DEVELOPMENT OF AN ADVANCED PAVEMENT DEICING SYSTEM

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16. Abstract

Current methods for winter maintenance of pavement surfaces consist of plowing and application of corrosive deicing agents. These chemicals are hazardous to the environment and hence, their use needs to be minimized. Over 20 years ago, the Connecticut Department of Transportation investigated the use of 300 psi pressurized salt brine jets to enhance the deicing performance. Despite promising results from several field trials, technical difficulties led to abandonment of this technology in the early 80's. Recent advances in high pressure jetting technology suggest that the use of high pressure jets in conjunction with improved chemical agents for pavement deicing may now be practical. In this study, the application of modern high pressure jetting technology as a means of pavement deicing is explored. The proposed system removes ice and snow through the combined action of mechanical jetting forces and controlled use of deicing chemicals. Appropriate operating parameters and consumption rates are identified and compared to the ConnDOT system developed in the 1970's.

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Development of an Advanced Pavement Deicing System

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ABSTRACT

Current methods for winter maintenance of pavement surfaces consist of plowing and application of corrosive deicing agents. These chemicals are hazardous to the environment and hence, their use needs to be minimized. Over 20 years ago, the Connecticut Department of Transportation investigated the use of 300 psi pressurized salt brine jets to enhance the deicing performance. Despite promising results from several field trials, technical difficulties led to abandonment of this technology in the early 80's. Recent advances in high pressure jetting technology suggest that the use of high pressure jets in conjunction with improved chemical agents for pavement deicing may now be practical. In this study, the application of modern high pressure jetting technology as a means of pavement deicing is explored. The proposed system removes ice and snow through the combined action of mechanical jetting forces and controlled use of deicing chemicals. Appropriate operating parameters and consumption rates are identified and compared to the ConnDOT system developed in the 1970's.

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BACKGROUND

Current Winter Maintenance Methods

The primary objective of any pavement deicing system is to maintain safe pavement surfaces. While current methods are very effective, application of large quantities of salt results in corrosion to highway and bridge structures, corrosion of automobiles and trucks and environmental damage due to runoff into streams and rivers. As a result, a need exists for improved deicing techniques which reduce the use of corrosive and environmentally hazardous deicing agents.

The traditional method for pavement deicing consists of plowing to remove the bulk of the snow cover followed by the application of sand and/or deicing chemicals. Sand improves traction and acts through mechanical action to break down ice. Deicing chemicals act to melt the remaining ice and packed snow and to prevent subsequent snow from accumulating on the pavement surface. For highway and bridge surfaces, sodium chloride, calcium chloride and sand are typically used. For airport runways and environmentally sensitive areas, non-corrosive, environmentally safe, acetate based chemicals are utilized.

Although sand improves safety and traction on icy roads, it is a large problem for the environment. An Oregon study found that 50 to 90 percent of the sand applied to the roadways remained in the environment after cleanup. The sand either stays on the road or is pushed to the side of the road into brush and trees. The Oregon Department of Environmental Quality stated that the dust created from road sanding might contribute to air pollution. Ideally sand particles should be larger that #50 sieve and smaller than three-eighths of an inch, but often very fine sand that can become airborne is generated.

The salt used on the roadways "usually comes from mined rock salt that has been crushed, screened, and treated with an anti-caking agent. Deicing salt is relatively light—just over one ton per cubic yard—and comes as a mixture of three-eighths inch granules to fine crystals" [1]. Even though deicing with salt is effective, it is labor intensive, costly, and harmful to surrounding areas. Road salt pollutes nearby lakes by introducing chlorine, a breakdown product of sodium chloride and calcium chloride, the two most common kinds of road salt. It is not difficult for the salt to contaminate the water since deicing chemicals are highly soluble. They follow the natural flow of the water, which usually affects groundwater and drinking water. This may not be obvious since the most visible environmental damage happens within 60 feet of the roadway. The environment is not the only thing damaged from the salt. Deicers also hasten corrosion rates in cars, bridges, and roadways. According to a federal estimate made in 1991, road salt causes corrosion damage valued at $3.5 to $7 billion per year.

As a result of several research projects and estimations, the need for other deicing chemicals that effectively melt ice and snow are being considered. In order to melt snow and ice, several variables must be taken into consideration. These variables include deicer concentration, time deicer takes effect, road temperature, weather conditions, road surface, topography, and traffic volume. It should also be noted that deicers don't actually melt ice in their solid form, rather the solid deicing particles penetrate the ice and dissolve into a brine. It is this brine that actually breaks the bond of ice and pavement.

Several alternate deicing chemicals have been considered in recent years. Cost estimates for several alternate deicing chemicals are shown in Table 1. One alternative to using rock salt (or sodium chloride) is calcium chloride. Calcium chloride is less harmful to concrete [2]. Calcium chloride is also more effective in colder weather conditions than regular road salt. Even though rock salt costs half the amount of calcium chloride by weight, calcium chloride will melt two times the area compared to rock salt [2]. Calcium chloride is delivered in dry pellets or flakes, or as a specified concentration of solution. Iowa has been using liquid calcium chloride solution to prewet rock salt. This allows for two effective deicers to work at once, and to reduce the environmental damage at the same time. A reported problem associated with using calcium chloride is that since it remains wet on the ground, any blowing snow sticks to it, contributing to additional snow build-up. Salt, on the other hand, leaves a dry pavement, but is not as effective in removing the ice off of roadways as calcium chloride. To overcome this problem, it is recommended that the calcium chloride treated roads be plowed clear on occasion to keep the pavement free of snow.

Table 1. Cost Estimates of Various Deicing Chemicals

Chemical	**Cost**	**Amount**
Road Salt	$30	Per ton
Sand	$4	Per ton
Commercial CMA	$700	Per ton
Whey-based CMA	$400	Per ton
Calcium Chloride	$60	Per ton
Magnesium chloride (flakes)	$49	Per Metric ton
Magnesium chloride (granular)	$129	Per Metric ton
Potassium acetate	$1050	Per ton

Another alternative chemical deicing agent is calcium magnesium acetate (CMA) [3-5]. CMA is non-corrosive and is considered safe for the environmentally because it is biodegradable and does not harm vegetation or aquatic organisms. CMA is created by fermenting potato peels, and then by adding limestone dust. Researchers have also discovered that cheap feedstocks, such as cheese whey can be used to make CMA. By fermenting the cheese whey to produce acetic acid, and then adding lime to it, it produces CMA. The use of CMA has been evaluated in numerous studies and has been shown to be an effective alternate to salt. Unfortunately, the cost of CMA, roughly 20 times that of rock salt, has prevented it from being widely used. It is used in environmentally sensitive areas. While road salt costs about $30 per ton and CMA costs about $700 per ton, a whey-based CMA is expected to be cheaper than commercial CMA. It is estimated that the cost of CMA made from cheese "are roughly 20 percent of the price of commercially available CMA" [4]. A similar concept is being developed at Michigan Technological University. In their CMA production method, agricultural or food wastes are fermented and combined with limestone dust. This product is then mixed with ground glass to produce a deicer and abrasive in one.

Recently, another chemical with the trade name "Ice Ban®" has been introduced. Ice Ban is also derived from a residue produced during the processing of grains. It has been

® Ice Ban is a registered trademark of Natural Solutions, Inc.

shown to have good adhesion properties and, as shown in Figure 1, it penetrates the ice and acts directly on the ice/pavement interface. By attacking the interface rather than melting the entire ice layer, the amount of chemical that needs to be applied is reduced. Ice Ban can also be used in combination with other chemical agents.

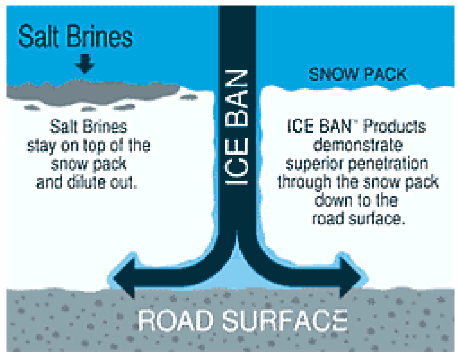

Figure 1. Schematic showing Ice Ban acting at ice/pavement interface.

Recently, a more effective strategy has been introduced for maintaining safe pavement surfaces. In this strategy, called "anti-icing," chemicals are applied to pavement surfaces before the snowfall begins. These chemicals act to prevent a bond from forming between the pavement and ice. A recent FHWA report concluded that "The key to a successful anti-icing strategy is knowing which chemical to use, in what amount, and when"[6]. Since effective use of this strategy requires accurate weather forecasting, this method involves access to the Road Weather Information System (RWIS) and the use of meteorological data. In addition, various sensors are being developed to monitor weather and pavement conditions. Anti-icing requires less time and energy to clear off the roads completely after a storm, thus saving agencies money by reducing winter maintenance costs. By using anti-icing strategies, Nevada estimates it will be able to save $7 million in labor, materials, and other costs over the next 25 years [7]. In addition to cost savings, the traveling public will benefit as well. Since anti-icing is deemed more effective, the number of automobile accidents will decrease, improving public safety and providing cost savings associated with a reduction in property damage. Anti-icing also reduces the amount of sand required to treat the roadway. Sand usually requires more than one application to be effective in a storm. This translates in to cost of materials, hours of labor, and equipment usage and wear. Plus, the sand must be cleaned up at the end of the season or storm. By placing an anti-icing agent on the roadway before the storm, this limits any possible ice from forming or bonding to the road, thus reducing the need for sand. By using the anti-icing strategy in Boulder, Colorado, they have realized a 55 percent reduction in sand use, and anti-icing costs the state half the amount of conventional sanding and deicing [8]. Since sand use is reduced dramatically while using an anti-icing agent, the environment benefits from the trade-off. A test performed by the Oregon DOT found that anti-icing could “significantly reduce the environmental problems associated with sand use by adopting an anti-icing strategy” [9]. The Virginia Department of Transportation is involved with a project to combat freezing bridge decks. They are “evaluating the effectiveness and practicality of automated bridge deck anti-icing spray system technology” [10].

In general, it is felt that using anti-icing agents is more effective than using deicers. Anti-icing helps to minimize air and water pollution, while at the same time keeps roads clear and safe. Even though anti-icing involves applying a salt mixture or other proper chemicals to the road before a winter storm hits, the amount of the salt product is reduced compared to traditional salt deicing. Since anti-icing agent prevents the ice from forming and bonding to the pavement, road surfaces remain wet or slushy. With anti-icing, the amount of sand required is reduced dramatically. Anti-icing improves travel conditions, saves money, and helps in protecting the environment.

Use of Jetting for Pavement Deicing

The application of jetting technology to pavement deicing was first explored over 20 years ago. In that study, the Connecticut Department of Transportation (ConnDOT) developed and tested a salt brine deicing system [11-20]. In this system, a pump pressure of nominally 300 psi was used. During operation, however, the pressure was believed to drop below 200 psi. The brine tank capacity was 1500 gallons. As shown in Figure 2, a linear array of twenty-eight nozzles with a diameter of .080" were mounted between the front and rear wheels of a snow plow. The consumption rate of this system was approximately 65 gallons/min, or, assuming a truck speed of 25 mph, the consumption rate was 150 gallons/mile. The resulting range for the system was 10 miles. Since this range was judged to be inadequate, the number of nozzles was reduced to seventeen, resulting in a range increase to 20 miles. The results of the deicing trials indicated that the system provided effective highway deicing at reduced salt consumption rates. The system effectively turned ice and snow into slush and delivered brine to the ice/pavement interface. Despite these positive results, several drawbacks were observed. As stated above, the limited range made the system difficult to implement. Also, several problems with the brine making system occurred. The time required to fill the tank was too slow to be practical. Other problems included corrosion of components and clogging of the nozzles. The fate of the system was summed up by an engineer at ConnDOT who stated that the system was "too sophisticated for its time" [21].

Advances in Jetting Technology

Since the study at ConnDOT, there have been extensive advances in high pressure jetting technology. The use of high pressure water as a machining tool was introduced in the early 1980's. Originally, these system utilized intensifier pump technology (Figure 3). As shown in Figure 4, intensifier pumps produce high pressure water through intensification of pressure of hydraulic fluid. The hydraulic fluid is pressurized by a hydraulic pump driven by an electric motor. As shown in Figure 3, intensifier pumps are large and not well suited for mobile applications. In the early 1990's, high pressure direct drive pumps became available. These pumps (see Figure 5) are compact and can be driven by electric or gasoline powered motors.

A typical commercial waterjet cutting system is shown in Figure 6. In addition to the high pressure pump system, this system includes a PC controlled x-y positioning system. The system software allows for 2-D CAD drawings to be imported for use in defining the

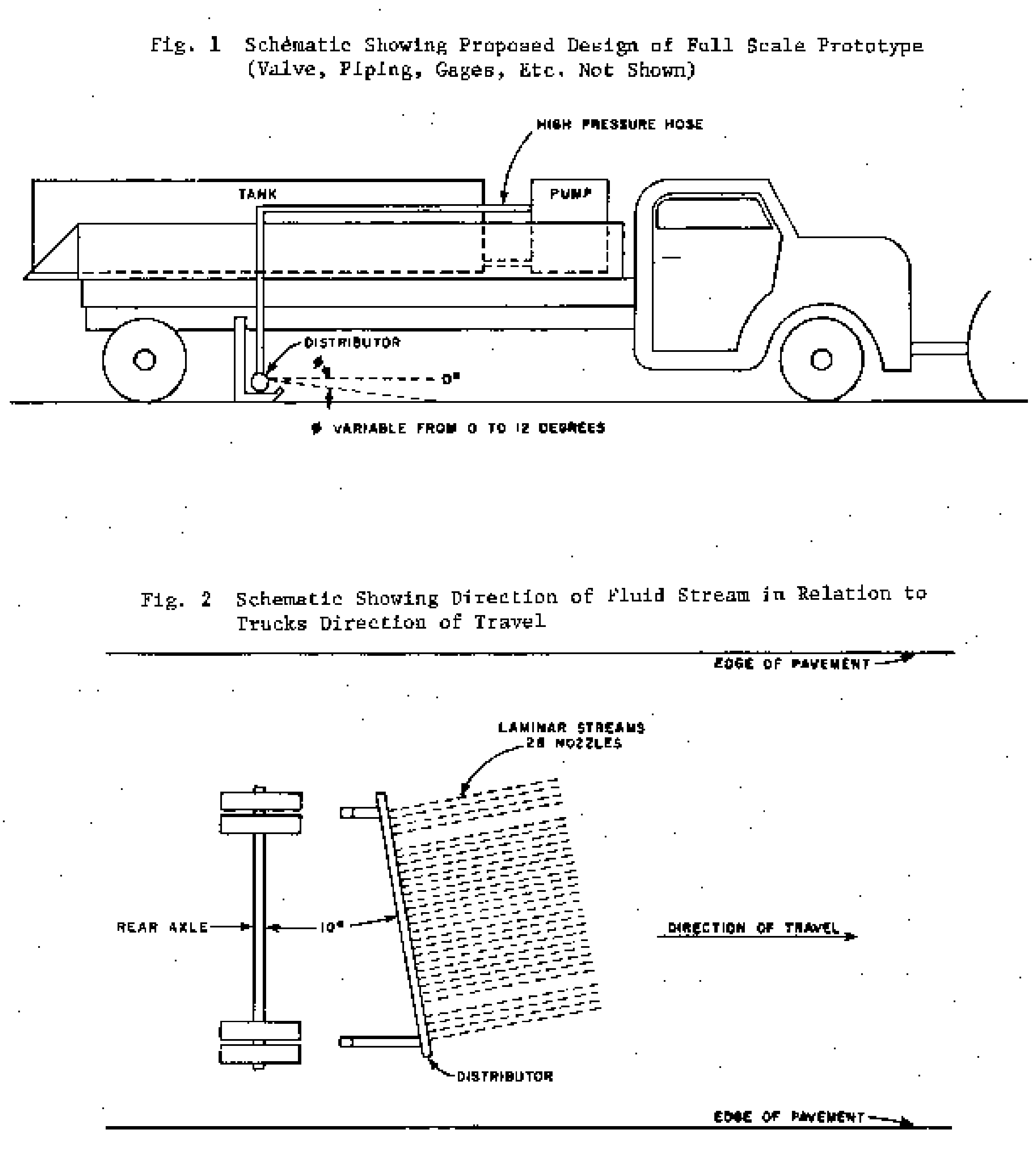

Figure 2. Schematic of Connecticut DOT’s Deicing system [].

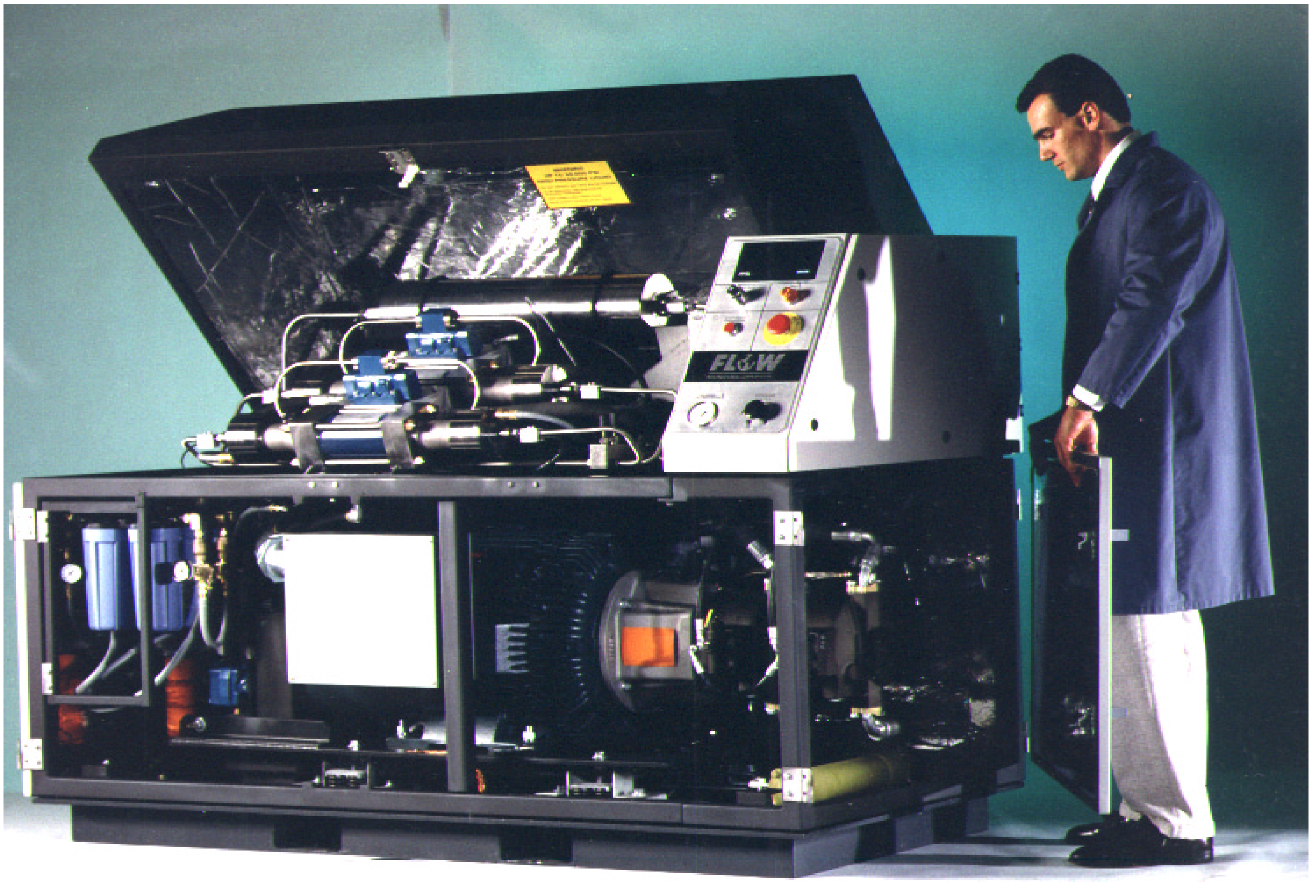

Figure 3. Industrial high pressure dual intensifier waterjet pump system (courtesy of Flow International)

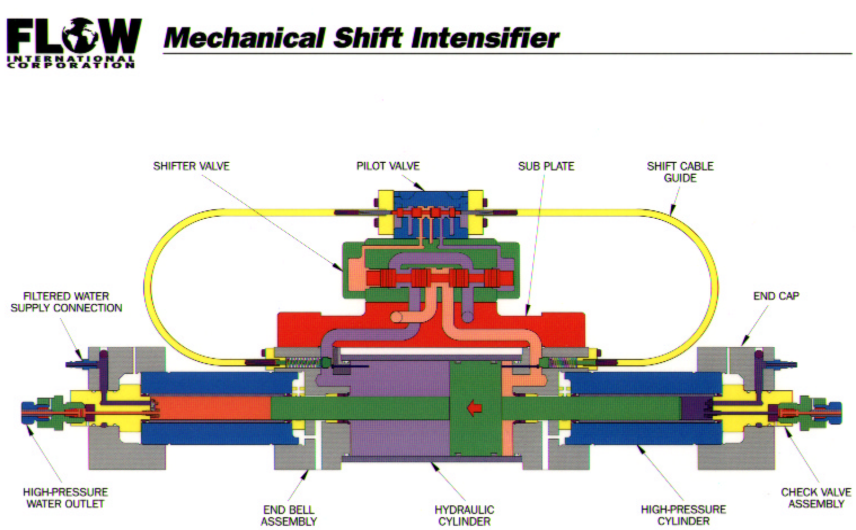

Figure 4. Schematic of intensifier pump (courtesy of Flow International)

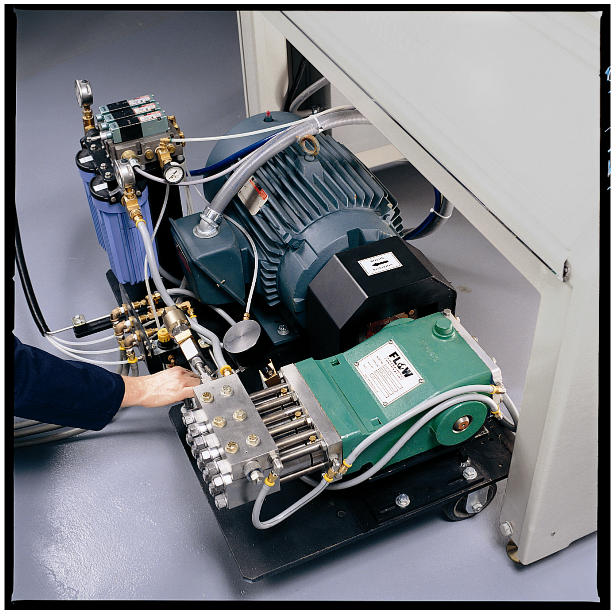

Figure 5. Industrial direct drive waterjet pump system (courtesy of Flow International)

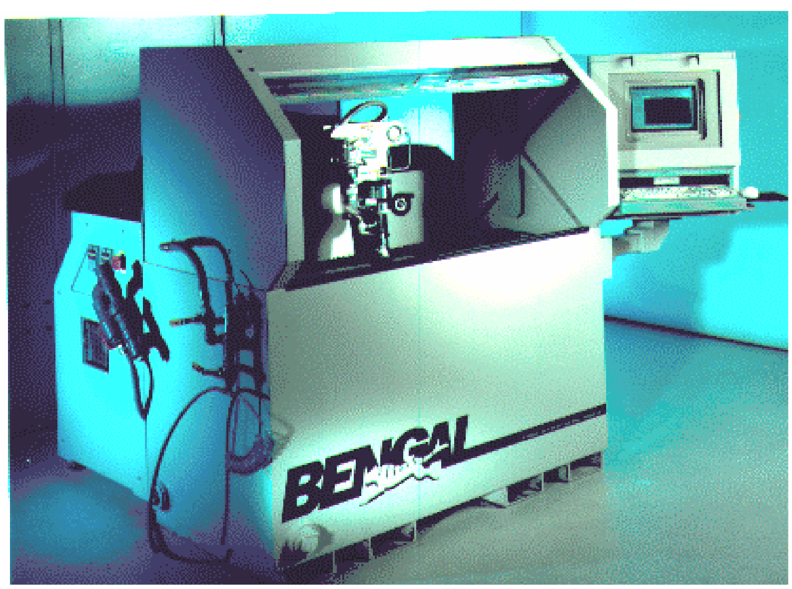

Figure 6. Industrial waterjet cutting system (courtesy of Flow International)

cutting path. In addition, the software determines the appropriate cutting speeds and waterjet cutting parameters. With such systems, intricate designs can be machined. As shown in Figure 7, pure waterjets with no abrasive can be used to machine relatively soft and/or thin materials. In pure waterjet cutting, the high pressure water is simply accelerated through a fine diameter orifice. For harder target materials, abrasive is entrained into the high velocity waterjet stream (Figure 8) to produce an extremely powerful cutting medium. Since the abrasive particles are traveling at very high velocities, abrasive waterjet machining has been referred to as "supersonic grinding." The abrasive delivery system, (Figure 9) consists of an abrasive hopper pressurized with air, an abrasive delivery hose, a mini-hopper which regulates the abrasive flow, an abrasive mixing head in which the abrasive is entrained downstream of the orifice into the waterjet stream, and a mixing tube or nozzle in which the abrasive is accelerated by the high velocity water. An exploded view of the orifice, mixing chamber and mixing tube are shown in Figure 10.

High pressure jetting applications have been successful and widely used in a variety of industries. High pressure pure water is used for cleaning and removing surface coatings. It is also used for cutting of soft materials such as paper, foam, plastics, diapers, food, automotive carpet, head liners and dashboards. For cutting hard materials such as steel, titanium, composites, aluminum, stone, glass, ceramics and laminates, abrasive is added to the jet stream. It is now claimed that high pressure waterjets can be used to cut virtually any material.

In this study, the feasibility of using high pressure jetting technology for pavement deicing is revisited, taking into account advances in jetting technology that have occurred over the past 20 years. It is believed that advances in jetting technology now provide the capability for reliable and safe operation of jetting systems under adverse conditions, and hence, this application may prove to be successful. This study includes a series of ice cutting trials, both with and without abrasive in the jet stream. The objective of these trials is to identify an appropriate combination of jetting parameters for use in pavement deicing.

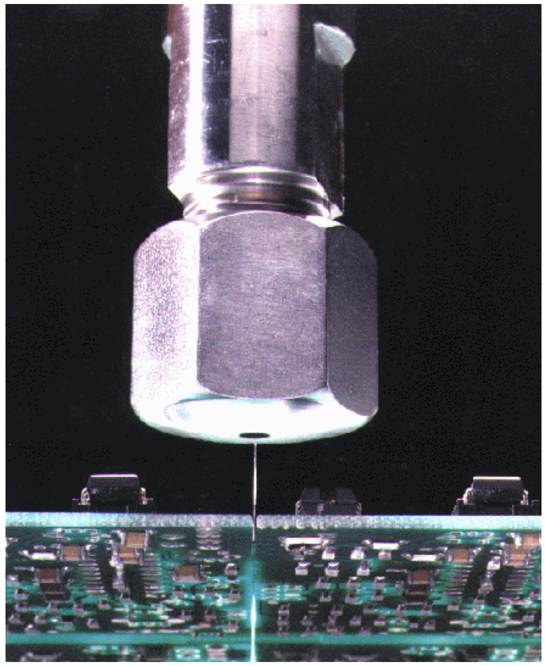

Figure 7. Waterjet cutting with no abrasive (courtesy of Flow International)

Figure 8. Abrasive waterjet cutting (courtesy of Flow International)

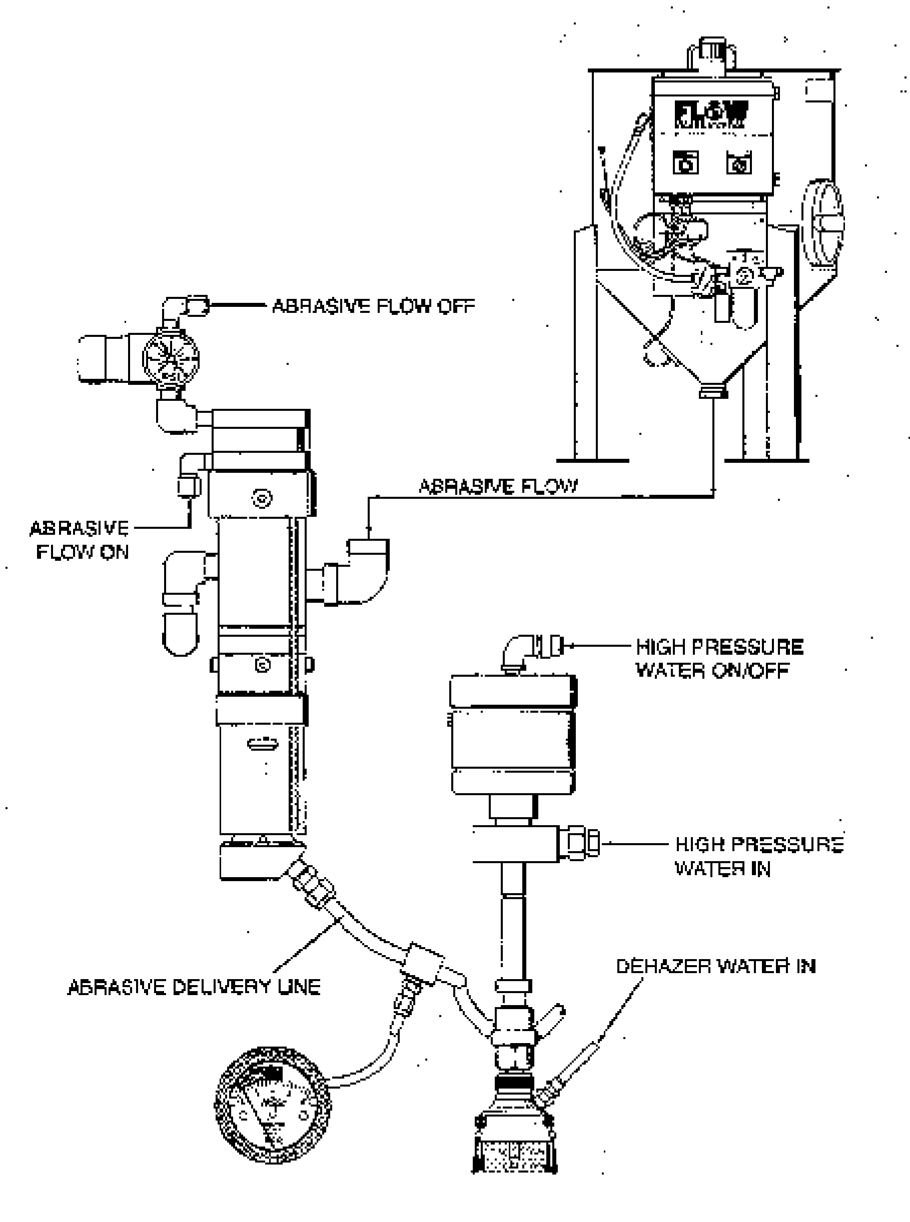

Figure 9. Abrasive delivery system (courtesy of Flow International)

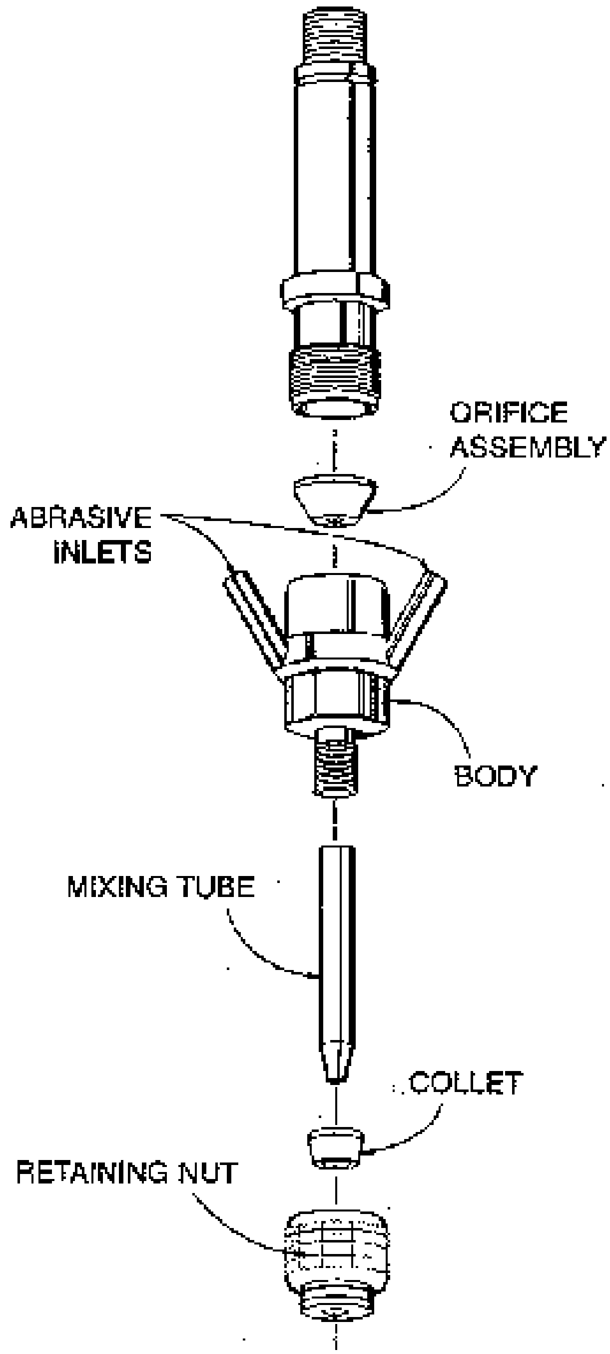

Figure 10. Exploded view of abrasive waterjet mixing head
(courtesy of Flow International)

EXPERIMENTAL STUDY

Several parameters are known to affect the performance of a waterjet cutting system. For example, when no abrasive is to be used, the effects of water pressure, orifice diameter, traverse speed and standoff distance (the distance from the tip of the nozzle to the target material surface) need to be characterized. When abrasive is used, the nozzle diameter, abrasive size and abrasive flow rate all effect cutting performance and hence need to be evaluated. To characterize these effects, a series of cutting trials (see Tables 2 & 3) were performed. In the abrasive waterjet trials (Table 2), the effects of pressure, standoff distance, abrasive size, abrasive flow rate and orifice/nozzle combination were characterized. In the pure waterjet trials, the effects of pressure, standoff distance and orifice diameter were characterized. For each combination of parameters, a series of passes at various traverse speeds was performed. Note that due to limitations in the maximum traverse speed available with the laboratory equipment, these trials were performed at speeds much lower than will be used in deicing applications. The results of these trials will provide, however, a reliable determination of an optimal combination of operating parameters that will also be applicable at highway speeds. The depth of cut was then measured by inserting gage pins into the groove created by the jet and plots of depth of cut vs. speed were generated. The resulting curve characterizes the cutting performance of each particular combination of cutting parameters.

Table 2. Ice cutting trials (with abrasive)

Pressure (ksi)	Standoff Distance (in)	Abrasive Flow Rate (lb/min)	Orifice / Nozzle (in)
5	1	.4	.013 / .040
10	1	.4	.013 / .040
15	1	.4	.013 / .040
10	.5	.4	.013 / .040
10	1.5	.4	.013 / .040
10	1	.3	.013 / .040
10	1	.6	.013 / .040
10	1	.4	.010 / .030
10	1	.6	.010 / .030

Table 3. Ice cutting trials (no abrasive)

Pressure (ksi)	Standoff Distance (in)	Orifice (in)
6	1.5	.010
8	1.5	.010
10	1.5	.010
5	2.5	.010
7.5	2.5	.010
10	2.5	.010
5	3.5	.010
7.5	3.5	.010
10	3.5	.010
5	1.5	.013
7.5	1.5	.013
10	1.5	.013
5	2.5	.013
7.5	2.5	.013
10	2.5	.013
5	1.5	.013
7.5	1.5	.013
10	1.5	.013

EXPERIMENTAL RESULTS

Abrasive Trials

Typical results for the abrasive waterjet trials are shown in Figures 11-15. In all of these figures, the inverse relation between depth of cut and traverse speed is clearly evident. Figure 11 illustrates the dramatic increase in depth of cut with increased water pressure. Figure 12 illustrates that decreasing the standoff distance increases the depth of cut. Figures 13 and 14 show that the optimum abrasive flow rate varies the particular orifice/nozzle combination being used. Conventional wisdom in the waterjet industry is that cutting performance increases with abrasive flow rate up to an optimal level, above which effective acceleration of the abrasive does not occur and cutting performance diminishes. Figure 15 shows that by increasing the orifice/nozzle diameter, thereby increasing the amount of energy being delivered to the target, results in an increase in cutting performance. Note that a nozzle to orifice diameter ratio of approximately 3 to 1 provides good mixing conditions and optimum acceleration of the abrasive.

An empirical cutting model based on the abrasive waterjet ice cutting trial results was developed. In the model, it is assumed that the depth of cut, d, can be expressed in terms of pressure, P, orifice diameter, d_o, and traverse speed, u as follows:

$$d = \frac{aP^b d_o^c}{u^e} \qquad (1)$$

where d is in inches, P is in ksi, d_o is in thousandths of an inch, and u is in inches/min. Using these units, the non-linear correlation analysis was performed to determine the empirical parameters: a=1.073, b=1.509, c=0.322, and e=0.930. Note that since the range of standoff distances considered did not dramatically affect the depth of cut, this parameter was not included in the empirical model. The accuracy of this correlation analysis was evaluated by comparing the predicted depth of cut to the measured depth of cut for all of the combinations of parameters evaluated. As shown in Figure 16, this comparison reveals that the correlation analysis provides a reasonable prediction of the depth of cut for a given combination of parameters.

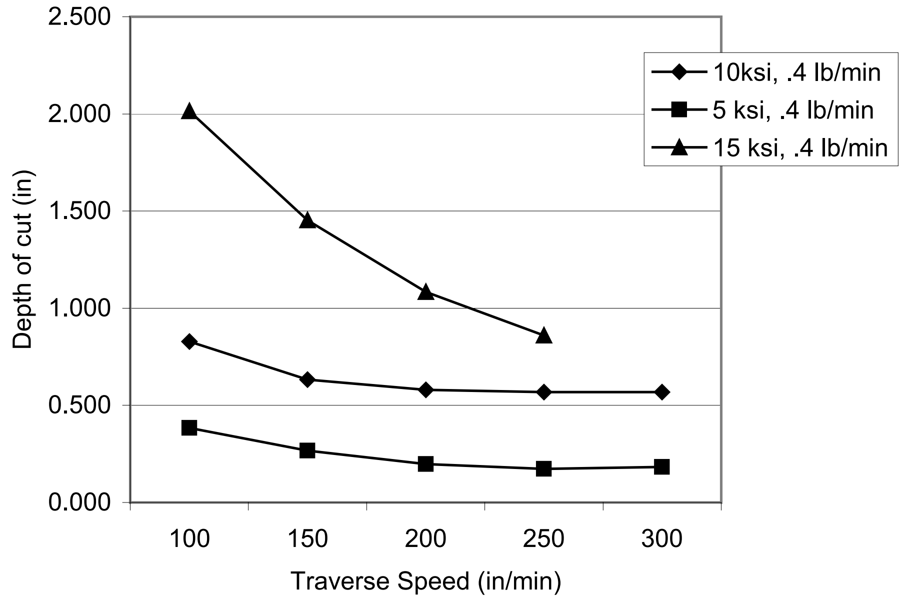

Figure 11. Effect of pressure on cutting depth (80 mesh garnet @ 0.4 lb/min)

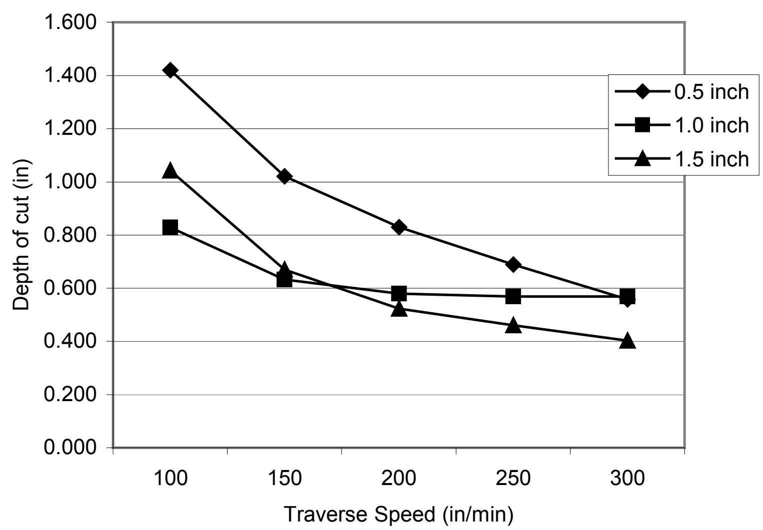

Figure 12. Effect of standoff distance on cutting depth.

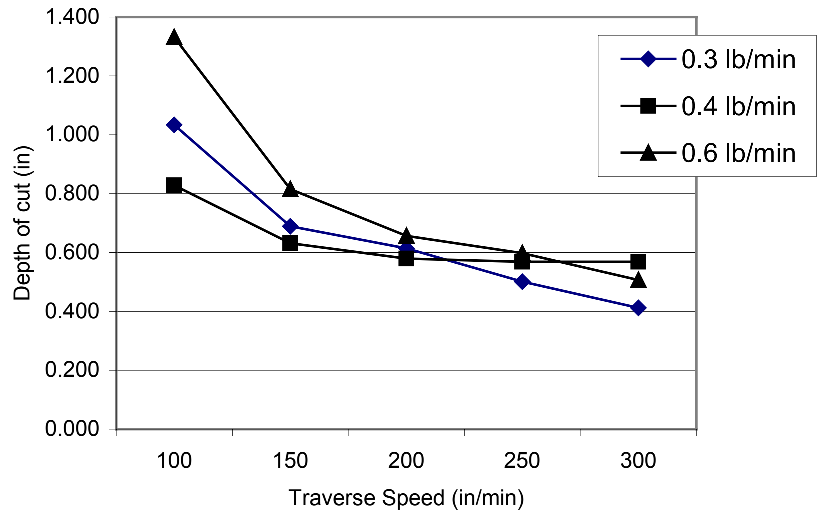

Figure 13. Effect of abrasive flow rate on cutting depth (orifice / nozzle = .013/.040")

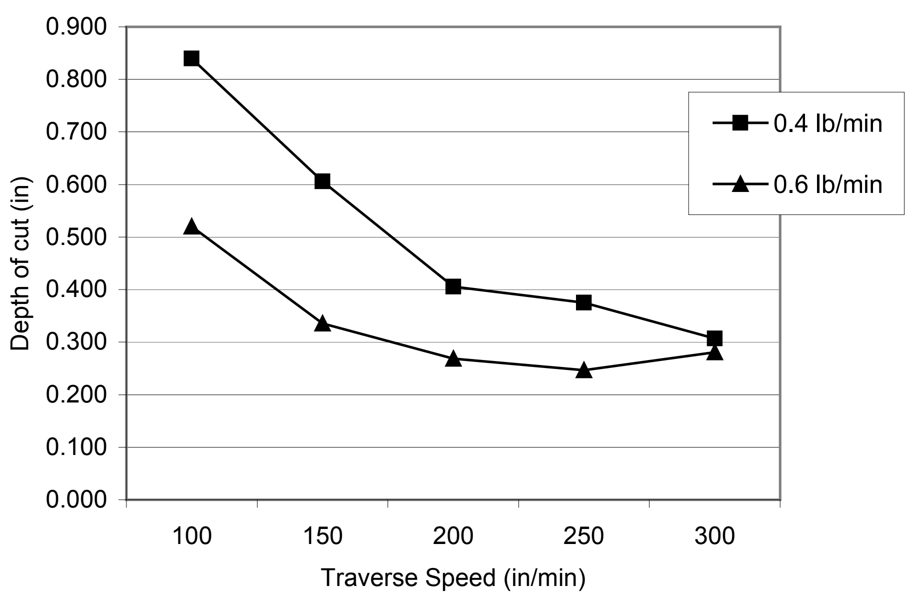

Figure 14. Effect of abrasive flow rate on cutting depth (orifice / nozzle = .010/.030")

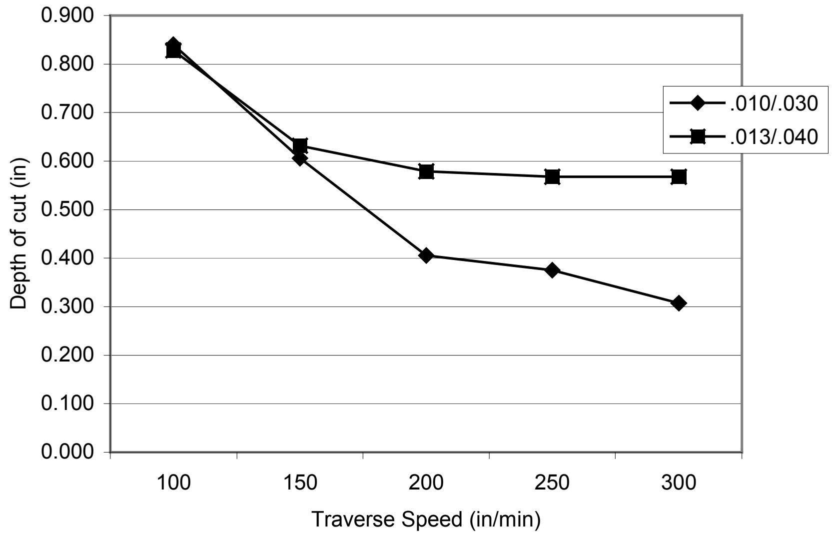

Figure 15. Effect of orifice/nozzle combination on cutting depth.

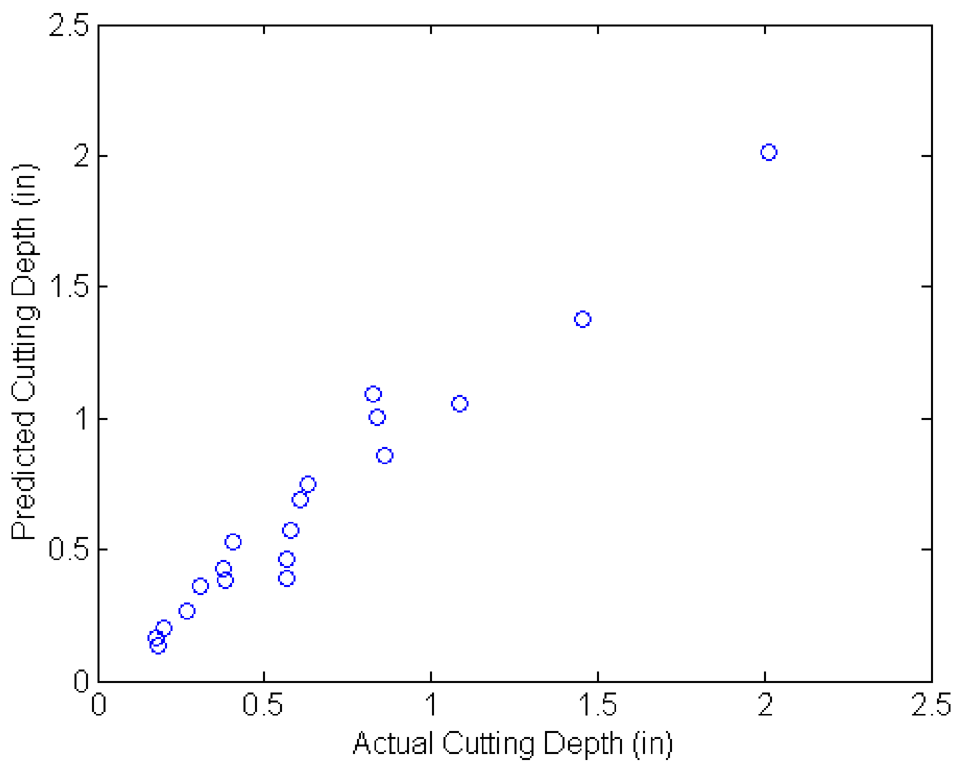

Figure 16. Comparison of actual and predicted depth of cut (with abrasive)

Pure Water Trials

For the case of pure waterjet cutting (Figures 17-38), the effects of pressure, standoff distance, orifice diameter and traverse speed were evaluated. For each combination of pressure, standoff distance and orifice diameters, the relation between depth of cut and traverse speed was evaluated. For all combinations of standoff distance and orifice diameter (see Figures 17-22), increasing the water pressure from 34 MPa (5 ksi) to 69 MPa (10 ksi) resulted in a dramatic increase in depth of cut. The effect of standoff distance is shown in Figures 23-28. Generally speaking, increasing the standoff distance decreased the depth of cut. In several cases, however, this trend was not observed. The effects of orifice diameter on cutting performance are shown in Figures 29-37. For most cases, increasing the orifice diameter results in an increase in depth of cut.

An empirical model including the effects of water pressure, standoff distance and orifice diameter was developed using a procedure similar to that for the abrasive waterjet trials. It this case it is assumed that the depth of cut, d, can be expressed in terms of pressure, P, standoff distance, s, orifice diameter, d_o, and traverse speed, u as follows:

$$d = \frac{a\, P^b\, d_o^c}{s^e\, u^f} \tag{2}$$

where d is in inches, P is in ksi, s is in inches, d_o is in thousandths of an inch, and u is in inches/min. Using these units, the non-linear correlation analysis was performed to determine the empirical parameters, a=0.994, b=2.020, c=0.763, e=0.320 and f=1.406. The depth of cut predicted for each combination of cutting parameters evaluated are compared to the experimental measurements in Figure 39. It can be seen that equation 2 provides reasonable estimates of the depth of cut and can therefore be used in determining the operating parameters for the pavement deicing system.

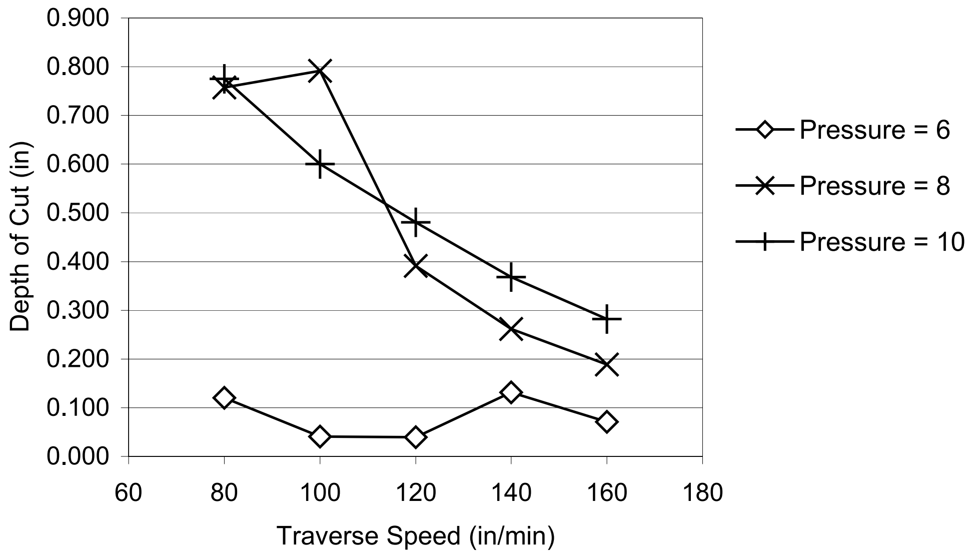

Figure 17. Effect of pressure on cutting performance
(standoff = 1.5”, orifice = .010”)

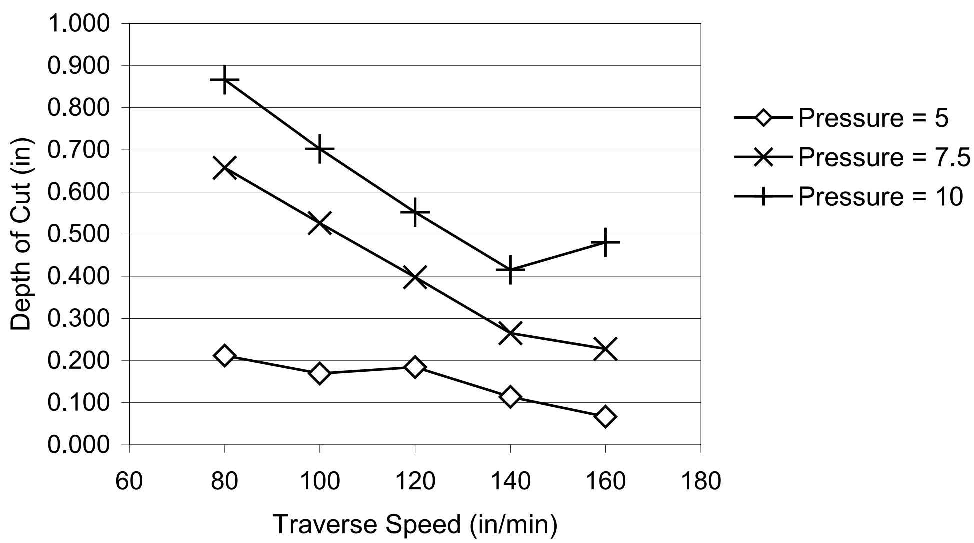

Figure 18. Effect of pressure on cutting performance
(standoff = 2.5”, orifice = .010”)

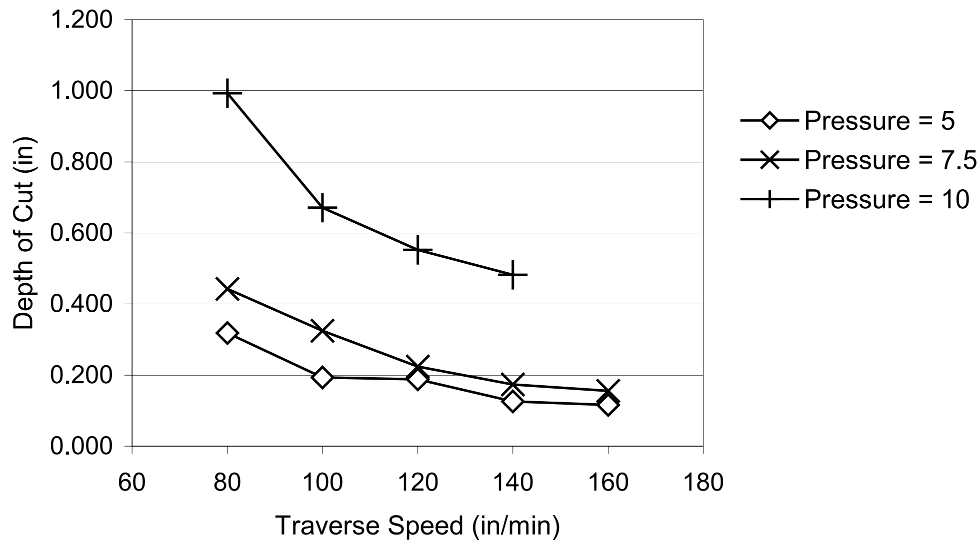

Figure 19. Effect of pressure on cutting performance
(standoff = 3.5”, orifice = .010”)

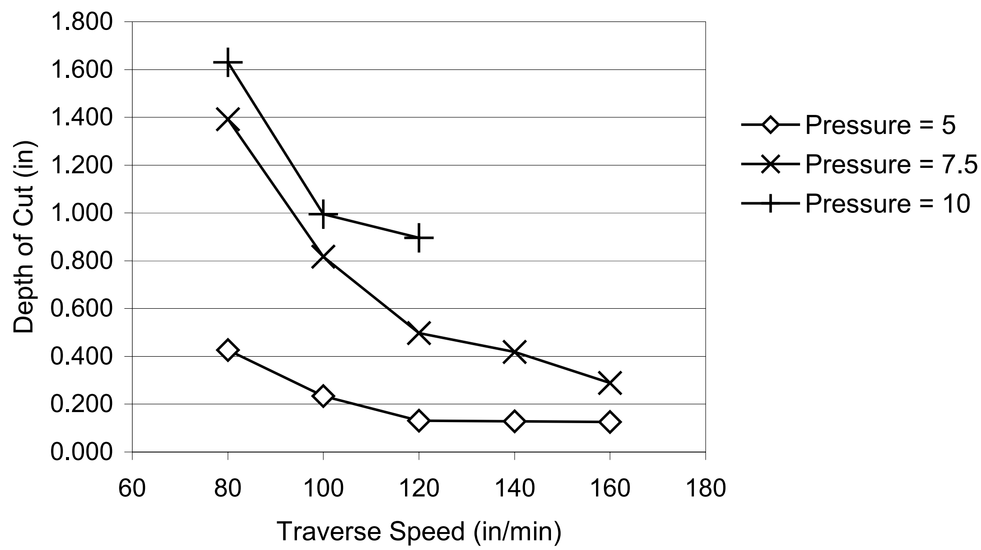

Figure 20. Effect of pressure on cutting performance
(standoff = 1.5”, orifice = .013”)

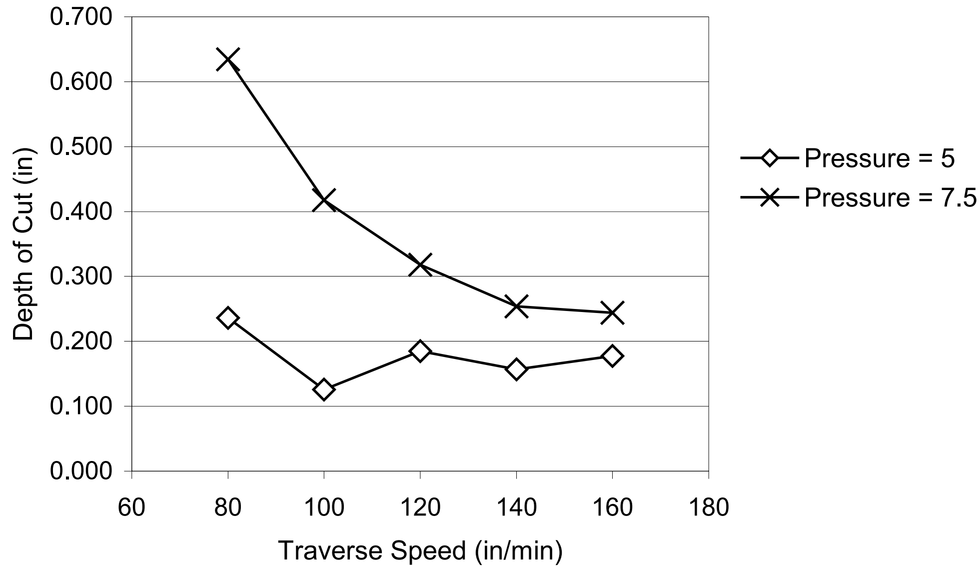

Figure 21. Effect of pressure on cutting performance
(standoff = 2.5”, orifice = .013”)

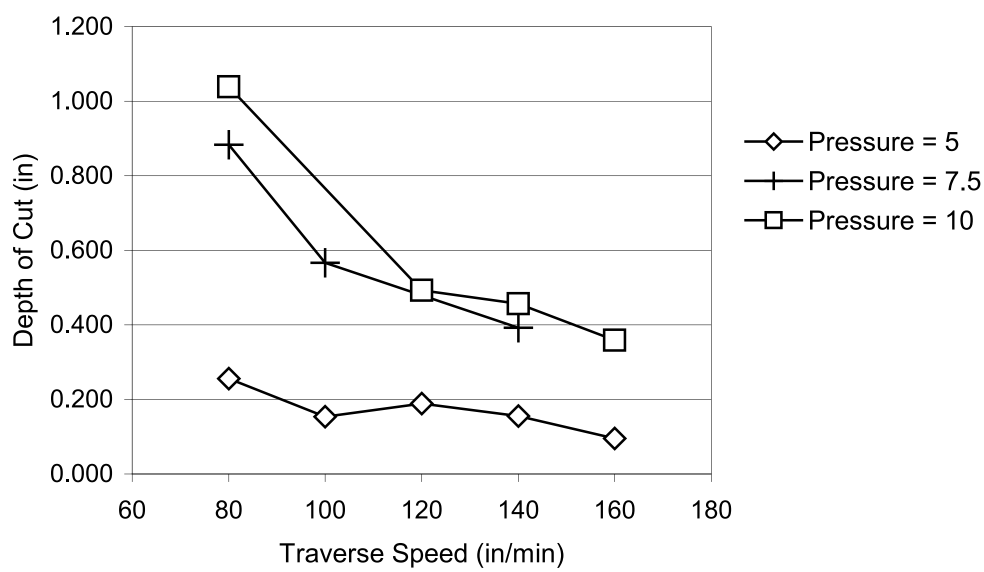

Figure 22. Effect of pressure on cutting performance
(standoff = 3.5”, orifice = .013”)

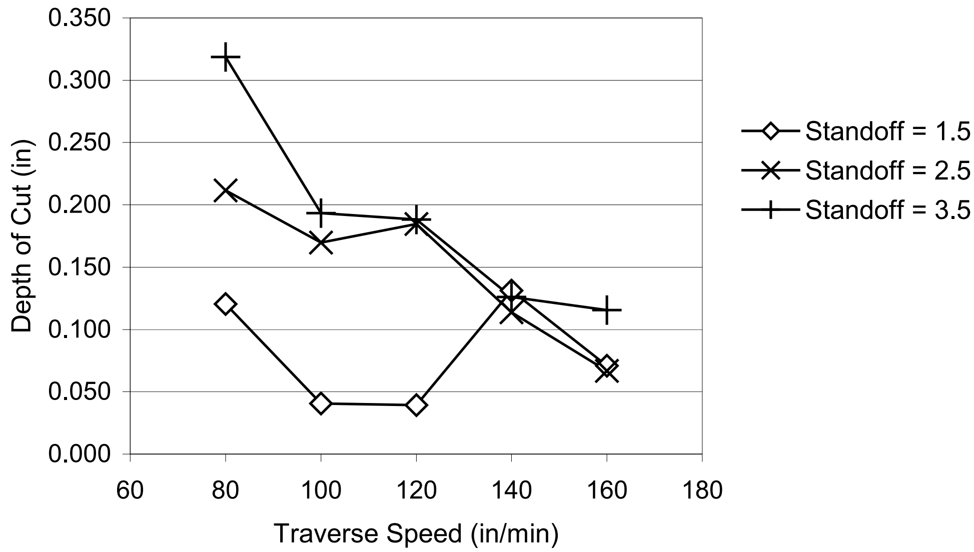

Figure 23. Effect of standoff distance on cutting performance
(pressure = 5 ksi, orifice = .010")

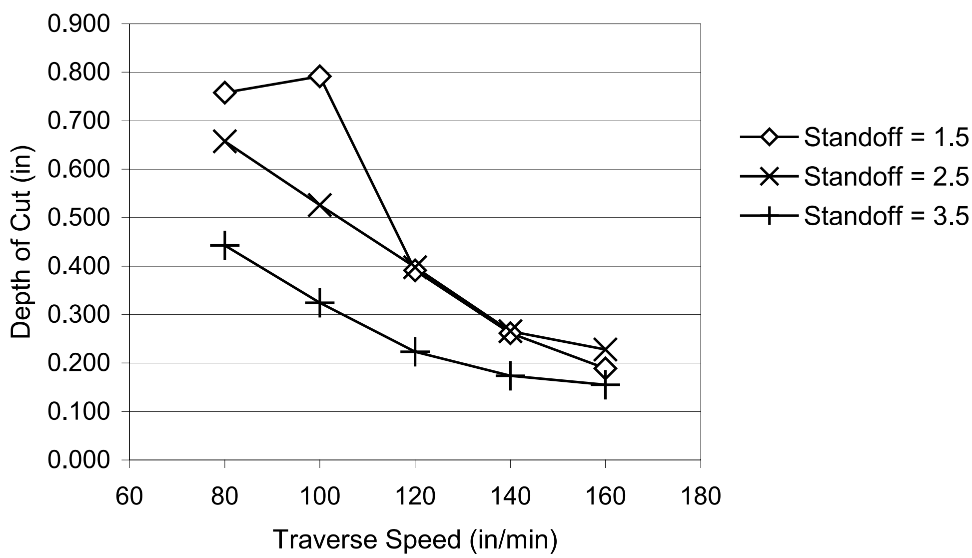

Figure 24. Effect of standoff distance on cutting performance
(pressure = 7.5 ksi, orifice = .010")

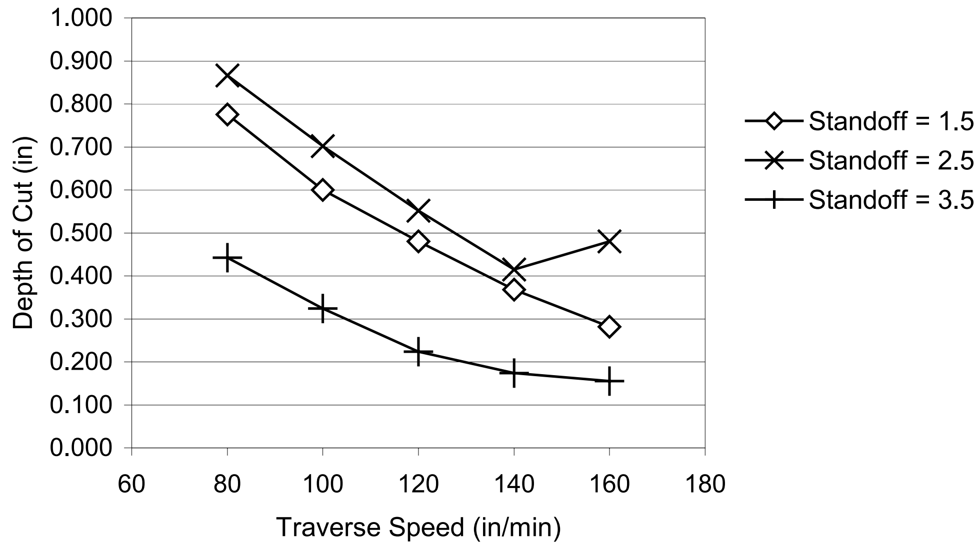

Figure 25. Effect of standoff distance on cutting performance
(pressure = 10 ksi, orifice = .010")

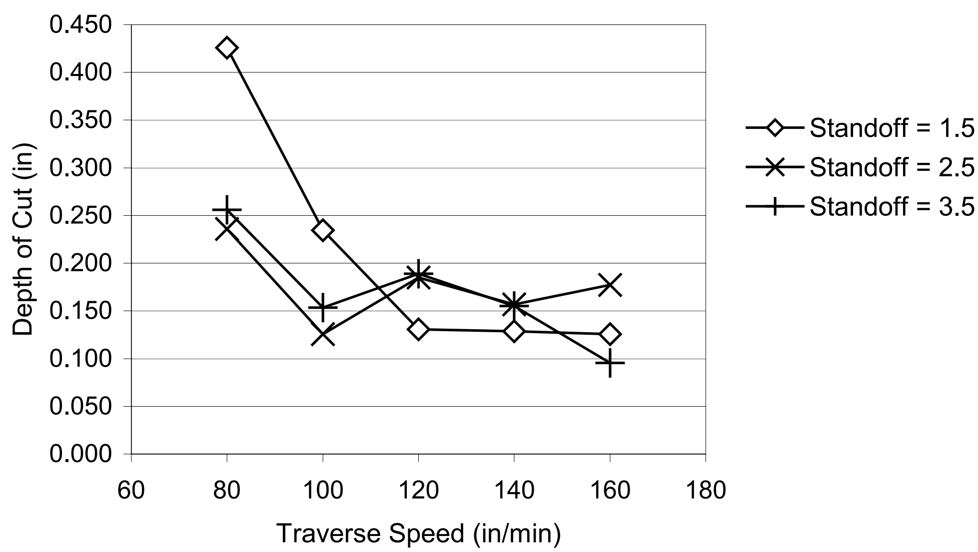

Figure 26. Effect of standoff distance on cutting performance
(pressure = 5 ksi, orifice = .013")

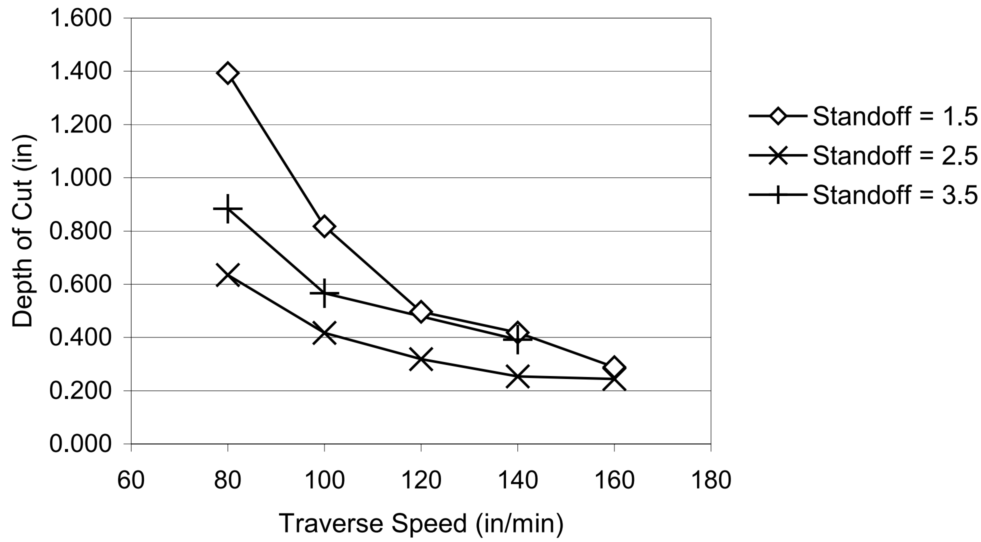

Figure 27. Effect of standoff distance on cutting performance
(pressure = 7.5 ksi, orifice = .013")

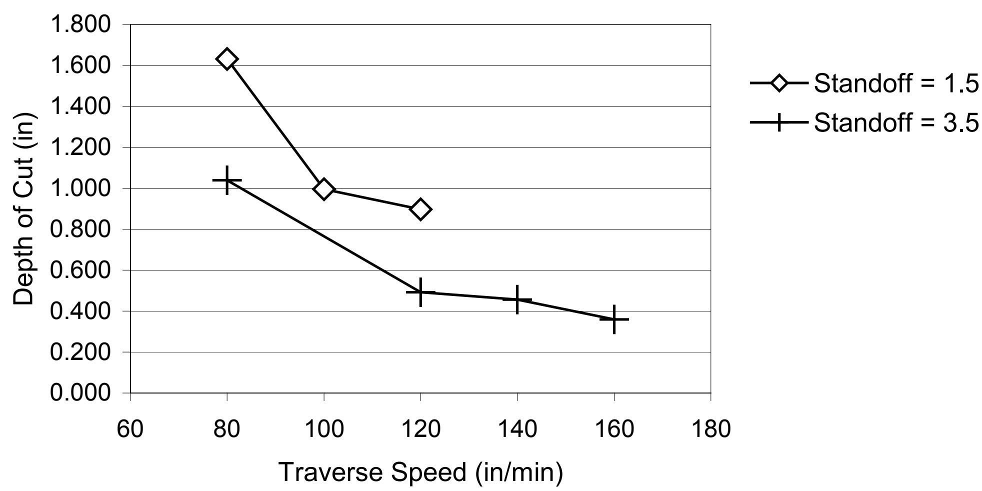

Figure 28. Effect of standoff distance on cutting performance
(pressure = 10 ksi, orifice = .013")

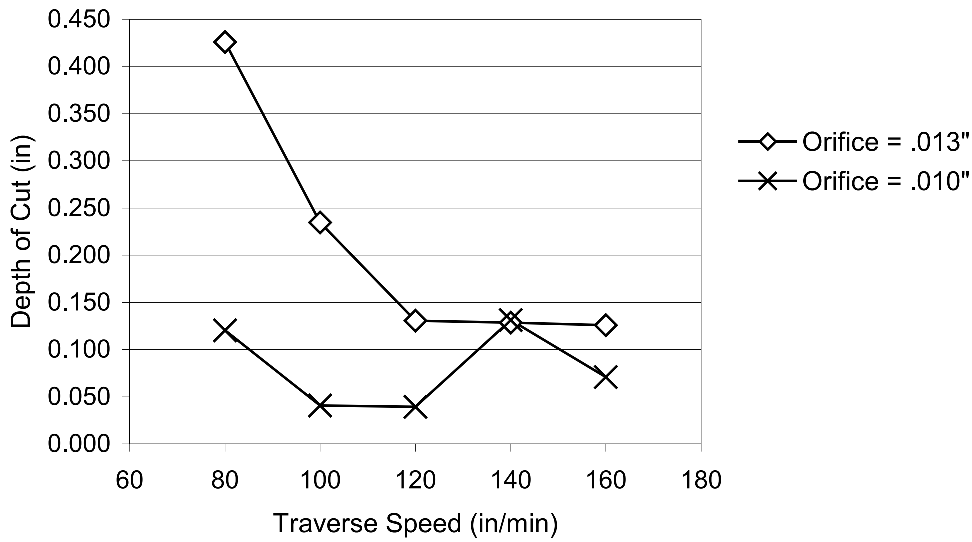

Figure 29. Effect of orifice diameter on cutting performance
(pressure = 5 ksi, standoff = 1.5")

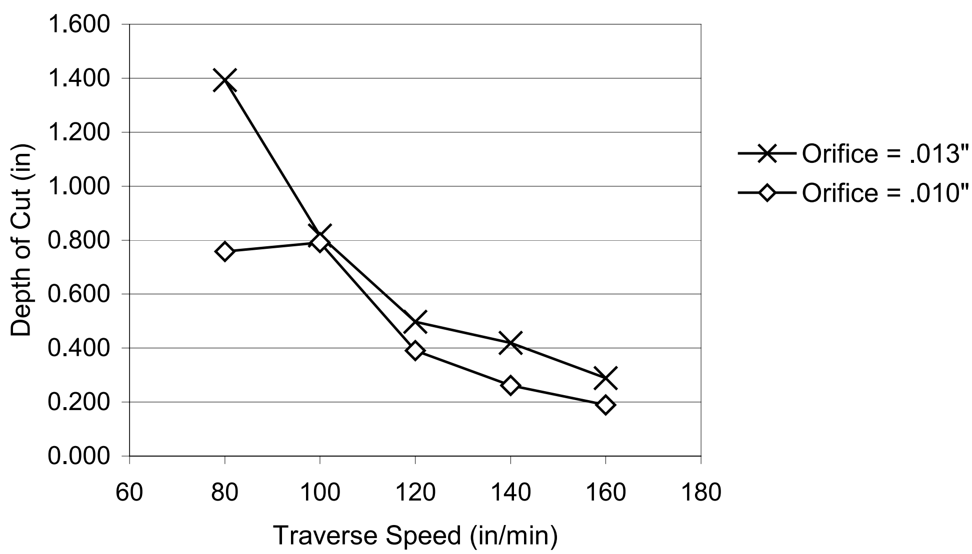

Figure 30. Effect of orifice diameter on cutting performance
(pressure = 7.5 ksi, standoff = 1.5")

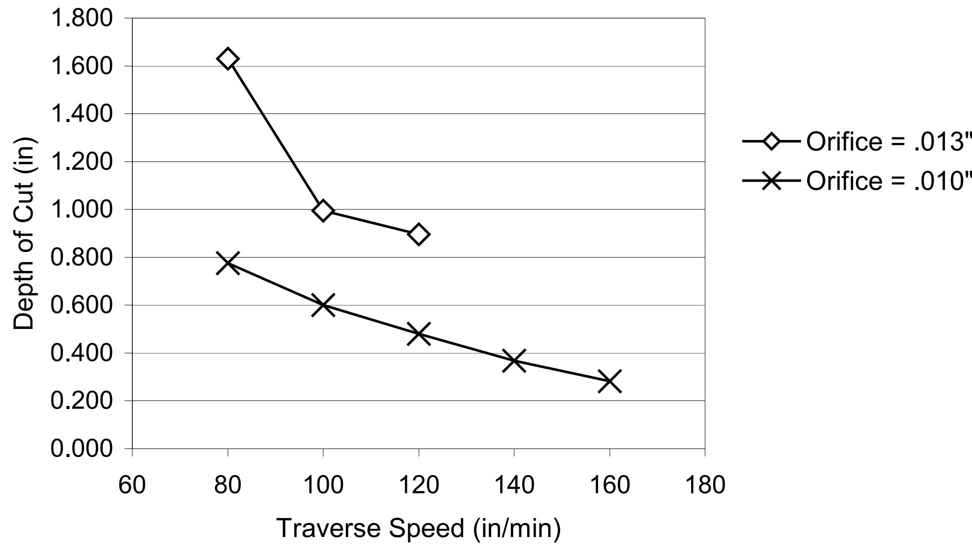

Figure 31. Effect of orifice diameter on cutting performance
(pressure = 10 ksi, standoff = 1.5”)

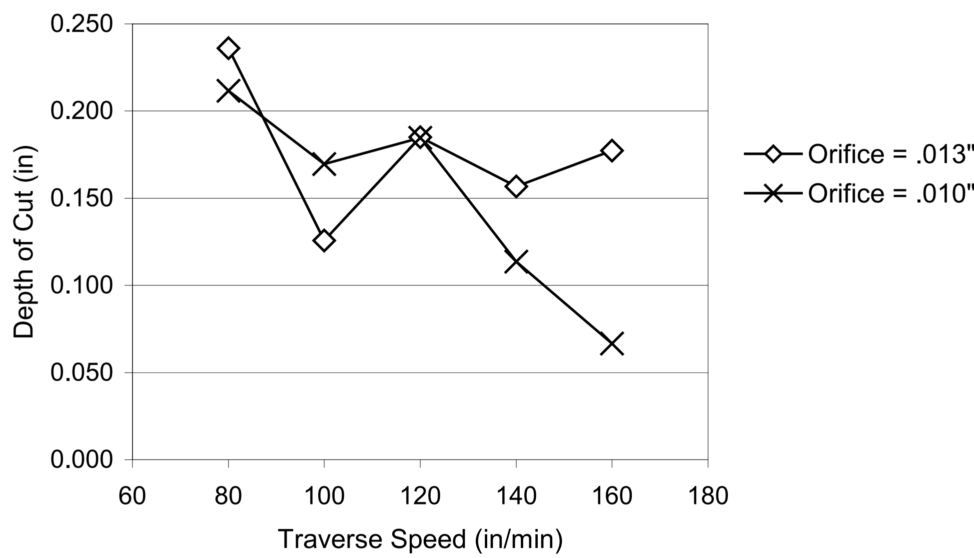

Figure 32. Effect of orifice diameter on cutting performance
(pressure = 5 ksi, standoff = 2.5”)

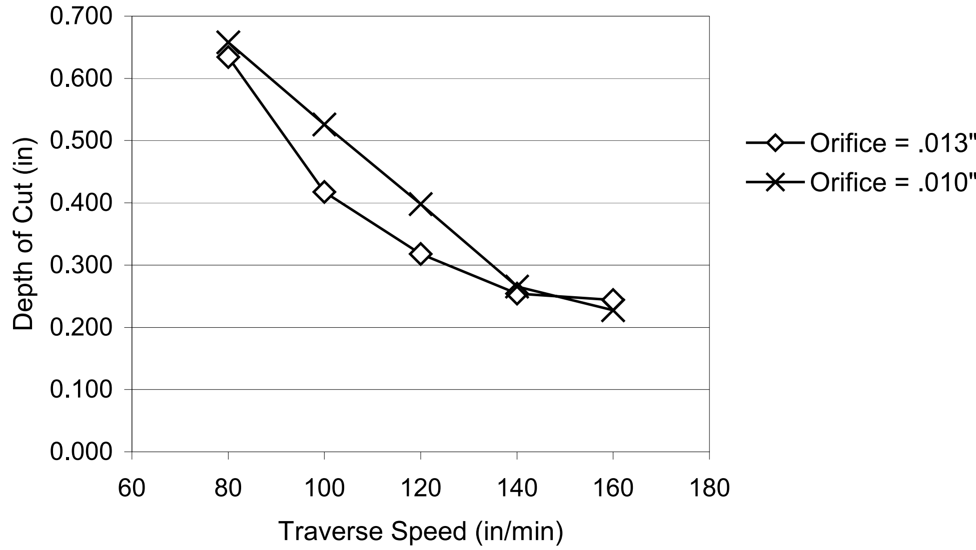

Figure 33. Effect of orifice diameter on cutting performance
(pressure = 7.5 ksi, standoff = 2.5")

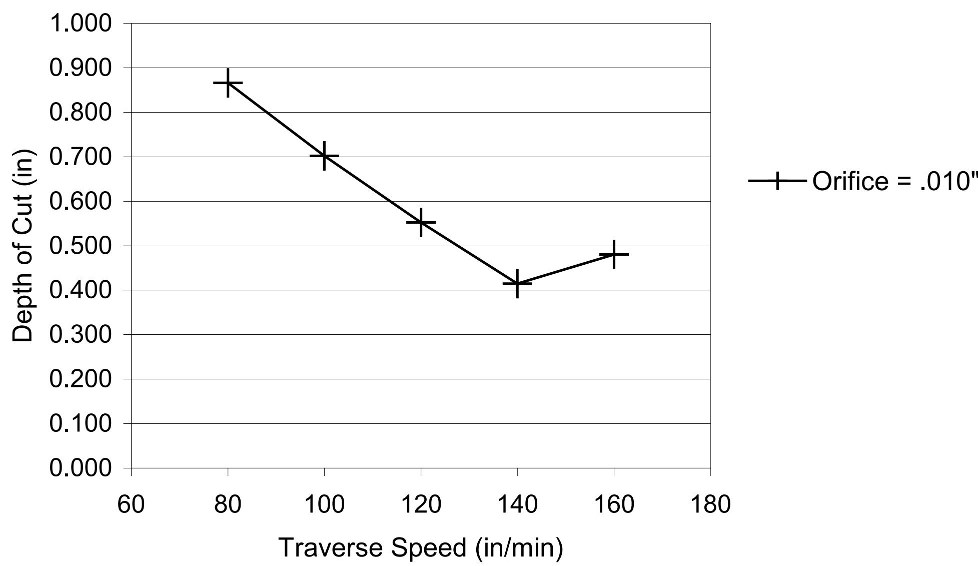

Figure 34. Effect of orifice diameter on cutting performance
(pressure = 10 ksi, standoff = 2.5")

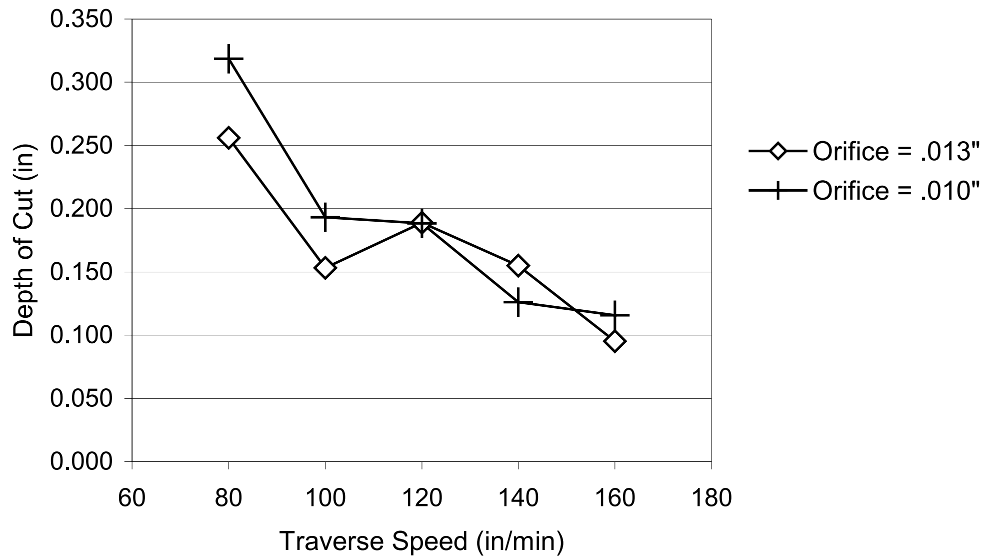

Figure 35. Effect of orifice diameter on cutting performance
(pressure = 5 ksi, standoff = 3.5")

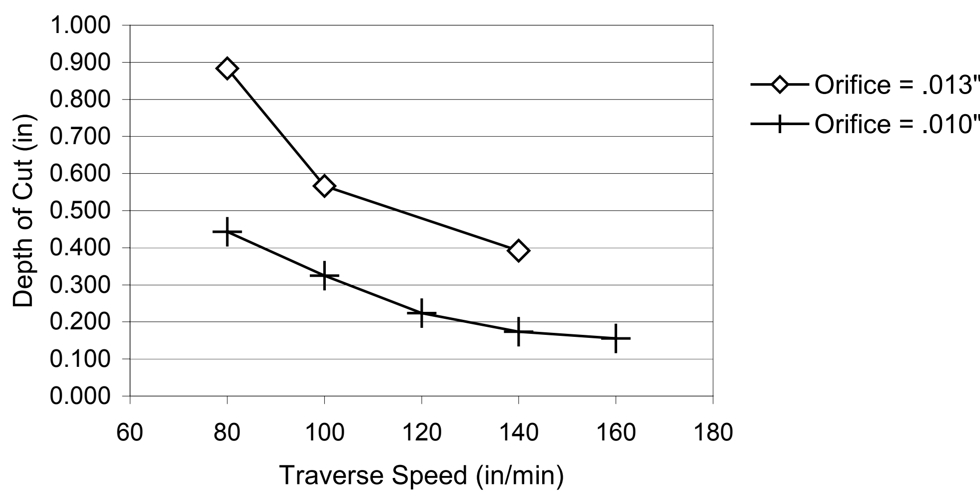

Figure 37. Effect of orifice diameter on cutting performance
(pressure = 7.5 ksi, standoff = 3.5")

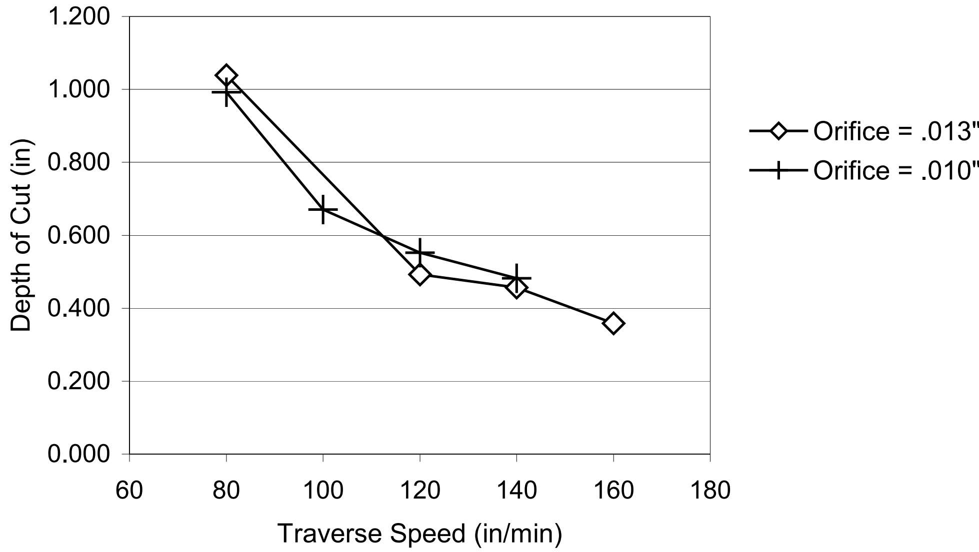

Figure 38. Effect of orifice diameter on cutting performance (pressure = 10 ksi, standoff = 3.5")

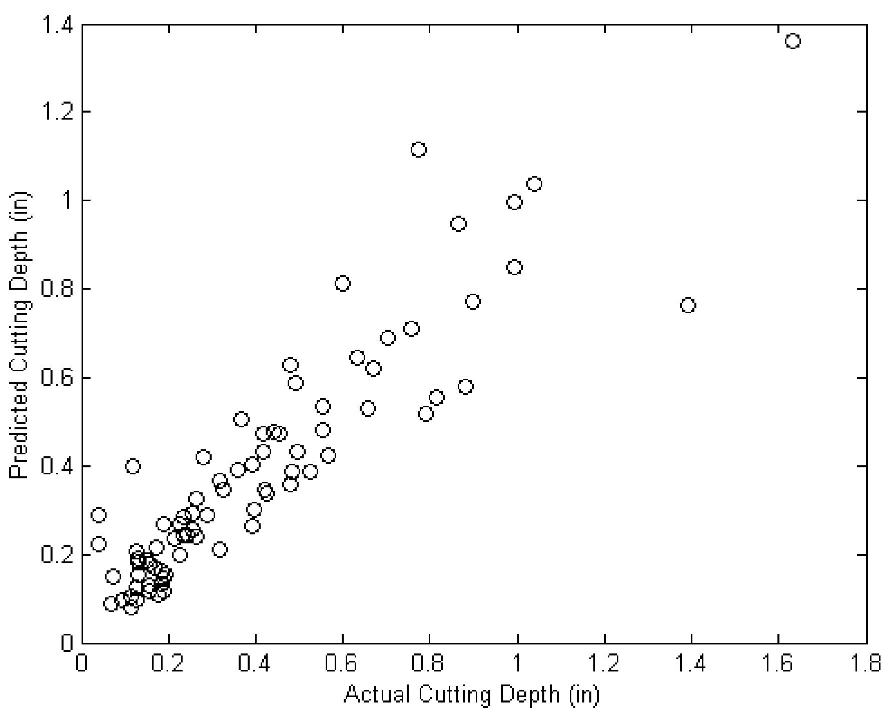

Figure 39. Comparison of predicted and actual depth of cut (no abrasive)

OPERATING PARAMETERS FOR PROPOSED SYSTEM

Based on the results of the ice cutting trials, it has been determined that the use of solid abrasive in the proposed deicing system should be avoided for the following reasons. Even though the ability to penetrate ice is enhanced through the use of abrasive, several characteristics of abrasive jetting make it undesirable for this application. One concern is potential damage to the pavement surface. As discussed above, abrasive jets are very effective in cutting a variety of materials and designing a system to penetrate ice without damaging the underlying pavement could be difficult. Another drawback related to abrasive jetting is that the entrainment process relies on a venturi effect in which the high velocity fluid passing through the nozzle induces a vacuum which is used to draw the abrasive into the jet stream. At pressures below 10,000 psi, however, the induced vacuum is often inadequate to assure consistent abrasive entrainment. The use of higher pressures to obtain good abrasive entrainment may again lead to the potential for damaging the pavement surface. Finally, the use of abrasive in the proposed system would lead to several design complexities which would lead to reduced system reliability. Effective abrasive entrainment requires that the abrasive be of uniform size and be kept dry to prevent clogging in the abrasive mixing chamber. Providing a dry, uniform abrasive with no contamination would be difficult under typical winter maintenance conditions. As a result, the proposed system will be based on using high pressure fluid jets.

To determine optimal operating parameters for the proposed system, several considerations are made. The experimental trials revealed that changing the standoff distance from 1.5 inches to 3.5 inches did not produce a dramatic chance in depth of cut. Therefore, a nominal standoff distance of 2” was selected since this seems to be a practical distance for field trials. The traverse (deicing vehicle) speed is not seen as a design variable. Rather, in the final system design, the traverse speed will be dictated by roadway conditions and will be used during operation to adjust the system to current conditions. Therefore, it is necessary identify both operating pressure and orifice diameter. While increasing the pressure and orifice diameter enhances ice penetration, increasing these parameters also increases the fluid flow rate. Since the desired function of the deicing system is to penetrate ice using a minimum amount of deicing fluid, it is necessary to determine the optimum combination of pressure and orifice diameter. If an objective function, *F*, is defined to be

$$F = \frac{Q}{d} \tag{3}$$

where Q is the volumetric flow rate and d is the depth of cut, minimization of this function will provide the optimal design. The flow rate of a pressurized fluid after acceleration through an orifice can be determined by the relation [22]

$$Q = C_d\, A \sqrt{\frac{2P}{\rho}} \tag{4}$$

where C_d is discharge coefficient, A is the orifice cross-sectional area, P is the pressure and ρ is the fluid density. A conservative estimate of $C_d = 0.7$will be used in subsequent calculations. The orifice cross-sectional area is given by

$$A = \frac{\pi}{4} d_o^2 \tag{5}$$

where d_o is the orifice diameter. Based on the parametric model (equation 2), it can be seen that

$$d \sim P^{2.020}\, d_o^{.763} \tag{6}$$

Combining equations 2 – 6 yields the result

$$F \sim \frac{d^{1.23}}{P^{1.52}} \tag{7}$$

From this relation it can be seen that the objective function is minimized by decreasing the orifice diameter and increasing the pressure.

Of course, other factors must be considered in limiting these parameters. Orifice diameters smaller than .010" are subject to clogging and high wear rates. Pump pressures are limited by pump availability and power requirements. Also, it is known that at high pressures, significant pavement erosion can occur. In fact, hydro-demolition technologies make use of this phenomenon. For de-icing purposes, however, high pressures are to be avoided to prevent damage to pavement surfaces. Taking these factors into consideration, an orifice diameter of 0.010” operating at pressures up to 10,000 psi are recommended for use in a prototype deicing system.

It is of interest to compare the operating parameters and expected performance of the proposed system to that implemented by the Connecticut Department of Transportation in the late 1970’s and early 1980’s. The Connecticut DOT system operated at nominally 300 psi, although the actual operating pressure was believed to be below 200 psi. The nozzle diameter was 2.0 mm. The proposed system is to have an operating pressure in the range 34 – 69 MPa with an orifice diameter of 0.25 mm. For each system, equation 4 was used to compute the corresponding flow rate per nozzle. The theoretical jet power is computed using the equation

$$Power = P \cdot Q \tag{8}$$

The results of these calculations are shown in Table 4. Several differences between the ConnDOT and proposed system can be observed. The proposed system operates at pressures over an order of magnitude larger than the ConnDOT system. By using a much finer nozzle diameter, the fluid flow rate is decreased dramatically while, due to the increased pressure level, the jet power is increased. Therefore, it is expected that the proposed system will provide improved performance as compared to the ConnDOT system with a dramatic reduction in the amount of deicing fluids required to penetrate the ice layer. This result, in conjunction with improved, environmentally friendly deicing chemicals which are now commercially available, suggests the strong potential for success of the proposed technology in deicing pavement surfaces.

Table 4. Comparison of ConnDOT and Proposed System Operating Parameters

	Connecticut System	Proposed System
Operating Pressure, MPa (ksi)	2.1 (0.3)	34 - 69 (5 – 10)
Nozzle Diameter, mm (in)	2.0 (.080)	0.25 (.010)
Flow Rate per nozzle, liter/min (gpm)	0.15 (2.3)	0.009 -.013 (.15-.21)
Jet power per nozzle, W (HP)	302 (0.4)	320 - 910 (0.4-1.2)

FUTURE WORK

This report summarizes the results of a Phase I feasibility study examining the potential for using high pressure jets for removing ice from pavement surfaces. Phase II of the study will include the construction of a prototype system for use in both laboratory and field trials. To facilitate field trials at various vehicle velocities, the prototype system will be trailer mounted. In addition, the Phase II study will include an evaluation of candidate deicing chemicals for use in conjunction with the prototype system.

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