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IMPACT OF ADVANCED FLUIDS ON COSTS OF DISTRICT COOLING SYSTEMS

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ABSTRACT

Three alternate fluids, ice-water slurry, friction reduction additive and the combination of them, have been compared for use in District Cooling Systems (DCS). The effect of the fluids on cost and cooling capacities were considered for the two cases of new and existing DCS separately. Two criteria were used in comparisons among fluids in each case: constant pumping power which allows for the most benefit, and constant velocity which is a more practical consideration. An economic assessment for a 500 ton system shows a potential cost difference in the total pipe cost for a new system of 70% when a 30% ice slurry is used in place of chilled water. The pipe diameter is reduced to 40% using the slurry. These results apply to the constant velocity comparison and are independent of the use of additive. Friction reduction additives serve to reduce pumping power and pressure drop. The ice-water slurry also has a significant impact on existing district cooling systems. It can potentially expand the cooling capacity by 500% without new piping being installed while maintaining the same pumping power, velocity and pressure-drop as the chilled water system. Again, friction reduction additives serve to reduce pumping power and pressure-drop. They do not influence cooling capacity. The cost for expanding the piping to increase the cooling capacity by the same amount by the use of conventional district cooling technology has been shown to be extremely high compared to the ice-water slurry system.

Keywords: Cost reduction estimates, district cooling systems, ice slurry, friction reduction additive.

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INTRODUCTION

While the energy requirements for building heating are declining, those for cooling are growing due to increased use of lighting, computerization, and high-technology equipment. District cooling systems provide a number of attractive benefits that individual building cooling systems do not. Because air conditioning cooling is a rapidly growing electric demand load for electric utilities, district cooling can provide demand-side load management for electric power. With growing environmental concerns and more stringent CFC regulations, district cooling is more appealing than ever and has good potential to grow in popularity. Although the benefits of district cooling systems are recognized and the technology has improved somewhat over the years, various barriers to its widespread application continue to make district cooling difficult to expand, particularly in North America. A principal barrier is the large initial capital cost, including that of installing pipe under often-congested urban streets. the^

Advanced fluids for district cooling systems are comprised of ice-water slurries, friction-reduction additives and the combination of them. A number of investigations have been carried out on friction-reduction additives [1-8]. There have been relatively few investigations of phase change slurries for district heating and cooling applications [9-10]. Knodel [11] has successfully demonstrated the technical feasibility of pumping an ice-water slurry in a piping network for district cooling systems. In his tests, ice slurries with ice fractions of up to 20% have been successfully pumped. A practical range of ice fractions is about 5% to 30%. Knodel and France [12-13] have considered some of the technical details of ice-water slurries as have other investigators for this and the other advanced fluids. The purpose of the present study is to make an assessment of the impact of these advanced fluids on cost reductions and benefit increases to district cooling systems.

In this study, realistic cost-reduction estimates for new and existing district cooling systems have been developed. The three advanced fluids were compared to the base system of standard chilled water. Two criteria were used in the comparisons: constant pumping power and constant velocity. An analysis has been performed to estimate reductions in pipe sizes for a new DCS and increase in cooling capacity for an existing DCS. An economic assessment for a 500 ton system has been made to show the potential decrease of costs associated with the advanced fluids for these two cases.

ANALYSIS

The advanced fluids were considered for the district cooling system (DCS) shown in Fig. 1 and were compared to a standard chilled water delivery system with a flowrate of m kg/s of water in the supply and return pipes. Considering the advanced fluid formed by using a drag reduction additive in the water, the frictional pressure-drop is reduced by a factor R* in the supply and return pipes. Drag reduction as high as $R^*=0.8$ has been achieved with some additives. An advanced fluid consisting of an ice-water slurry with a specific ice fraction ϕ in the range of 5% to 30% was considered. Finally a fluid was considered consisting of an ice-water slurry with this same ice fraction range plus the drag reduction additive with the reduction factor R* reduced by a factor of 2. This reduction accounts for the additive being effective only in the water return pipe and not in the ice-water slurry supply pipe for ice fractions in the range considered.

Considering the general problem, several parameters were defined as a ratio of an advanced fluid to the base case of a chilled water system. An advanced fluid consisting of an ice-water slurry is denoted by subscript I with a drag reduction additive denoted by subscript R. The advanced fluid system has a specific pipe size, mass flowrate, average pipe velocity, pressure-drop and cooling capacity all of which may differ from the base case chilled water system. The chilled water parameters are unsubscripted. Consider first the ratio of the supply and return pipe diameters of an ice-water slurry system to the pipe diameter of a chilled water system, δ, given by

$$\delta = \frac{D_{IR}}{D} \tag{1}$$

The ratio of the average pipe velocity of the slurry system to the velocity of the water system is

$$\gamma = \frac{V_{IR}}{V} \tag{2}$$

Using Eqs. (1)-(2), the ratio of the mass flowrate of the slurry system to the mass flowrate of the water systems is defined as

$$\mu = \frac{m_I}{m} = \gamma\,\delta^2 \tag{3}$$

The enthalpy change Δi between the supply and return pipes for the water system is $C_p \Delta T$ where ΔT is the temperature difference between the pipes, and C_p is the specific heat of liquid. It is assumed that the return temperature for the ice-water slurry system is the same as for the water system, but the supply temperature is 0°C with ice fraction ϕ. The ratio of enthalpy changes for the slurry to the water systems is

$$\kappa = \frac{\Delta i_I}{\Delta i} = \frac{C_p\,\Delta T_I + i_{sl}\,\phi}{C_p\,\Delta T} \tag{4}$$

where i_{sl} is the heat of fusion.

Finally, the ratio of the frictional pressure-drops of the slurry to the water systems is given the symbol η. Using the Blasius smooth pipe turbulent Fanning friction factor, $f = 0.079/Re^{0.25}$, the pressure drop ratio becomes

$$\eta = \frac{\Delta P_{IR}}{\Delta P} = \frac{\gamma^{11/4}\,\delta^{3/4}\,(1 - R)}{\mu} \tag{5}$$

where $R = R^*/2$ for the slurry, and $R = R^*$ for chilled water alone.

For a given drag reduction additive, the reduction factor R^* is known, and the enthalpy ratio κ is known for an ice-water slurry with ice fraction ϕ and a specific return pipe temperature. Comparisons can be made between the advanced fluids and water systems by specifying two additional conditions. One condition used in this work is that of equal pumping power for the two systems. This condition establishes a basis for fair comparison of other parameters since the distribution energy is constant. It also represents the largest advantage for the advanced fluids as compared to chilled water. The pumping power is

EQ 6 goes here

In the calculations to follow, either the pumping power was maintained constant or the velocity ratio was constant (representing a practical limitation), and the second parameter specified depended on whether

$$\Psi - \mu \eta \tag{6}$$

the system of interest was a new DCS with flexibility in pipe size selection or an existing DCS with installed pipes. For a new DCS, comparisons were made for constant cooling capacity ratios of an advanced fluid system to a water system. This parameter is

$$Q - \mu \kappa \tag{7}$$

For an existing DCS with fixed pipe size, comparisons were made at constant δ.

NEW DCS FLUID OPTIONS

Constant Pumping Power

If a new DCS is to be built, the basis of comparison of advanced fluid and water systems was that of equal cooling capacities; $Q=1$. (The inherent energy storage feature of an ice system was not considered, but it has the potential for even better performance.) With R^* and κ specified, $Q=1$ and constant pumping power $\Psi=1$, Eqs. (1)-(7) were solved for the mass flowrate ratio μ, diameter ratio δ, velocity ratio γ and pressure-drop ratio η. The results apply to an ice-water slurry with or without additive as well as to a friction reduction additive in water without ice:

$$\delta - \frac{(1-R)^{4/19}}{\kappa^{11/19}} \tag{8}$$

$$\gamma - \frac{\kappa^{3/19}}{(1-R)^{8/19}} \tag{9}$$

$$\eta - \kappa \tag{10}$$

$$\mu - \frac{1}{\kappa} \tag{11}$$

The results of Eqs. (8)-(11) are given in Figs. 2-5. The most striking result shown in Fig. 2 for supply and return pipe diameters is for an ice slurry with drag reduction additive. This result comes from Eq. (8) with $R^*=0.8$, and $R=0.4$. (Whenever a drag reduction additive was used in a calculation, the value of R^* was taken as 0.8.) The value of κ was calculated from a 10°C return water temperature and a 5.6°C difference between supply and return water pipes. At the high ice fraction of 30%, the required pipe diameter using the advanced fluid is 30% of the pipe diameter for a chilled water system. Even at a low ice fraction of 5%, the advanced fluid pipe diameter is nearly half of the water pipe diameter. Two intermediate results are shown in Fig. 2. Using an ice-water slurry without an additive as the fluid in a DCS amounts to setting $R=0$ in Eq. (8). The resulting pipe diameters are shown in Fig. 2 as slightly higher than the combined fluid pipe diameters. Also shown in Fig. 2 are the results for a fluid consisting of drag reduction additive and no ice. Here the pipe diameter is reduced to 70% of the water pipe diameter.

Considering the four DCS fluids shown in Fig. 2 (water and three advanced fluids), it is seen that the additive alone can decrease the required pipe diameter to 70% of the water pipe diameter. An ice-water slurry with a 1% ice fraction accomplishes essentially the same result. The pipe diameter continues to decrease with higher ice fractions reaching 35% of the water pipe diameter at 30% ice fraction. The combination of ice and additive reduces the diameter even further to 30% at 30% ice fraction. All of these comparisons of required pipe diameters are based on equal pumping powers ($\Psi=1$) and equal cooling capacities ($Q=1$) and show substantial reductions in pipe sizes. However, practical velocity considerations are not considered.

The changes in fluid velocities for the three alternate DCS fluids are compared to the water system velocity in Fig. 3. The additive increases the velocity substantially to nearly twice the water velocity while the ice-water slurry velocity is considerably lower increasing to a maximum of 1/3 over the water velocity. The velocity of the combination fluid of slurry and additive is also high reaching 2.6 times the water velocity at an ice fraction of 30%. Thus, the large reductions in pipe diameter, displayed in Fig. 2 for this ideal case of constant pumping power, come at the expense of increased fluid velocity as shown in Fig. 3. If practical considerations do not allow such velocity increases over the water case, an alternative comparison can be made on the basis of equal velocities, $\gamma=1$. Before that comparison is made, it is instructive to examine flowrate and pressure-drop ratios for this constant pumping power case.

The fluid flowrates are compared in Fig. 4. In order to maintain constant cooling capacity with a drag reduction additive alone, the mass flowrate of the fluid must stay the same as for the water system. However, using an ice-water slurry greatly reduces the mass flowrate because of the heat of fusion. At a high ice fraction of 30%, the mass flowrate is reduced to 16% of the water system flowrate. Even at a low ice fraction of 5% the flowrate is 40% of the water flowrate. As seen in Fig. 4, use of an additive with the ice-water slurry does not alter the mass flowrates results, and neither does the assumption of constant velocity instead of constant pumping power.

Pressure-drops are shown in Fig. 5. Since an additive alone does not alter the mass flowrate from the water system value ($\mu=1$), so it does not alter the pressure-drop either because of the condition of constant pumping power ($\mu\eta = 1$). The ice-water slurry produces a significant increase in pressure-drop as seen in Fig. 5. The pressure-drop for the slurry reaches six times the water pressure-drop at an ice fraction of 30%. This result is uninfluenced by the addition of a drag reduction additive for this case of $\Psi=1$. Clearly, the pump characteristic required for the ice-water slurry would be quite different from the characteristic for water alone in this case.

Constant Velocity

Replacing the constant pumping power condition with the more practical constant velocity condition produces the following parameter results using $Q=1$ and $\gamma=1$ in Eqs. (1)-(7).

$$\delta = \frac{1}{\kappa^{0.5}} \tag{12}$$

$$\eta = (1 - R)\kappa^{5/8} \tag{13}$$

$$\Psi = \frac{1 - R}{\kappa^{3/8}} \tag{14}$$

and the flowrate ratio is given by Eq. (11). Results for this case are shown in Figs. 6-9.

As shown in Fig. 6, under the condition of no change in pipe velocity, the friction reduction additive offers no decrease in pipe size while the slurry produces a reduction to 40% at an ice fraction of 30%. Although this maximum pipe diameter reduction to 40% is not as large as in the constant pumping power case of 25%, it is still certainly a substantial decrease. The associated pumping powers for the constant velocity case are shown in Fig. 7 where the ice slurry is seen to decrease the power to as low as 50% of the power for water, and the effect of the additive is to decrease this power further to 30%. The additive also decreases the pressure-drop of a slurry as shown in Fig. 8. It is noted that the pressure drop for the ice-water slurry alone without additive is less than half of the value for the constant pumping power case.

Under the condition of constant velocity ratio, it is seen that the ice-water slurry has the effect of decreasing pipe diameter to as low as 40%, and the friction reduction additive does not decrease pipe size. The additive has the effect of decreasing pumping power somewhat over the slurry alone, and the additive reduces pressure-drop ratio for the slurry from 3 to 1.8 bringing the required pump characteristic closer to that of a water system.

NEW DCS PIPING COSTS

The largest reduction in advanced fluid system pipe diameter for the practical case of constant velocity ratio was shown in Fig. 6 to be a reduction to 40% of the water system pipe diameter. This reduction occurs with an ice-water slurry with or without the use of a friction reduction additive. This limit was used to estimate the cost differential of the piping required for the ice-water slurry system and a water system, both being newly constructed. A 500 ton system was used as an example using a 12 inch supply and return pipe for a chilled water system. The cost of the 12 inch pipe material and installation is shown in Fig. 9 to be approximately 70% higher than a five inch pipe. The five inch pipe is the required size for the slurry system, and the costs of installation were based on an urban community of 20,000 to 60,000 people.

EXISTING DCS OPTIONS

Constant Pumping Power

The use of the three advanced fluids was considered for an existing DCS. The pipe size was fixed at the existing size in which each fluid would be used so that $\delta = 1$ in Eq. (1). The condition that the pumping power is kept the same for all fluids was again used to show the maximum potential advantages of the advanced fluids. Thus, $\Psi = 1$, and the cooling capacity ratio Q changes with each fluid.

Under these conditions, Eqs. (2), (3), (5) and (7) were solved for the variables γ, μ, η and Q. The results are

$$\gamma = \mu = \frac{1}{(1-R)^{4/11}} \tag{15}$$

$$\eta = \frac{1}{\gamma} \tag{16}$$

$$Q = \gamma\,\kappa \tag{17}$$

Equations (15)-(17) were applied to a DCS using a slurry with additive, slurry alone and additive alone. The results are shown in Fig. 10 for the cooling capacity. The ice-water slurry increases the cooling capacity of the DCS by the very large factor of 6 at an ice fraction of 30%. The additive increases that capacity even further. Using a drag reduction additive alone ($\kappa=1$, $R=R^*=0.8$) creates a small cooling capacity increase at the expense of velocity which increases 80% over a water system as seen in Fig. 11. The velocity of the slurry remains the same as the water system as does the pressure-drop.

Constant Velocity

The results of Eqs. (15)-(17) are confirmed from the calculations for an existing DCS ($\delta=1$) with constant velocity ratio ($\gamma=1$) given as

$$\mu = 1 \tag{18}$$

$$\Psi = \eta = (1-R) \tag{19}$$

$$Q = \kappa \tag{20}$$

The results are given in Figs. 12-13 which show for an ice-water slurry: the cooling capacity reaches as high as 500% greater than water alone while the pumping power, pressure-drop and mass flowrate are all unchanged from the water system values. Thus, in an existing DCS, the conditions for an ice-water slurry are the same for both criteria of constant pumping power or constant velocity. Using a friction reduction additive in addition to the slurry decreases pumping power but has no effect on cooling capacity. Even at an ice fraction of 5% the cooling capacity for the slurry is more than double the water system with all other parameters unchanged.

EXISTING DCS EXPANSION COSTS

The most dramatic cooling capacity increase of 500% for an existing DCS was considered on the basis of cost. Shown in Fig. 14 is the cost of adding 500% piping capacity to a chilled water DCS. The cost estimate was based on the same costs used for 12 inch pipe as used in Fig. 9. In contrast, there is no additional piping required for the slurry system. The cost shown in Fig. 14 for this system is for ice generation equipment.

CONCLUSIONS

Three advanced fluids were compared for use in district cooling systems. Both new systems and existing systems were considered separately. Under the ideal conditions of constant pumping power for all systems independent of other parameters, the largest benefits occurred using a combination of ice-water slurry with friction reduction additive.

Based on the practical consideration of equal fluid velocities, the major benefits are attributed to the ice-water slurry. For a new DCS, an ice-water slurry can decrease the required pipe size to 40% of the water pipe which represents a 70% cost difference. Under this condition of constant velocity, the friction reduction additive serves to reduce pumping power and pressure-drop, but it does not influence the major factor of pipe size.

For an existing DCS, parameters for an ice-water slurry are the same whether compared for constant pumping power or constant velocity. The ice-water slurry can increase the cooling capacity by 500% over the water system using the same pipe with the same pressure-drop and pumping power. The cost of the slurry system is almost immeasurable compared to the cost of additional pipe for such an expansion. Here again the effect of using the additive in addition to the slurry has no effect on the major parameter of cooling capacity, but it does decrease pressure-drop and pumping power.

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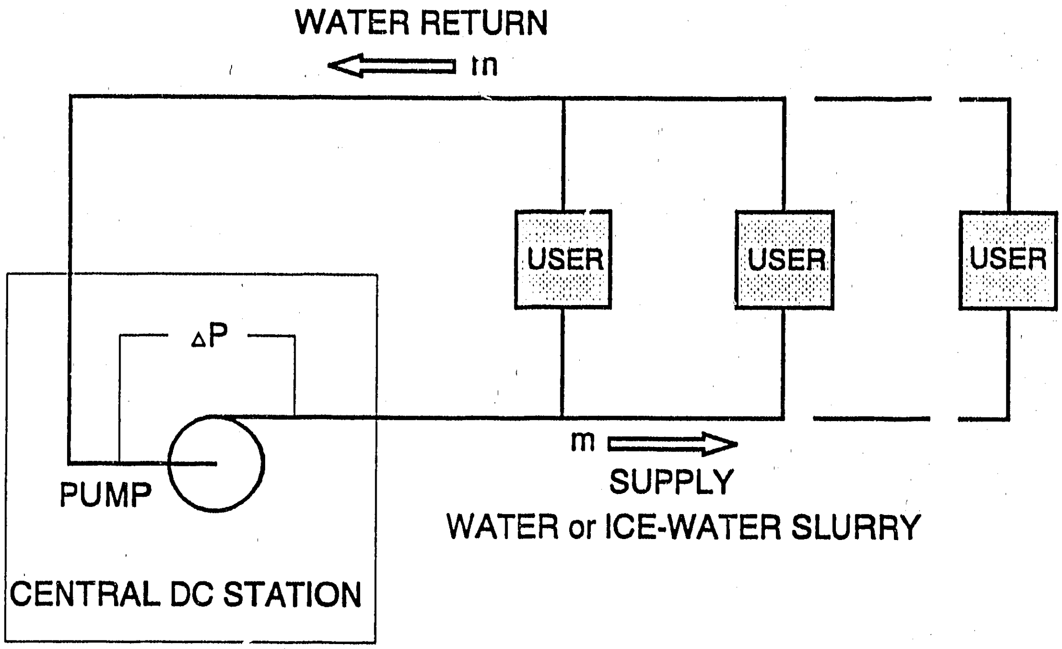

Figure 1 District Cooling System Schematic

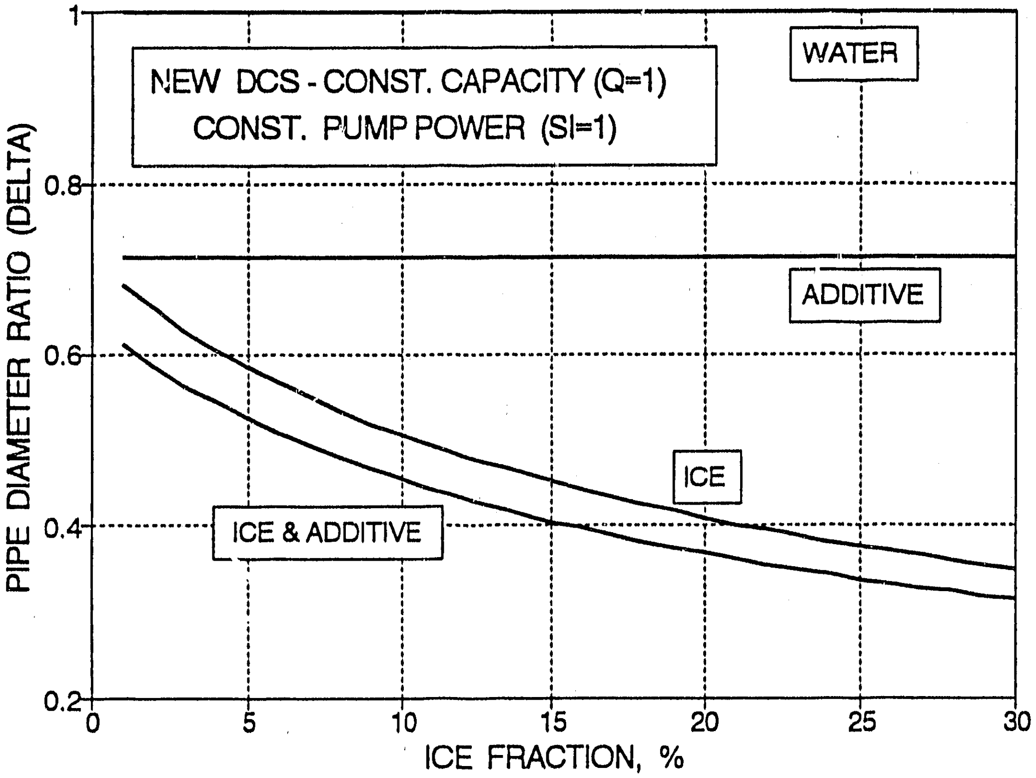

Figure 2 New DCS Pipe Size Reduction, $\Psi = 1$

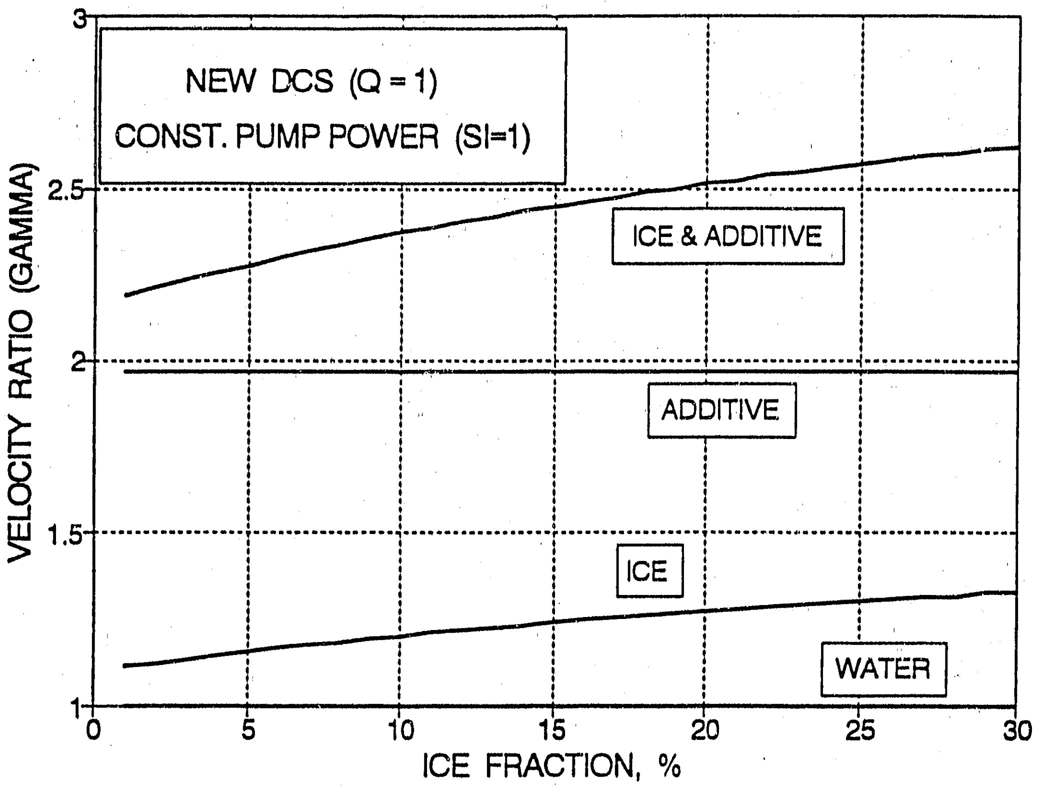

Figure 3 New DCS Velocity Increase, $\Psi = 1$

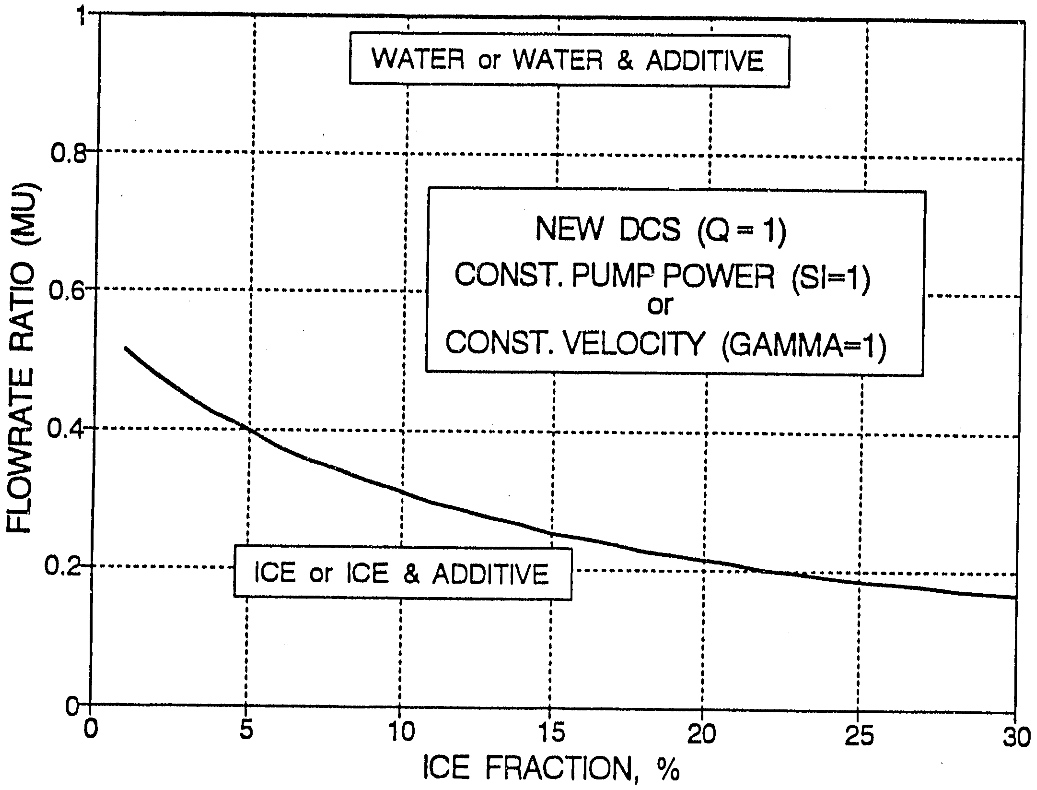

Figure 4 New DCS Flowrate Reduction, $\Psi = 1$

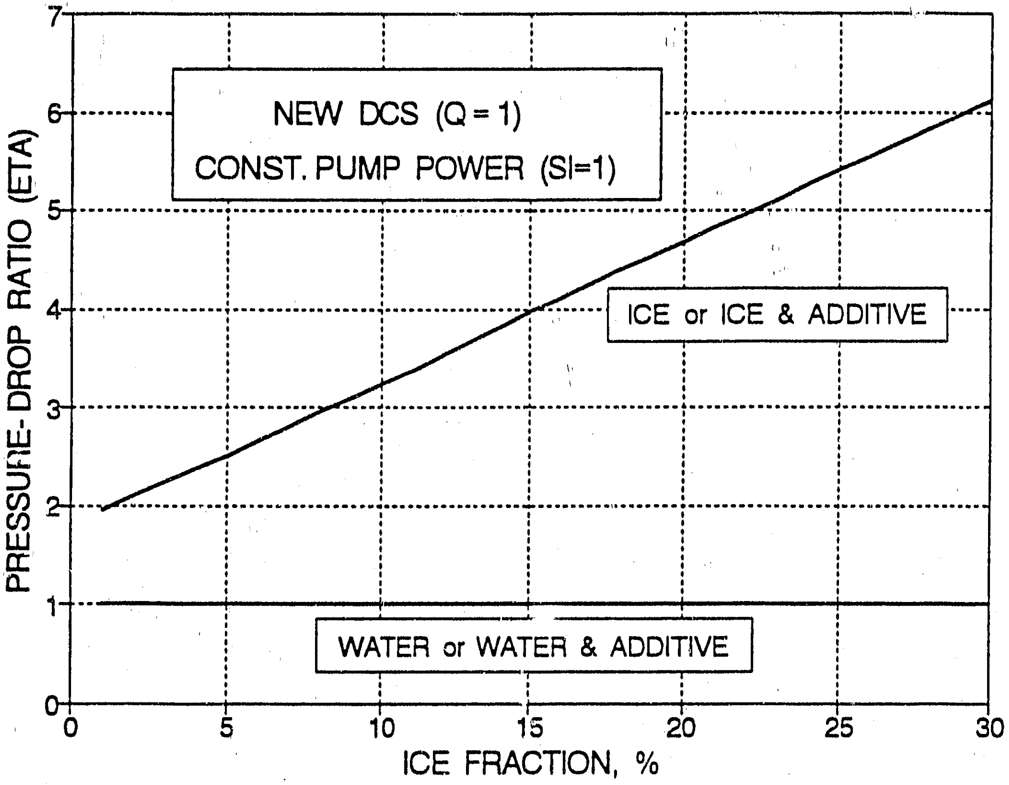

Figure 5 New DCS Pressure-Drop Increase, $\Psi = 1$

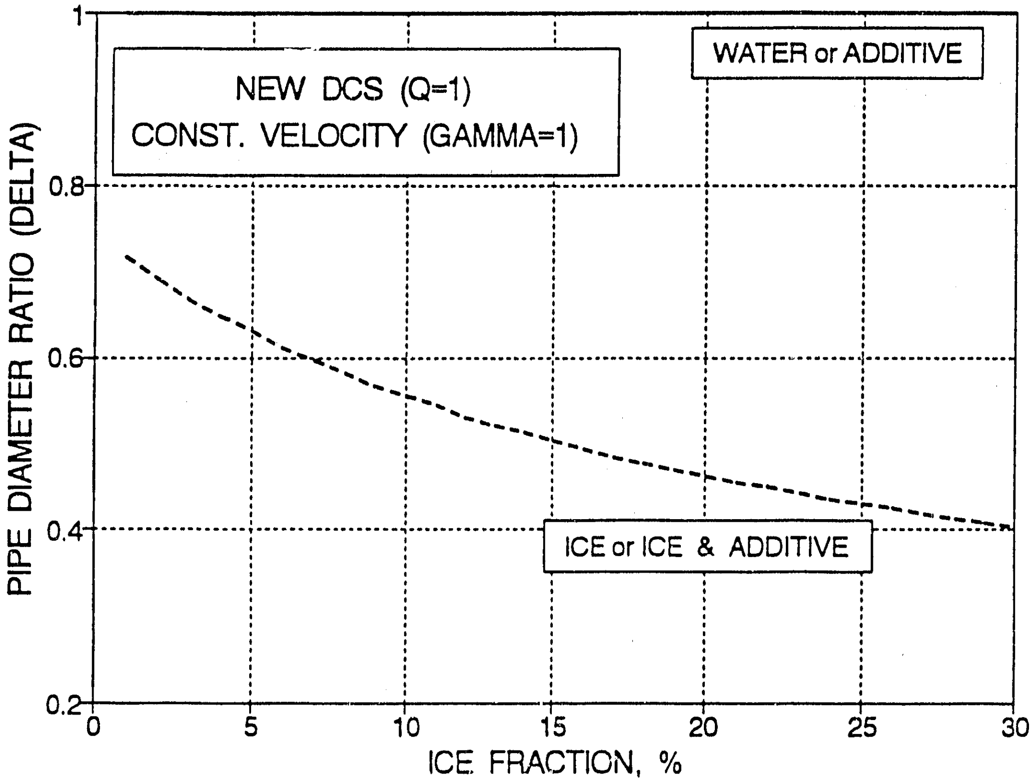

Figure 6 New DCS Pipe Size Reduction, $\gamma = 1$

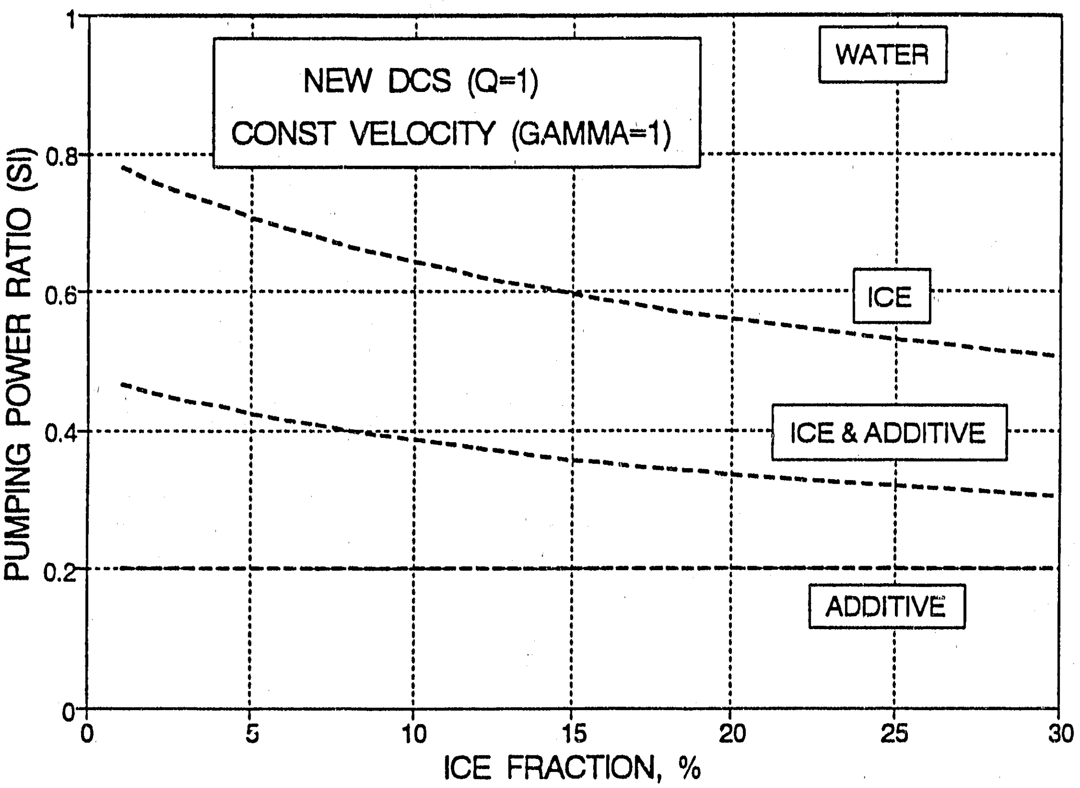

Figure 7 New DCS Pumping Power Reduction, $\gamma=1$

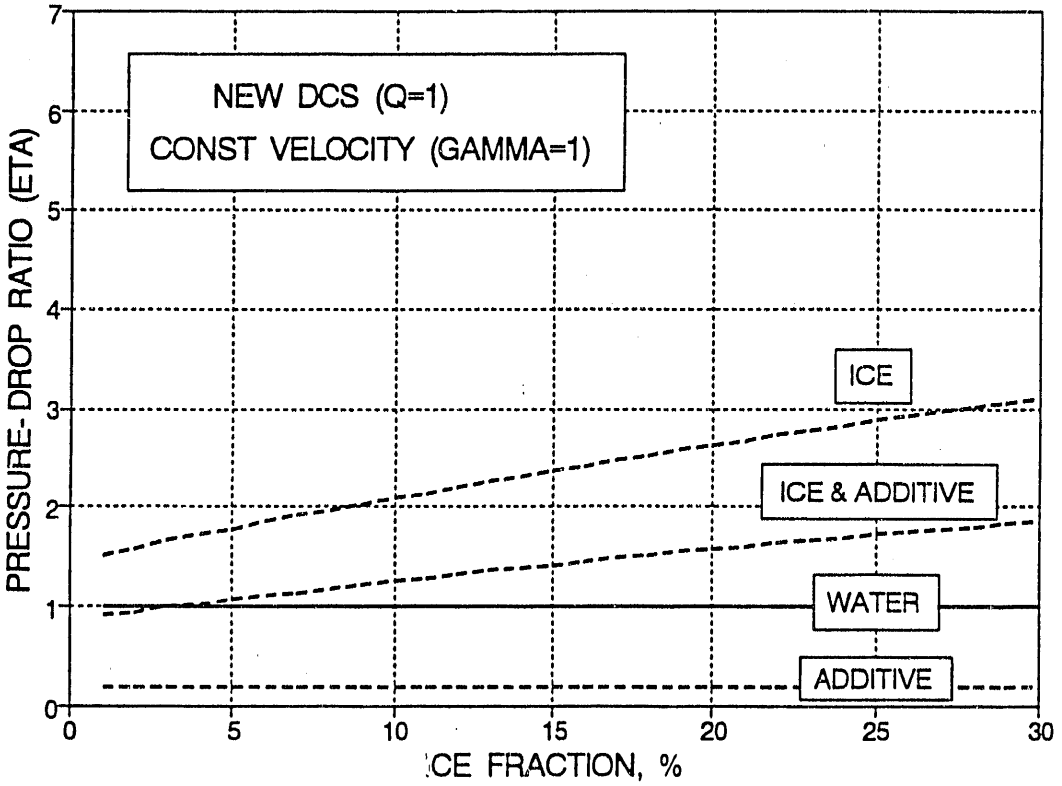

Figure 8 New DCS Pressure-Drop Increase, $\gamma=1$

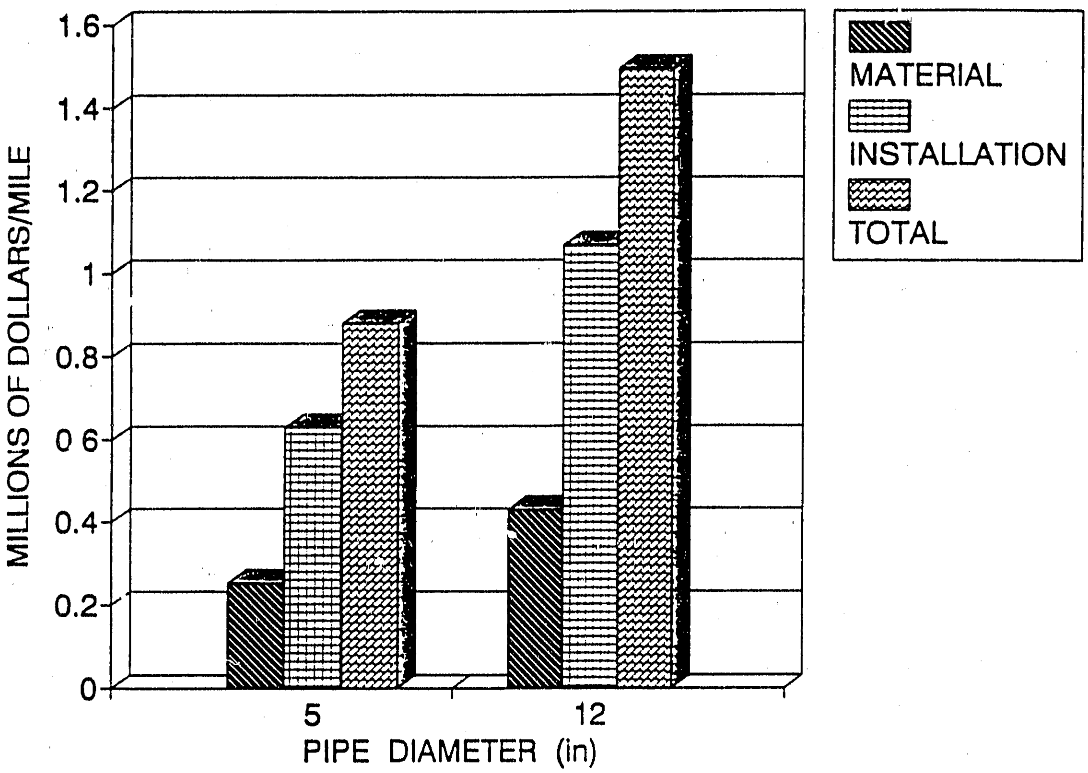

Figure 9 Installation and Material Costs for New DCS Pipe

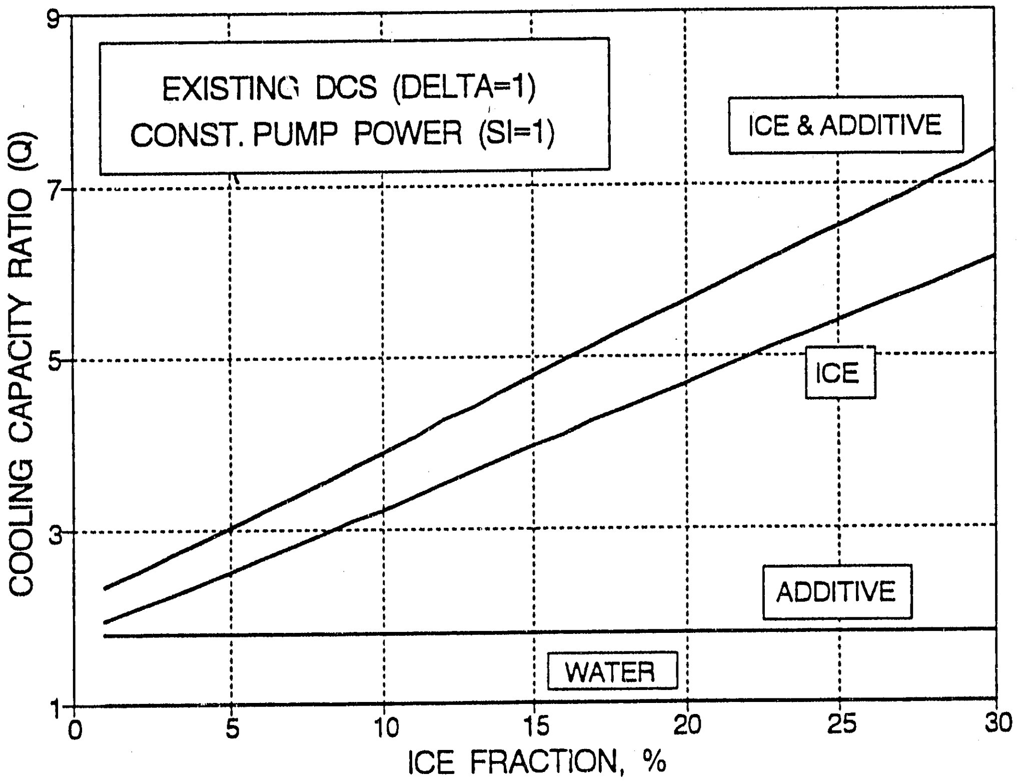

Figure 10 Existing DCS Cooling Capacity Increase, $\Psi = 1$

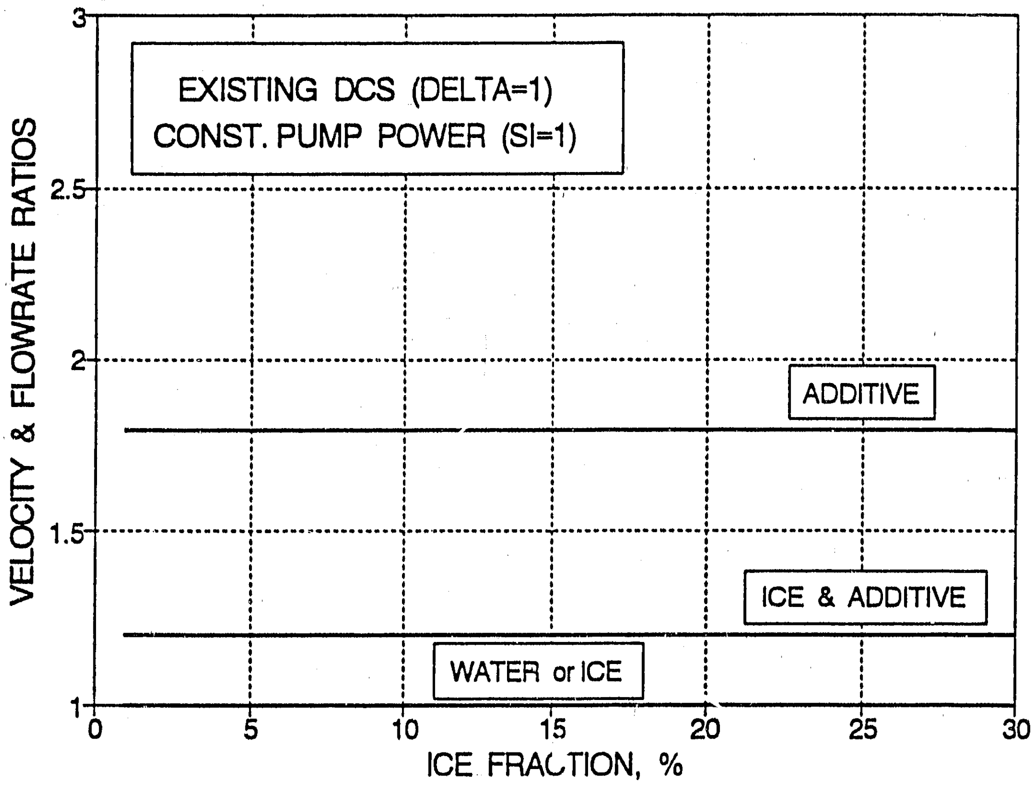

Figure 11 Existing DCS Velocity Increase, $\Psi = 1$

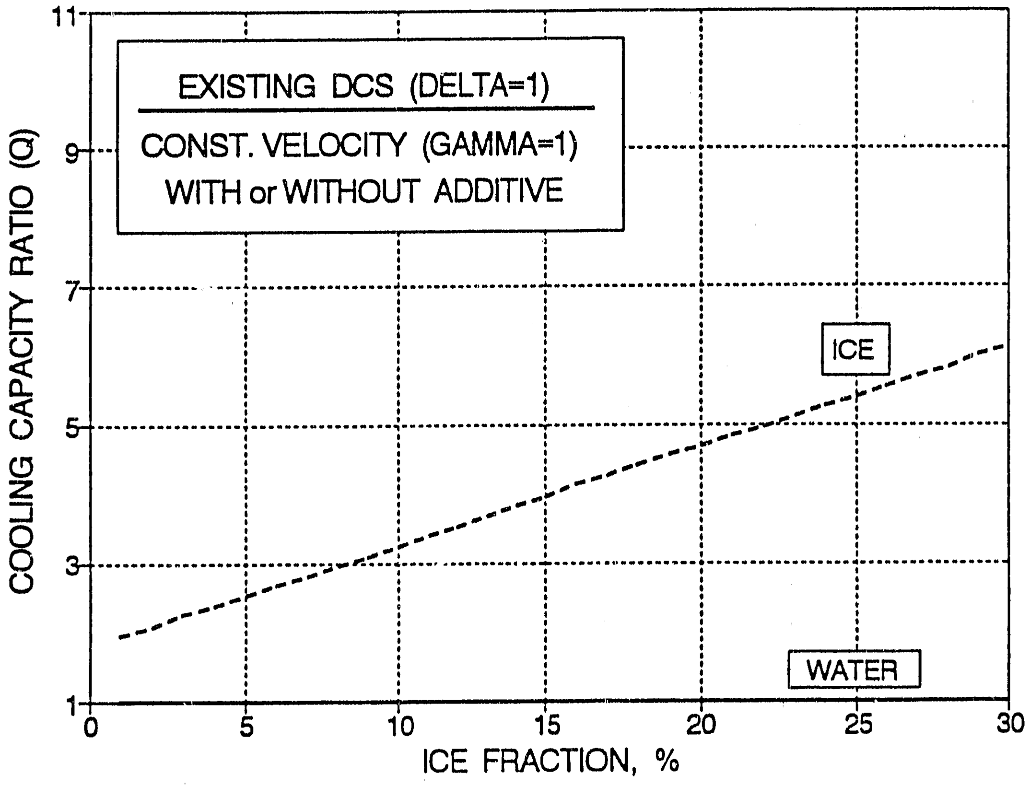

Figure 12 Existing DCS Cooling Capacity Increase, $\gamma = 1$

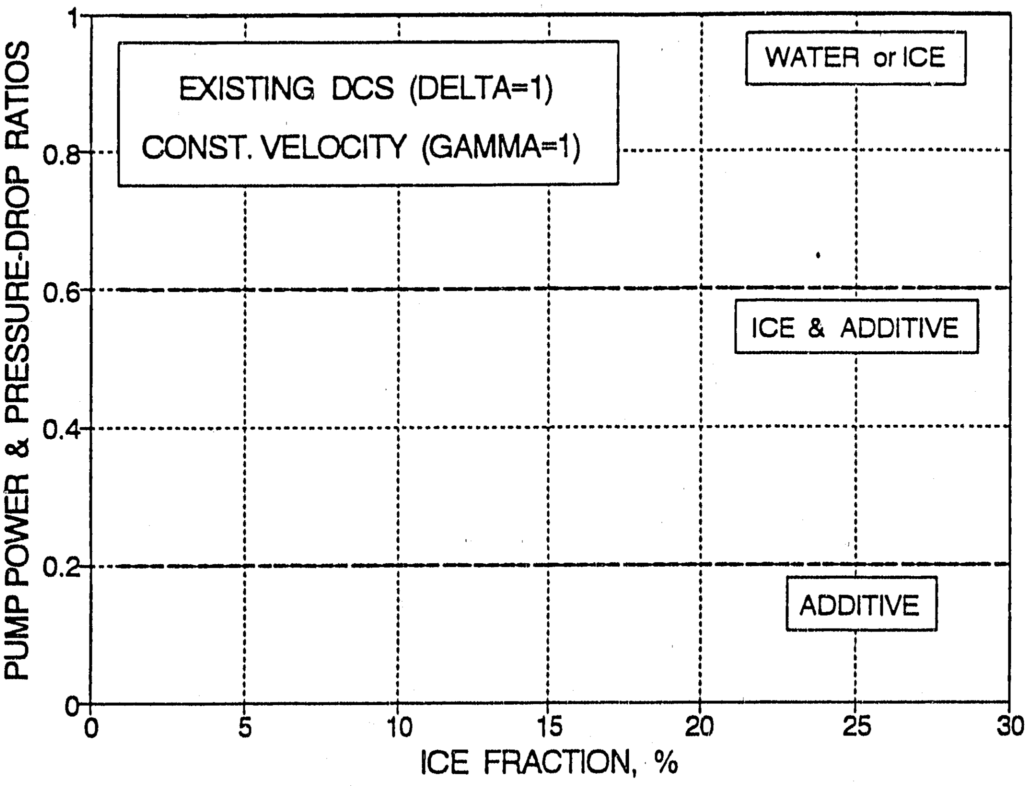

Figure 13 Existing DCS Pumping Power and Pressure-Drop Decrease, $\gamma = 1$

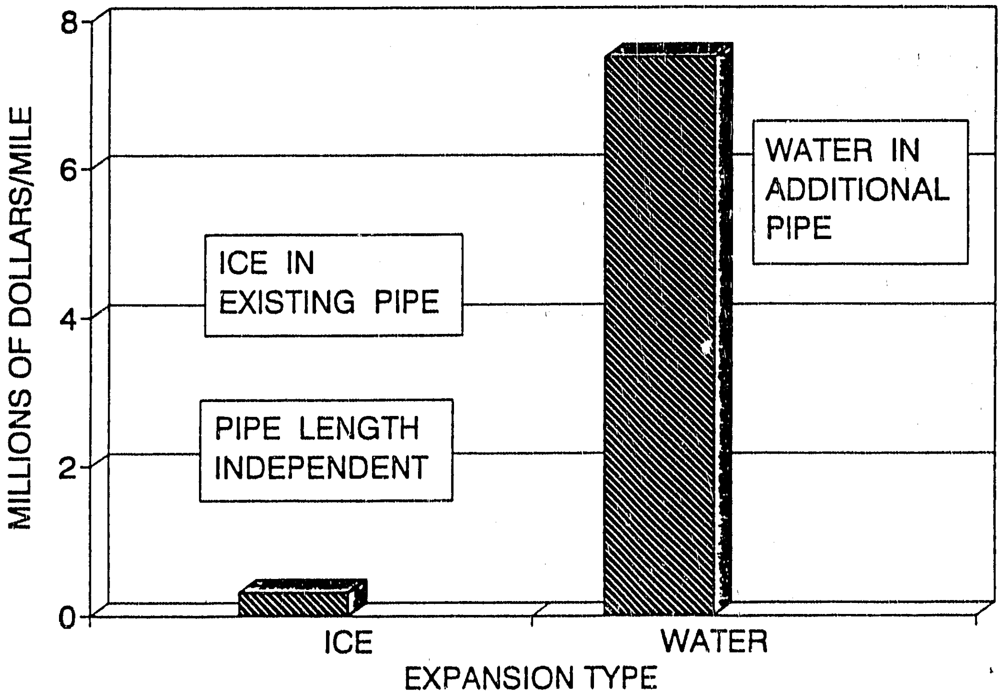

Figure 14 500% Expansion Costs for Existing DCS

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