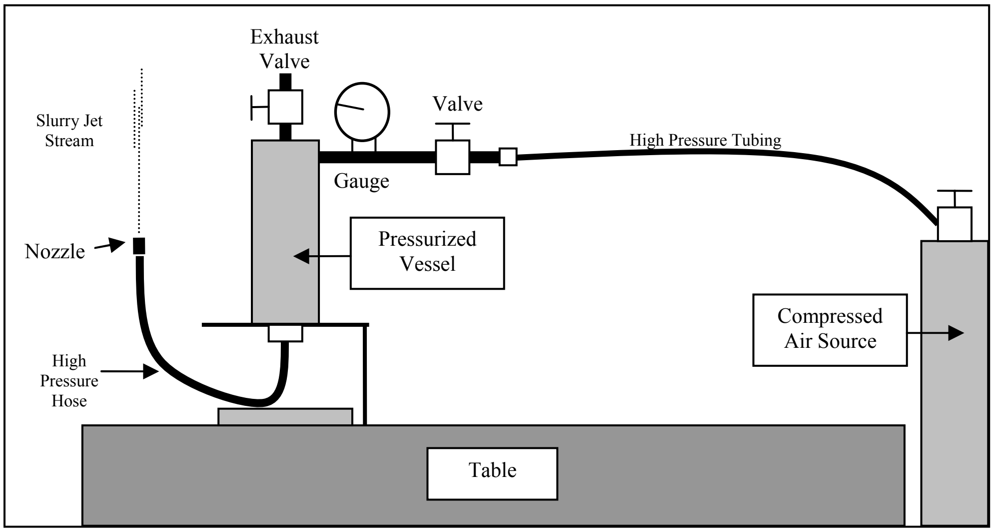

Figure 5.5 Schematic of water jet test apparatus with high pressure hose attachment

Figure 5.5 shows a similar setup as before; however, it also includes a high pressure hose connected to where the nozzle orifice was previously located. The orifice was moved to the end of the hose, as labeled in the schematic. This design allowed the determination of whether clogging occurs because the abrasive particles are settling at the inlet of the orifice or for some other unanticipated factor. If settling abrasive particles are the cause of the clogging, then the addition of the hose should avoid this problem. The additional hose would be oriented so that it is pointing upwards (away from the direction of gravity); therefore, the settling abrasives should fall to the lowest point inside the pressure vessel and hose. Since the xanthan is more viscous than water, it is assumed that no particle settling is occurring.

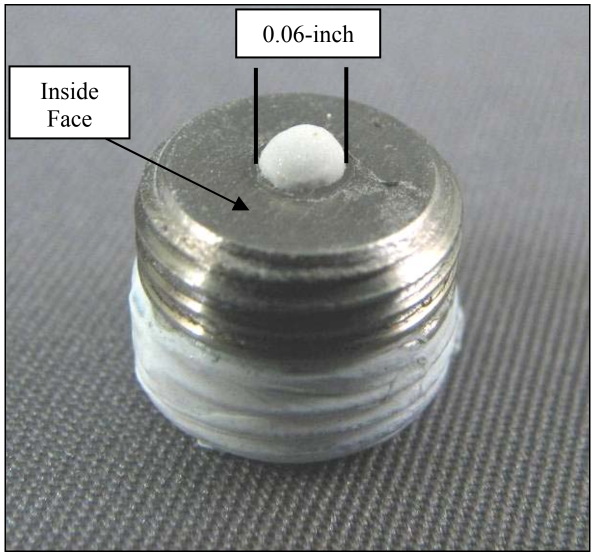

Figure 5.6 Aluminum Oxide particles clogging the nozzle orifice

The same series of tests were again performed with the xanthan slurry mixtures in the new setup. Yet again, clogging prevented testing from being performed. The clogged nozzle orifice is shown in Figure 5.6. The side with the clogging is located inside the water jet hose when it is attached. As seen in the figure, there are no settled particles lying on the input face of the nozzle. The "clump" of aluminum oxide particles is centered exactly on the opening of the nozzle orifice.

The question arises, if the nozzle is pointed in the opposite direction of any potentially settling abrasives, what is causing the nozzle orifice to clog? The matter was discussed with Dr. Daniel Maynes of the mechanical engineering department at Brigham Young University, an expert in fluid dynamics.

Figure 5.7 illustrates the low pressure effect of fluid flow through a thin plate orifice. As shown in the figure, eddies are formed just after the inlet in which a low pressure zone is created. Fluid mechanics as presented by Fox (2002) suggests that suspended matter can build up at the inlet side of a concentric orifice on a pipe. It is presumed that the aluminum oxide particles are clogging the nozzle orifice due to this principle.

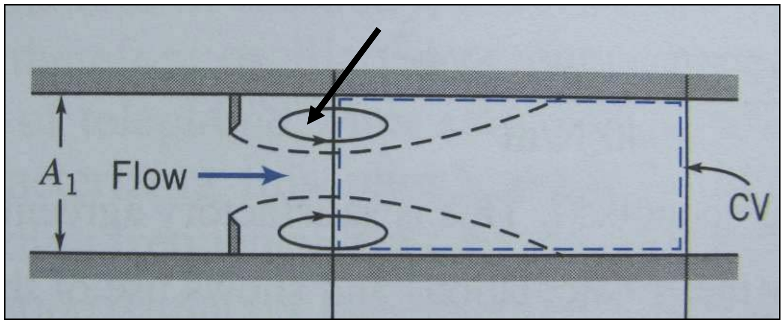

Figure 5.7 Flow profile through an orifice plate (Fox 2004)

In order to circumvent this problem in the future, it is suggested that the inlet profile be tapered so that there is no blunt change in diameter. The best way to accurately describe the optimal design is to imagine a smooth contoured funnel that slowly decreases in diameter until the desired orifice diameter is achieved. This may prove to be difficult from a manufacturing stand point; however, this is already a common practice in the medical device industry. Variable diameter tubes are often used for syringes. The anticipated desired design might look similar to that illustrated in Figure 5.8.

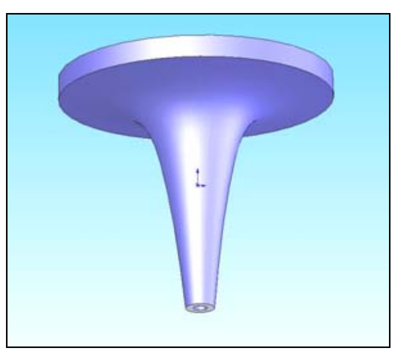

Figure 5.8 Possible nozzle design to improve slurry flow

5.1.3 Xanthan Test Results

The xanthan polymer suspension concept proved to be successful in entraining and suspending the aluminum oxide particles, which was the main functional goal of this research investigation. The slurry itself is simple to prepare and is easily added to the water jet apparatus. The results show that the xanthan slurry appears to cut tile specimens with the similar potential as the tests performed by previous research at BYU.

Though this concept proved to be successful, it still had the undesirable consequence of obscuring the target by leaving a built-up layer of slurry. Since the xanthan increases the viscosity of the slurry, it holds the particles in place. The thicker the more viscous slurry build-up was, the more obscure the target would become. Also, it should be noted that nozzle orifice clogging hindered testing. In order to continue testing for this method or any other method, it must be determined what unknown factor is causing the orifice to clog.

5.2 Magnetic Stirring

The method of mixing and suspending abrasives with magnetic forces was explained briefly in section 3.5. The concept of creating a magnetic mixing action is elementary. A rotating magnet or electromagnetic field is placed outside a water-abrasive filled container. Inside the container is another magnet or ferrous metal rod. As the magnetic field rotates, it forces the ferrous bar inside the container to respond. If the bar is placed in the center of the rotating field, it will also begin to rotate. This concept is represented in Figure 5.9.

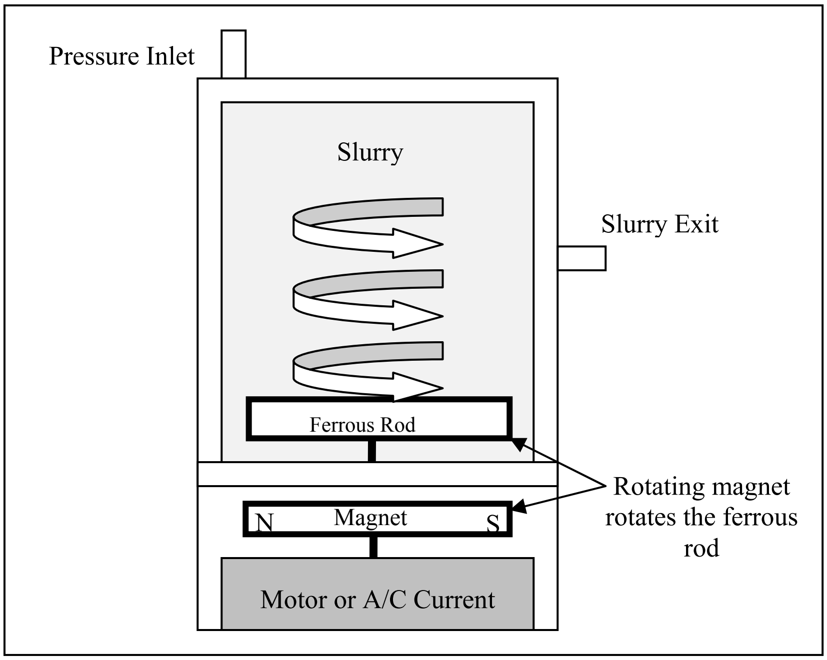

Figure 5.9 Rotating magnet forces the rod to rotate through magnetic fields

5.2.1 Validation and Test Results for the Magnetic Stirrer

In order to validate the magnetic stirrer as a possible abrasive particle suspension method, a test was performed. A magnetic stirring table (hot plate) apparatus shown in Figure 5.10 was used to simulate the desired mixing characteristics. The table has a small motor underneath a non-ferrous plate that rotates a magnetic bar. The same 80-ml container used in previous experiments was filled with aluminum oxide and water. A magnetic bar was inserted and situated at the bottom of the container. The magnetic stirring table has a variable control knob to change the rotations per minute of the motor (some unknown value).

The first test utilized the desired slurry proportions that produce optimal cutting rates as suggested by the research of Hansen, which was 11.0% aluminum oxide and 89.0% water by weight. The magnetic table was turned on and its magnetic bar began to rotate. The bar inside the container homogeneously entrained and suspended the particles within seconds. Provided that the motor and magnetic bar continued to rotate the ferrous bar, the slurry stayed well mixed. As soon as the motor was turned off, rotation stopped, and the particles quickly began to settle.

Figure 5.10 Magnetic Stirring Table, BYU

It may also be desirable to create slurry with a higher content of abrasive material. DIAjet, as explained in section 2.6, mixes a higher concentration of abrasive slurry in a pressurized vessel. That slurry is then injected into the main water line at the proper proportions to achieve the desired slurry concentration jet stream. Chapter 3 of this thesis suggests that the DIAjet method would be too difficult to employ for this low pressure dental system. This is true, primarily due to the fact that the low pressures and velocities might not be able to independently produce the required forces to achieve a homogeneous slurry. However, it is conceivable that a combination of the DIAjet bypass method and the magnetic stirring method may be a viable integrated system.

Figure 5.11 Slurry entrained by rotating magnetic bar: left, slow rotation; right, fast rotation

To get the general idea of how much abrasive-water slurry can be suspended, more aluminum oxide was added to the mixture. The magnetic bar was able to efficiently entrain and suspend up to 40% aluminum oxide abrasive by weight. When greater contents of abrasive material were added, it became obvious that the ability of this system to entrain the abrasives would dependent on many factors such as, the amount of abrasive material, the size of the rotating magnet and rod, the dimensions of the container, and the speed of the motor. All of these factors would have to be considered if this concept is chosen for future research.

5.2.2 Magnetic Mixing Results

The magnetic stirring concept showed that it was able to entrain and suspend the abrasive particles quickly and continuously. The benefit of this concept is its simple design and inexpensive setup.

The tests concluded that the most critical consequence of adding more abrasive material was its hindrance on the magnetic bar's ability to "start-up." If too much abrasive was added, the stirrer was not capable of initiating the rotation the ferrous bar inside the container. Also, if the particles were stored and allowed to settle for extended periods of time, it took longer to get the magnetic bar to begin rotation. However, experiments showed that if the rotation of the bar was initially assisted, the bar was able to continue stirring the slurry.

If disposable batch cartridges would be used, it is suggested that the cartridge could be stored upside-down before use. Consequently, when the cartridge is inserted into the handpiece for use, the settled abrasives would be on the top side of the cartridge. When the magnetic stirrer commenced rotation, the settled abrasives would not inhibit the mixing ferrous bar from rotating. Eventually, the abrasives would begin to fall through the water and be mixed into a homogeneous slurry.

The only available mixing bar for testing did not have a protective coating to prevent it from rusting. It was obvious after a few days that the bar located inside of the slurry would need a protective coating. It should also be reiterated that the bar itself does not need to be a magnet. Provided that the bar that is connected to the motor outside of the container is magnetic, the bar inside the container could be a ferrous metal as demonstrated in Figure 5.10. This would be recommended since the ferrous bar would be located inside a disposable cartridge which would be discarded after each use. This would also decrease material costs.

The ability of the magnetic bar to produce a homogeneous slurry, even with extreme amounts of abrasive materials, demonstrates the potential of the magnetic stirrer as an entrainment and suspension method. One of the greatest benefits of this method is the fact that no mechanical device is required to pass through the pressure vessel. This reduces the complexity of the design significantly. The magnetic slurry method was not tested while under pressure; however, it is presumed that its suspension capabilities would be unaffected under these conditions. These tests were performed to gain a perspective for future work. If this concept is pursued for future research, the optimal combination of factors will need to be determined.

5.3 Ultrasonic Cavitation

In order to determine whether ultrasonic sound waves have the ability to entrain and suspend aluminum oxide particles in water, a sonicating apparatus was setup as demonstrated in Figure 5.12. Though this system is large and generates far more power than is needed for this research application, the concepts and principles as set by to the low pressure water jet are anticipated to still apply.

This system is designed as a sonic dismembrator, model 550 by Fisher Scientific. It is intended to breakup cells and bacteria. It is a standard unit that works at a constant 20 KHz. This system uses a 1/8 inch diameter micro-tip. The amplitude of the tip ranges (semi-linearly) from 0-240 microns. At a setting of 3 the amplitude is about 120 microns and at a setting of 5 (the maximum for the micro-tip) the amplitude is about 240 microns according to Misonix lead representative Marc Lustig (Misonix 2006). The intensity of this machine is designed to create cavitation.

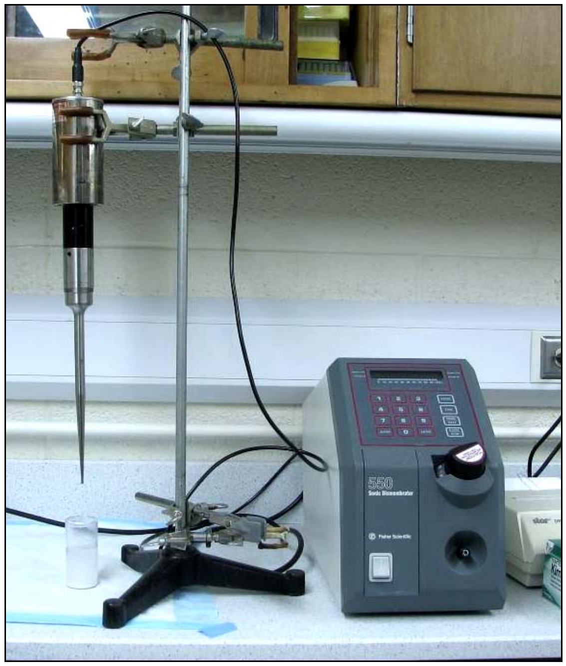

Figure 5.12 Sonicating machine apparatus (BYU Biology dept).

The dismembrator produces its vibrations through a series of piezoelectric crystals aligned in the handle. An alternating current passes through the crystals which causes them to expand and contract. The vibrations occur longitudinally and axially down the shaft, which is called a horn or a probe. The purpose of the horn is to magnify the amplitude. These systems are set up to automatically change the input power (Watts) as the viscosity of the fluid changes. This enables the frequency and amplitude of the system to stay constant.

5.3.1 Validation of Ultrasonic Cavitation

Suspension Tests

There were three main objectives to accomplish. The first was to determine whether the transient streaming caused by the wave propagation and cavitation would be strong enough to mix and suspend the abrasive particles. Second, though difficult to measure, it was important to visualize whether or not cavitation destroyed the particles. Third, since cavitation produces extreme amounts of heat, a simple test would be performed to determine the rate of temperature increase for a given volume of water. It must be determined if the heat generated would produce an unsafe slurry. It was anticipated that these experiments would provide useful foresight and a starting place for the research that is expected to follow.

After the system was tuned (recalibrated), a sample of 50 ml slurry, with 11.0% AL_2O_3 particles by weight and 25 microns in diameter was prepared. The horn was lowered into the solution and the sonicating dismembrator system was turned on with the amplitude set to ZERO. Next, the amplitude knob was slowly increased until noticeable streaming was visible. This occurred at a setting of about 1 and is shown in Figure 5.13. Some cavitation appeared at the tip of the horn, but it was not sufficient to create a complete mixing effect with the particles. Most of the abrasive material stayed settled as pointed out by the arrow in the figure. As the amplitude was increased to a setting of 1.5-2.0, the cavitation and mixing became stronger and suspended about 75% of the abrasive particles.

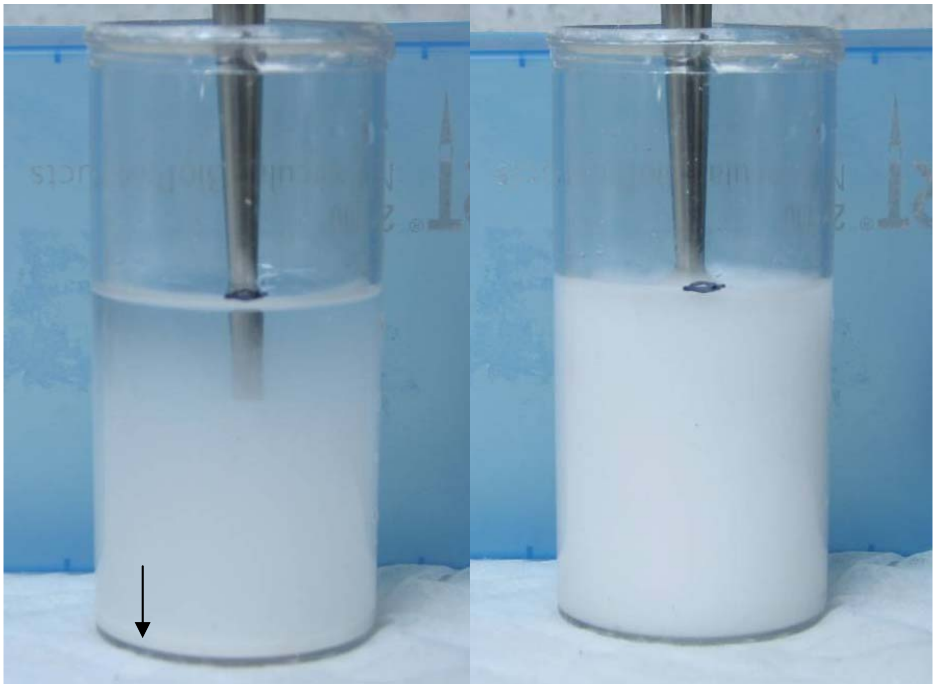

Figure 5.13 Sonic dismembrator in a 50-ml solution with 11.0% Aluminum Oxide: (left) setting of 1.5 (right) setting of 3

The amplitude was then increased to a setting of 3, which mixed and suspended all of the abrasive particles. It became apparent that this type cavitation had capability to stir the solution into homogeneous slurry. It was interesting to note that the flow profile in this amplitude range produced the flow profile which was explained in 3.5.3. The flow appeared to shoot out from the tip of the horn probe and circle back radially to the top of the container, moving the particles with it.

Though an amplitude setting of 3 was sufficient to create the desired slurry, the system was increased to its maximum setting of 5. The cavitation became so intense that the water almost appeared to be boiling (not due to temperature). The amount of micro-bubbles increased greatly and water sputtered out of the plastic container. This again demonstrated that the system was much larger and more powerful than is needed for a low pressure water jet system.

Temperature Tests

Cavitation produces extreme amounts of heat and pressure as a bubble collapses. It was necessary to perform several experiments to determine the increase in temperature of the slurry mixture during cavitation. The same 50 ml volume amount of water was used, which is in the volume range that may be used for the handpiece. The tests were performed at amplitude settings 3 and 5 without the addition of abrasive material. These points were chosen because setting 3 seemed to efficiently suspend particles and setting 5 would provide information for the extreme upper limit.

	Time (min)	0	1	2	3
Setting 3	Temp (°C)	21	22.2	23.4	24.6
Setting 5	Temp (°C)	21.2	24.2	27.3	29.9

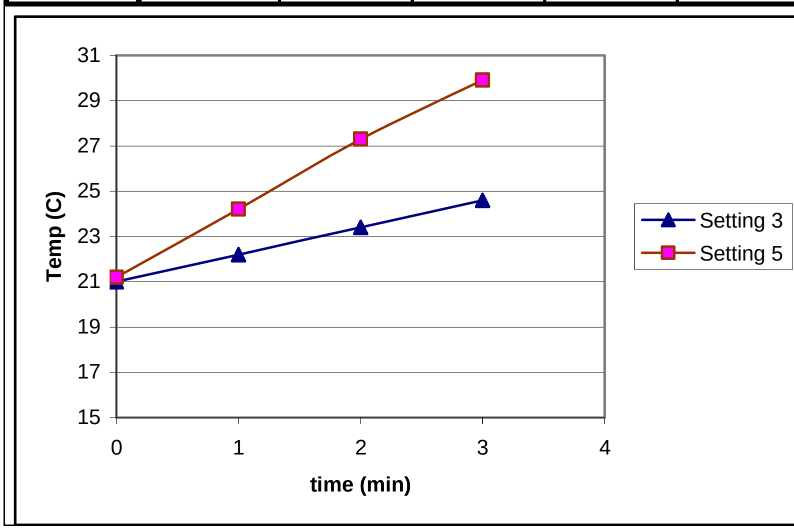

Figure 5.14 Increase of temperature in 50 ml of water due to cavitation at settings 3 and 5

Room temperature was recorded to be 23.5°C. The same clear plastic container was filled with 50 ml of tap water. A type-k thermocouple was inserted into the water. The test began at time zero and temperatures were recorded each minute for three consecutive minutes on setting 3. The same test was then repeated for setting 5.

The temperature increase, due to cavitation, is graphically represented in Figure 5.14. The incremental increases appear to be linear. More notably, the temperature rise on setting 3 increases at exactly 1.2°C/min. This value may or may not be acceptable depending on the duration of the mixing by cavitation that is needed, but it is intended to be useful information for future consideration.

Particle Damage

It was suggested by Dr. Donald Feke of Case Western University (Feke 2006) that the cavitation may destroy the aluminum oxide particles in the slurry. It was apparent some particle "dust" still remained suspended after the majority of the abrasive material settled; however, it appeared to be a very small fraction of the total amount of abrasive material. This analysis was observed after all of the tests were performed. It is the opinion of the author that the amount of particle damage accrued is negligible for the average amount of time (less than a minute) that is anticipated that the particles would be ultrasonically suspended for the proposed application.

5.4 Concept Validation Review

This chapter reported on the results obtained from tests performed on the magnetic stirring, polymer suspension, and ultrasonic cavitation concepts. The tests were performed to validate their suspension and entrainment abilities. All three of these methods proved they were able to achieve their objectives.

The xanthan slurry was prepared and tested at different concentrations levels. A method and order for mixing the water, abrasive material and xanthan polymer was suggested, It was determined that a xanthan concentration of 0.50% provides sufficient viscosity to suspend the 25 micron aluminum oxide. The xanthan slurry was also noted to obscure the cutting point due to its cloudy characteristic.

A magnetic stirring apparatus was set up using a magnetic stirring table. A 50 ml container was filled with water and 11.0% abrasive material by weight. A ferrous rod was placed inside of the container. The container was placed on the table and the rotating magnetic bar inside the table was turned on. The rod inside the container quickly began to rotate, which created a mixing action with the water and abrasives. It appeared that the magnetic mixing concept was able to create the desired homogeneous slurry.

It was suggested that ultrasonic waves could be utilized to produce "streaming" and mix the abrasive particles in the water. A sonicating horn was lowered into a 50 ml container filled with the abrasive material. The machine was turned on and raised to several different intensity levels (0-5). Complete mixing was achieved at a setting of three. The machine demonstrated that ultrasonic cavitation and streaming have the potential to entrain and suspend the abrasive particles as desired by this research.

The results from this chapter should help validate the chosen method's abilities to suspend and entrain the abrasive particles and allow conclusions to be made with regard to each concept, which will be discussed in Chapter 6.

6 Conclusions

The objective of this chapter is to report on the process steps that were taken throughout this research, discuss the information and data that has been found, and to offer conclusions on the concepts chosen through the screening and scoring processes. Also, some discussion on where to place the entrainment and suspension device will be presented along with a possible handpiece configuration.

This research has provided a number of possible concepts to entrain and suspend abrasive particles which are intended to be used in a low pressure abrasive dental jet. Previous work at Brigham Young University has demonstrated the potential of using low pressure water jet streams to effectively remove tooth material. This research also showed that adding abrasives to the water jet stream improved its cutting potential. A patent for BYU's water jet concept has been applied for and is pending. Further work using abrasives was halted due to the difficult nature of adding abrasives to a relatively low pressure system. The purpose of the current research has been to investigate the advantages and disadvantages of several possible methods to entrain aluminum oxide as the abrasive material in water for a dental drilling application.

A vast literature review covering high pressure water jets, mechanisms of material removal, and patent information was reviewed. The literature search guided the direction of this research. High pressure water jets have used many different methods to entrain particles. Through the years, the high pressure water jet industry has yielded several methods that have failed and eventually several that have been successful.

The direct injection method of entraining abrasives in the water jet stream is very difficult because the particles erode the pump valves and piping components. Mohammed Hashish of Flow International Corporation invented the conventional post-orifice entrainment method. This method uses the low pressure zone in a mixing chamber to pull in the abrasives from a connected feed tube, which is either pressurized or at atmospheric pressure. This method cannot be feasibly utilized for a low pressure system since a low pressure water jet system does not generate enough jet stream velocity to create an adequate low pressure zone in the mixing chamber.

The bypass method designed by the DIAjet Corporation adds the abrasive material into the system after the pump and before the nozzle. This is accomplished by feeding the abrasive material into the system in batches. This design has merit; unfortunately, this method also requires a relatively large amount of pressure and water stream velocity to be able to homogeneously mix and suspend abrasive particles. The bypass method could still be considered if a second concept is integrated to help assist in mitigating this shortcoming.

Research efforts were also focused on current and past relevant patents. After careful examination and review of other patent-protected work, it is anticipated that the results of this research will merit its own patent.

During the literature review, potential methods to entrain and suspend abrasive material were generated. These concepts have been inspired or influenced by a variety of different factors, most of which transpired from the review of analogous systems. The list of considered concepts is re-presented:

- Stirring Mechanisms
- Vibration
  - Piezoelectric
  - Electromagnetic
  - Ultrasonic (also piezoelectric)
- Rotating Vessel
- Recirculation Mixing
- Bubble Mixing
- Abrasive Ice Cube
- Pulsing Bladder
- Magnetic Stirring

Each of these generated concepts is presented in some detail in chapter section 3.4. A schematic of each design has been provided, and their advantages and disadvantages discussed. After careful review of each concept, screening and scoring processes were performed and reported in chapter 4. In chapter 5, tests were performed on several of the leading candidate concepts in order to validate their entrainment and suspension abilities and to gain further insight for future work.

6.1 Recommendations

Each of the concepts was scored. The methods that received the highest scores were the magnetic stirring and the polymer suspension methods, which the magnetic stirring method ranked first out of all the concepts considered. It is opinion of the author that these two methods received the highest scores because of the simplicity and effectiveness of their entrainment abilities. Neither of these methods requires a mechanism to cross through the pressure vessel to be able entrain and suspend the abrasive particles. Preliminary testing was also performed on the use of piezoelectric driven ultrasonic vibrations to understand its abilities further.

It is the recommendation of this research that magnetic stirring, polymer suspension and ultrasonic vibrations be considered as possible entrainment and suspension methods for further consideration for use in a low pressure abrasive dental jet.

6.1.1 Concept Validation

The xanthan suspension method was tested to better understand its suspension and water jetting capabilities. It was concluded that a 0.50% xanthan concentration by weight slurry completely suspended aluminum particles that have a diameter of 25-microns. The slurry was allowed to sit for 4 weeks and it has shown no sign of particle settling. The 0.40% xanthan slurry suspended the abrasive particles sufficiently for one week. If the slurry is used inside that timeframe, it should still be considered since it has lower viscosity characteristics. This method was tested with a low pressure water jet apparatus, primarily due to the fact that it was believed that the increased viscosity from the xanthan would affect the slurry flow and fluid rheology.

The tests were performed using 0.004 and 0.006 inch diameter orifices, with three different xanthan concentration levels, and all tests were performed at 500 psi. The xanthan method seemed to have similar cutting abilities to previous tests performed by previous research at BYU. The slurry was well suspended and the particles appeared to be homogeneously entrained. The slurry was easy to prepare and it is suggested that this may be the best method to pre-manufacture a disposable cartridge. This would provide an even better solution to influence a dentist's acceptance of a low pressure abrasive dental jet.

The magnetic stirring, polymer suspension, and ultrasonic vibration methods were tested to validate their entrainment and suspension abilities. It has been determined that the magnetic mixing method has potential to be used in a low pressure abrasive dental jet. A mixture of 11.0% Al_2O_3 slurry was prepared for the tests. The magnetic bar inside the slurry container efficiently mixed the abrasive material into a homogeneous slurry. It is conceivable that this method could be utilized up near the dental handpiece. It is suggested that using this method would be relatively inexpensive and easy to employ.

Efforts were also spent testing the streaming and mixing phenomena of ultrasonic cavitation. It is apparent that this method has potential to meet the objectives set by this research. Further understanding and modeling are necessary to design a system that would sustain the delimitations of the low pressure water jet application.

6.1.2 Delimitations Considered

A list of delimitations for this application was presented in Chapter 1 & 3. It was suggested that the proposed low pressure abrasive dental jet would have to be comparable to the existing mechanical, laser and air abrasion handpieces in the following areas:

- Performance (rate and accuracy)
- Cost
- Noise
- Function
- No need of anesthetics for common caries removal
- Minimize heat and vibration

It is the opinion of the author that the presented and selected concepts in this research will provide the knowledge to produce a low pressure abrasive jet for a dental drilling application that meets the listed criteria.

6.2 Concept Location

The idea of placing the concepts in the main table unit or the handpiece has been broadly covered. One of the major goals of this research was to suggest possible methods to entrain and suspend abrasive particles to keep them from settling. If a suspension device is placed in the main unit (1), then something must keep the particles from settling after they leave and enter locations (2) and (3) in Figure 6.1.

If the slurry flowing from the main unit to the handpiece is continuous, then the abrasive particles may not settle. However, it is likely that the system flow will pause often in a dental environment. Therefore, it would be advantageous to be able to miniaturize any considered concept to fit in the handpiece. It is the opinion of the author that the final chosen concepts, magnetic stirring, polymer suspension, and ultrasonic vibrations may be designed to be applied at the handpiece location.

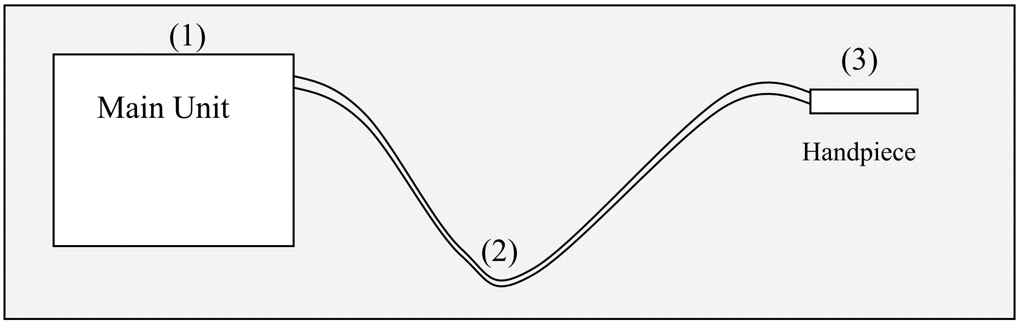

Figure 6.1 Illustration of a typical dental handpiece set-up

Another benefit of placing the entrainment and suspension device at or near the handpiece would that the main unit could be avoided altogether. This would simplify the overall design and possibly reduce costs, both of which are necessary to help make the low pressure water jet an attractive dental tool. However, the final design must also take into consideration the volume of slurry that may be required. As presented in 3.1.1, it is anticipated that a slurry an estimated volume of 1-4 tablespoons would be needed.

6.2.1 Possible Handpiece Configuration

It has been suggested that placing the entrainment and suspension device at the handpiece would be plausible and advantageous. Below in Figure 6.2 is an illustration that may be viable. In general, the main part of the handpiece would be permanent, while a cartridge filled with the water and abrasive material could be removable and disposable.

This basic schematic could be shared by several of the chosen concepts. This design was already discussed earlier for the polymer suspension concept. It is proposed that the same basic design could be used for the magnetic stirring method. The cartridge would contain a ferrous rod that was free to rotate. The main handpiece would contain the rotating magnetic rod. This design would allow the inexpensive cartridge to be discarded and the mixing forces to be permanently located in the handpiece. It is anticipated that this or a similar design would produce a functional low pressure abrasive dental jet.

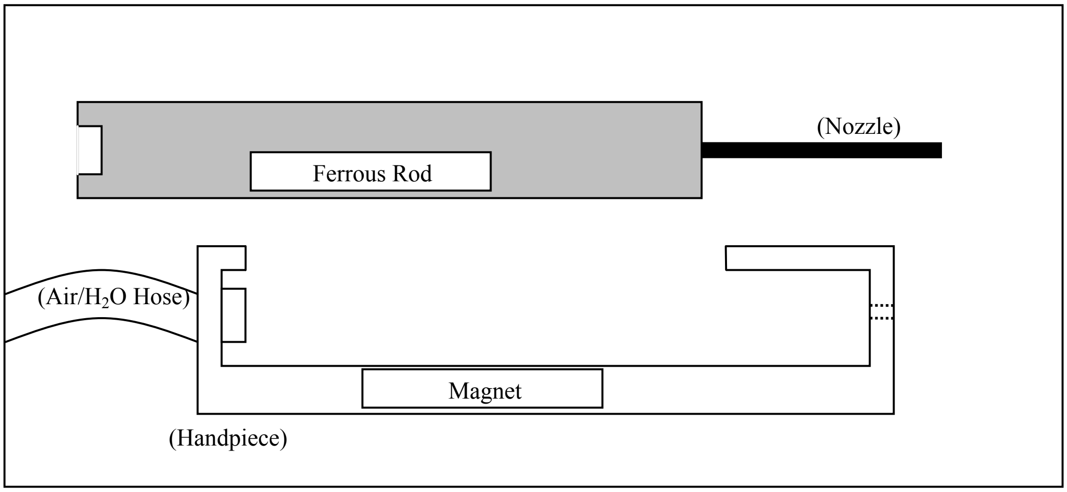

Figure 6.2 Possible handpiece and disposable cartridge design

6.2.2 Batch vs. Continuous

The option to add abrasives to the water jet system in batches or continuously has been discussed. Through this research process, the author has come to the conclusion that it would be difficult to entrain the particles and meter them into the system while it is pressurized. The concepts that have been generated and considered here would most likely utilize the batch entrainment method. The only designs discussed that could meter the abrasives continuously are the conventional post-orifice entrainment method (after the stream is formed) and the direct-injection method (before the system is actually pressurized). The author suggests that neither of these methods offer viable solutions to BYU's low pressure dental water jet design.

6.3 Review

This chapter has presented the general process steps taken to meet the objectives of this research. The overall objective of this research has been to investigate and suggest several possible methods to entrain and suspend aluminum oxide abrasive particles in a low pressure dental water jet. This was accomplished by reviewing the development of high pressure water jet systems and studying the methods they use to entrain abrasives. Time was spent looking for analogous and unique systems to generate a list of entraining and suspending concepts.

Each of the concepts was discussed in Chapter 3 and illustrated in a basic schematic. In order to narrow down the list of concepts, product and design principles were applied. Screening and scoring processes were used to narrow down the list of concepts to a select few. These concept methods were then tested to validate and elucidate their potential and to provide valuable information for future research.

Throughout the performed research, many questions and problems were presented. Several of the author's most pertinent thoughts and concerns with respect to important future work will be discussed in Chapter 7.

7 Future work

This research was the next step in refining a low pressure abrasive water jet, which is intended to perform safe and effective dental caries removal operations in a dental office. As a result of this research, there were a number of concepts generated as possible ways to entrain and suspend abrasive particles in a low pressure abrasive dental jet system. Many of these concepts were methodically screened out according to a selection criteria based on functional specifications developed for this application. However, it is suggested that each concept presented in chapter 2 of this thesis still offers many valuable characteristics that should continue to be further understood and considered.

7.1 Improving the Nozzle Orifice Design

A major obstacle for BYU's low pressure abrasive dental jet is the continued dilemma of nozzle orifice clogging. As discussed in 5.1.2, new understanding and experience might have provided another possible source for the clogging. If clogging can be eliminated, then the cutting ability of the abrasive jet may be increased significantly.

The nozzle piece that was used for this and previous research is shown in Figure 7.1. In the center of the nozzle, a thin sapphire disc is set inside the metal orifice holder and is outlined with a white circle in the figure. The 0.006-in hole in the center of the sapphire disc is drilled out with a laser. The sapphire disc is very thin. It is suggested that a smooth contoured nozzle as illustrated in Figure 7.2 would prevent the clogging problem.

Figure 7.1 Nozzle with a 0.006-in diameter orifice in a sapphire disc

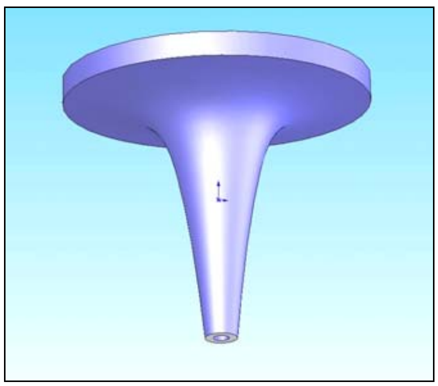

Figure 7.2 Possible nozzle design to improve slurry flow

The research reported by Scott C. Hansen (2000) concludes that larger abrasives are more efficient at removing material, but they could not be used due to clogging. It is suggested by this research that the lack of ability to suspend abrasive particles homogeneously is only part of the clogging problem that has been reported. It is believed that a prominent reason for the clogging is due to the orifice design that is being used.

It is suggested that if the orifice design were changed, that even larger abrasive particles may be efficiently entrained. The result, as discussed in earlier sections, would be lower cutting pressures or higher cutting rates. A series of tests may need to be performed to determine an optimal nozzle orifice design and the correlated cutting rates.

7.2 Concept Integration

It was suggested that several of the various concepts for entraining abrasives presented in this research might be used in combination with one another to produce a new alternative entraining method. One such possibility is the integration of the DIAjet bypass and magnetic stirring methods. It would appear that this combination could overcome their individual disadvantages.

One of the benefits of the bypass method is the extended use of the slurry. In the bypass system, slurry is suspended and then united with the main water stream. It was discussed that the Post-Orifice (aspiration/Venturi) and DIAjet bypass methods require more pressure and jet stream velocity than the low pressure system offers to be able to suspend abrasive particles. If the magnetic stirrer is capable of suspending a high content of abrasive slurry, then the bypass principle may be a very viable alternative method.

It is suggested that a combination of the provided concepts to entrain and suspend abrasive particles should also be considered and tested in future research.

7.3 Xanthan Obscurity

The xanthan slurry method offers many potential advantages and as a result should not be dismissed due to its disadvantages. The disadvantage of most concern is the fact that the xanthan polymer suspends the abrasive particles even after it has exited the nozzle and impacted the target material. As the used slurry settles, it begins to cover and obscure everything that it coats. This effect will make the cutting target to be cut more difficult to see.

It has been suggested that a secondary jet of air or water, or a vacuum, may be used to sufficiently clear away the slurry and avoid the obscuring problem. A series of experiments should be run to determine the pressures and medium that is most effective for removing the slurry.

7.4 Ultrasonic Vibration

Experiments were performed using ultrasonic cavitation and combined streaming. It was apparent that this method more than sufficiently mixed and suspended the aluminum oxide abrasive particles. It is feasible that ultrasonic waves above 1 MHz would provide similar mixing characteristics, which frequencies would still produce fluid streaming, but would avoid the creation of cavitation bubbles.

Also, it may be preferable to use a flat transducer rather than a sonicating horn. The flat transducer could be placed somewhere on the handpiece on the dental unit. A disposable pressure vessel cartridge could be placed in contact with the transducer, which would produce the needed ultrasound waves to generate fluid streaming. When the pressure vessel dimensions are determined, the frequency, amplitude, and input power can be determined for this application.

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Appendix A.

Aluminium oxide	
General	
Other names	Alumina, Aluminium(III) Oxide
Molecular formula	Al_2O_3
Molar mass	101.96 g/mol
CAS number	[[1344-28-1] [1]]
Properties	
Density and phase	3.97 g/cm³, solid
Solubility in water	Insoluble.
Melting point	2054°C
Boiling point	~3000°C
Thermal Conductivity	18 W/m·K
Structure	
Coordination geometry	Octahedron.
Crystal structure	Cubic.
Thermodynamic data	
Standard enthalpy of formation $\Delta_f H^\circ_{solid}$	-1675.7 kJ/mol
Standard molar entropy S°_{solid}	50.92 J/(mol K)
Heat capacity C_p	79.04 J/(mol K)
Flash point	Non-flammable.
Supplementary data page	
Structure and properties	n, ε_r = 9.5, etc. Refractive index at different wavelengths
Thermodynamic data	Phase behaviour Solid, liquid, gas
Spectral data	UV, IR, NMR, MS