REC-ERC-74-15

PREVENTION OF FRAZIL ICE CLOGGING OF WATER INTAKES BY APPLICATION OF HEAT

Engineering and Research Center
Bureau of Reclamation

September 1974

Prepared for
ICE RESEARCH MANAGEMENT COMMITTEE

MS-230 (8-70)
Bureau of Reclamation

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO. REC-ERC-74-15	2. GOVERNMENT ACCESSION NO.
3. RECIPIENT'S CATALOG NO.	
4. TITLE AND SUBTITLE: Prevention of Frazil Ice Clogging of Water Intakes by Application of Heat	5. REPORT DATE: September 1974
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S): T. H. Logan	8. PERFORMING ORGANIZATION REPORT NO.: REC-ERC-74-15
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Bureau of Reclamation, Engineering and Research Center, Denver, Colorado 80225	10. WORK UNIT NO.
	11. CONTRACT OR GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
	14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

16. ABSTRACT

The phenomenon of ice formation in flowing water and the technology of heating trashrack bars to prevent clogging by frazil ice are reviewed. The report includes: (1) A description of frazil ice formation, (2) development of heat transfer equations for trashrack bars immersed in a fluid, (3) correlation between conditions assumed in developing the theoretical expressions and actual conditions present in a water intake, (4) economics of heating trashrack bars, (5) methods of heating trashrack bars, and (6) recommendations for future studies. Has 64 references.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS-- / *frazil ice/ ice/ canals/ floating ice/ ice cover/ open channels/ slush/ intake structures/ *heating/ trashracks/ barriers/ bibliographies

b. IDENTIFIERS--

c. COSATI Field/Group 13M

18. DISTRIBUTION STATEMENT: *Available from the National Technical Information Service, Operations Division, Springfield, Virginia 22151.*	19. SECURITY CLASS (THIS REPORT): *UNCLASSIFIED*	21. NO. OF PAGES: 20
	20. SECURITY CLASS (THIS PAGE): *UNCLASSIFIED*	22. PRICE

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Prepared by
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for the
Ice Research Management Committee

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Division of Design
Engineering and Research Center
Denver, Colorado

UNITED STATES DEPARTMENT OF THE INTERIOR * BUREAU OF RECLAMATION

ACKNOWLEDGMENT

This study was conducted under the supervision of the Ice Research Management Committee. The committee wishes to acknowledge the cooperation of the Pacific Northwest Region in jointly funding this study with the Engineering and Research Center's Research Division.

PREFACE

Ice formation on reservoirs, rivers, canals and associated structures hinders and, at times, prevents winter operation on a number of Bureau of Reclamation (USBR) projects. In an effort to increase the reliability and efficiency of our present projects and improve design criteria related to future projects in cold regions, the USBR established the Ice Research Management Committee. The objective of the Committee is to develop and manage an ice research program directed toward solving ice problems on USBR projects.

This report is the first in a series of reports sponsored by the Ice Research Management Committee. This and subsequent reports are being prepared to familiarize USBR personnel with the art and/or science of winter operation of water resource projects in cold regions. It is hoped that the report will be a valuable aid to design and operation personnel and will stimulate continued creative approaches to ice problems during winter operation. The Committee encourages USBR personnel to relate their problems and success in ice engineering so that this and future reports may be current with the latest technology in the field of ice engineering.

The reference bibliography material presented in this report is available on a limited loan basis to Reclamation personnel, from the Ice Research Management Committee, Code 1531, USBR, E&R Center, Denver, CO 80225.

P. H. Burgi
Chairman, Ice Research Management Committee

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I. INTRODUCTION

Frazil ice creates major operation and maintenance problems for many hydroelectric plants all over the world [1, 2, 3, 4, 5, 7, 14, 15, 21, 23, 35, 36, 37, 39, 40, 41, 42, 43, 58]*. For many plants it can be the major design consideration. Available literature relates a number of plants which were not designed properly to handle icing problems and as a result had to be abandoned and of others which incur 100 percent loss of station availability for extended periods of time [5, 12]. The extent and type of ice problem encountered varies with the hydrological conditions on the river, the severity of the winter, and location of hydroplant. Since these factors are usually known, an estimate of the severity of the icing problem can be made at the planning stage.

Sweden and Norway have dealt with icing problems since before the turn of the century. Their climates vary from arctic conditions in the north to mild conditions in the south. Contrary to expectations, the worst problems are not caused by ice in the extreme north, as the occurrence of frazil ice is infrequent and, generally, the ice menace is so evident that adequate measures are usually taken. However, in the central and southern parts, such measures might be considered too expensive compared with tolerating the inconvenience or occasional ice problems during particularly severe winters.

Actually, it is the occurrence of frazil ice which is particularly troublesome. In the northern areas where water velocities are not too high, bodies of water will freeze in early winter and the ice cover formed will remain intact until spring. This restricts the risk of frazil ice to a fairly short duration. In southern areas, short, intense periods of cold occur, interrupted by periods of mild weather. Thus, the ice cover that does form is often broken up and frazil ice can occur repeatedly throughout the winter.

The evaluation of the potential for severe frazil ice conditions at any particular site is of paramount importance. The methodology for correcting the problem will depend largely on this evaluation. Usually, for any particular area or site, it should be possible to estimate the severity and type of icing problem to be anticipated from local meteorological and hydrological data at the site. Jarocki [20] presents a comprehensive study that relates meteorological and hydraulic conditions to ice formation.

II. FRAZIL ICE

A. Description of Frazil Ice

Wh flowing water undergoes cooling through heat exchange with the atmosphere, turbulent mixing causes the entire body of water to be cooled uniformly. If the water is at a temperature above freezing and is cooled rapidly, it will undergo supercooling; that is, it will reach temperatures below the freezing point, 32° F (0° C). If the above conditions are present, formation starts to take place throughout the flow section as the water's latent heat is released in an effort to restore thermal equilibrium to the flow. Ice formed in this manner is called frazil, a French word for "forge cinders" which it is supposed to resemble.

An important distinction should be made at this point to emphasize the type of ice formation that is to be denoted frazil. The water temperature must start above 0° C and pass through a supercooled region to produce frazil ice (see fig. 1). Water which is at 0° C and

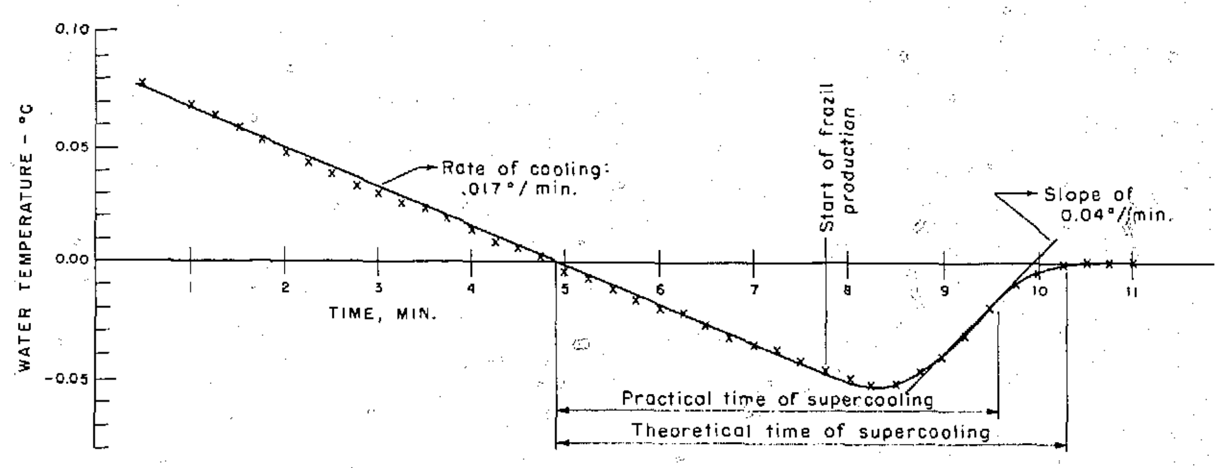

Figure 1. Temperature of water during frazil ice production. 101-D-620

*Numbers in brackets designate bibliography references following section X.

undergoes cooling will not form frazil but rather will agglomerate to already existing ice crystals as it freezes. Frazil ice formation is a transient phenomenon, the continuance of which in a body of water destroys the conditions necessary for its occurrence.

B. Formation of Frazil Ice

A good description of frazil ice production by B. Michel [11] follows. Michel's results are from laboratory tests conducted in an outdoor flume at Laval University, Quebec, Canada.

> "When it was not snowing, the mechanism of frazil ice production was always the same and can be illustrated by reference to figure 1. The water temperature which is initially above zero degrees Centigrade cools down at some rate depending on the heat transfer rate between the water and the outside air. The temperature of the water passes through the zero degree centigrade point and then continues dropping for a few hundredths degree more at the same rate. It will attain some minimum value depending on hydraulic and meteorological conditions. At some point the rate of cooling starts to diminish until it becomes zero and the minimum temperature is reached. As the rate of cooling starts to drop, very small particles of ice appear suddenly and uniformly throughout the water mass. These particles are too small to be visible with the naked eye, but they are easily seen by the reflection they give from an incident light. The frazil ice particles grow rapidly in size and form needlelike fragments approximately 1/8-inch (3.2 mm) long.
>
> "After the water temperature reaches a minimum it returns asymptotically to zero degrees with a continuously decreasing rate. Individual particles agglomerate together and form foamy packs, whose size is dependent upon the turbulence and velocity of the flow.
>
> "In the flume where these tests took place all this happened within 3 to 6 minutes, after which time no more frazil particles of the type described were produced. If the flume used was allowed to run for a long period of time, the new ice that is produced either grows on the existing particles or forms border ice.
>
> "Of most importance is that once a body of water has settled to 0° C, the type of ice that is formed is physically very different from the frazil ice that is formed during the period of supercooling. Finally, frazil ice is always and only formed if a body of water being initially above 0° C is subject to some rate of cooling as its temperature passes through 0° C.
>
> "This type of ice also has a high water ratio and thus occupies a large volume in relation to the quantity present. This is important because it causes large river discharge variations and other problems."

There is some disagreement concerning the physics of frazil production and the characteristics of frazil. The purpose of this report is to present an explanation of frazil that engineers can use for designing water intakes; Michel's description fills that need. Further research is presently underway at the Engineering and Research Center to investigate these controversial points.

Michel's tests showed good correlation between the quantity of frazil produced and the rate of cooling of the water, figure 2. His work demonstrated that the quantity of frazil produced and the degree of supercooling increased as the rate of cooling increased. Michel describes a method of calculating the quantity of frazil produced. Unfortunately, it may not be very practicable to perform these calculations in a real situation. It is sufficient to note at this time that the production of frazil ice involves loss of heat at the air-water interface, supercooling resulting from the flow dynamics, and conversion of water to ice throughout the cross section. This conversion is accompanied by latent heat release, which balances the heat loss to the atmosphere.

C. Active Versus Inactive Frazil Ice

A very important distinction must be understood concerning the difference between active and inactive frazil ice. The term "active frazil" was coined by Michel to describe frazil during its early history of production and during which it has the quality of being able to adhere very tightly to submerged metals and most other materials. This phenomenon is important in this study since only when frazil is in this active state is it necessary to heat the intake trashrack. Inactive frazil has no tendency to adhere and therefore heating is not a solution to handling this type of frazil. The production and stickiness of active frazil are closely connected with the degree of supercooling of the water, which is in turn related to the rate at which the mass of water cools. As will be seen, an extreme temperature drop following a mild spell can cause large quantities of frazil to be produced.

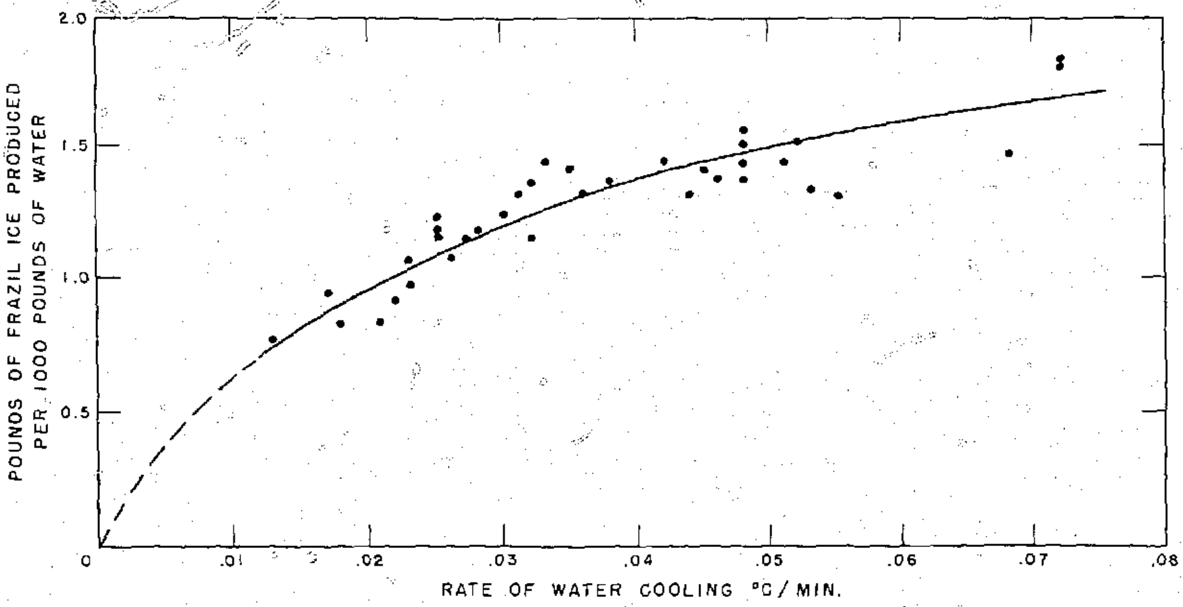

Figure 2. Quantity of frazil ice produced versus rate of water cooling. 101-D-621

Frazil ice particles maintain their adhesive quality for only a few minutes, after which they become inactive. This means they are in this extremely dangerous state for only a short distance after their production as the water approaches the intake. This has design importance since areas where frazil production is most likely to occur can be predicted, possibly eliminated, and intakes properly located to eliminate or minimize problems related to frazil. Certainly the necessity to heat intake components must be viewed with this in mind.

D. Conditions Relating to Frazil Ice

The role of the major factors related to the frazil ice problem is briefly reviewed here.

1. Frazil adhesion to objects.—Frazil ice will not adhere to objects with temperatures above freezing. This fundamental property is the basis for heating trashrack bars and other appurtenances at water intakes as a means of combating ice problems. The designers' objective is to maintain the vulnerable surface only slightly above freezing which minimizes the loss of thermal energy to the fluid flow while preventing ice adhesion.

2. Role of water velocity.—Frazil ice is formed under dynamic conditions; thus, velocity plays a major role in determining how ice forms. Figure 3 shows the three regimes of river ice and how they depend on velocity. Ice production is assumed to fit into one of the three regimes shown below.

3. Meteorological Conditions.—This factor is so important in the icing problem that it is difficult to over assess its influence. In any specific instance meteorological conditions determine the rate of supercooling and thus the quantity of frazil produced. The conditions also determine whether heat addition or insulation techniques are appropriate in any given instance. Meteorological conditions along with hydraulic conditions determine the prevalence or severity of icing problems at any site.

4. Quantity of frazil produced.—When conditions exist along a watercourse where frazil is continuously produced, the quantity should be estimated to determine whether provisions have been made to handle the frazil. This problem should be handled at the design stage [11, 7, 20, 9, 16, 23m, 23o, 23q, 42d, 47, 172].

5. Rate of cooling.—This factor controls when active frazil will be produced and is the basis for designing a sensing system which can warn of danger from frazil [1]. As shown in figure 4, an increased rate of cooling gives a corresponding increase in the maximum supercooling, residual supercooling, and rate of temperature recovery. The rate of cooling is also a major factor in determining the quantity of ice that will be produced in a given river reach.

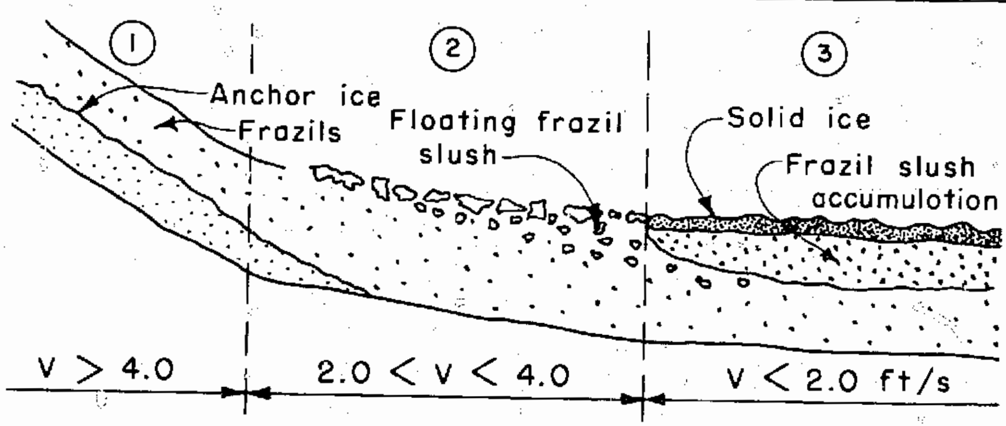

Figure 3. Regimes of river ice. 101-D-622

1. High flow velocities ($v > 4.0$ ft/s).—Free water surface, strong cooling, supercooling, and local ice formation. Some of the locally produced ice, as well as some of the ice from upstream, is accumulated as anchor ice; however, most of the ice moves downstream.

2. Medium flow velocities (2.0 ft/s $< v <$ 4.0 ft/s).—The water surface is more or less covered with moving frazil slush, cutting down on the heat loss and the subsequent ice production. The water temperature is at or close to the freezing point. There is little anchor ice and a general tendency for the ice to move on.

3. Low flow velocities ($v < 2.0$ ft/s).—The solid ice cover prevents large heat losses, so the local ice production is small. Frazil slush from upstream is deposited underneath the ice cover, and there is a general tendency for the ice to accumulate.

6. Ice covers.—If an ice cover can be formed on a canal, river, or reservoir, frazil ice production can be prevented. The ice cover acts as an insulating blanket between the cold atmosphere and the water surface. From a heat transfer standpoint it reduces the flow of thermal energy by as much as a factor of 100. Frazil ice that passes under an ice cover no longer retains its strong adhesive quality. In the case of the Beauhaurnois Canal, which is 60,000 feet (18,300 meters) long, as much as 75 percent of the frazil entering the canal passes under the ice cover and through the turbines. Some of the frazil increases the thickness of the ice cover, some is melted, and the rest passes through the system.

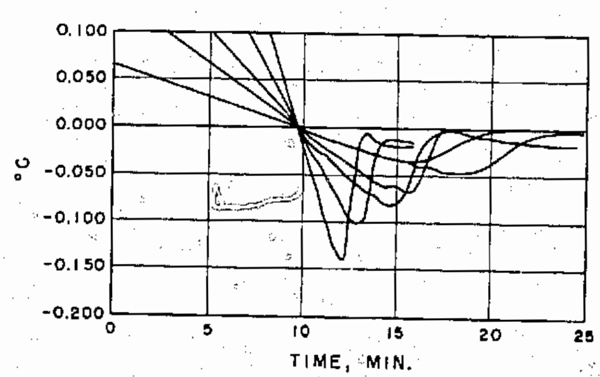

Figure 4. Effect of rate of cooling on supercooling. 101-D-623

Ice covers can be started on canals by stopping the flow (for a short time) or by using a boom stretched across the canal. These methods are particularly useful in climates where the cover is to be maintained permanently.

7. River discharge affected by frazil.—A great deal of information and field measurements are available on this topic. The two major factors affecting discharge are the variation in friction caused by an ice cover and the large water ratio of frazil ice packs which cause them to occupy large volumes without much actual ice being produced. Flooding and variation in hydroelectric output are two of the more serious problems resulting from the occurrence of frazil ice in rivers [3, 4, 5, 8, 10, 14, 20, 23d, 23f, 23x, 26, 51, 55].

8. Ability of the hydraulic circuit to handle inactive frazil.—Inactive frazil is frazil ice which has lost its supercooling and also the quality of stickiness. Relatively large amounts of this type of ice can be passed through the hydraulic circuit (turbines, gates, penstocks, etc.) and usually without any problem, though it will tend to settle out in areas of low flow velocity. Heating hydraulic structure control elements to combat this type of frazil is of little value. For instance, at Safe Harbor Dam on the Susquehanna River [1] electrically heated racks are energized only when active frazil is anticipated. Conditions for its formation are known at this site.

III. CLOGGING OF WATER INTAKES

Three ways in which frazil can clog intakes are identified below [12]:

A. Active Frazil Ice

When frazil ice is in a state of production in supercooled water, it is termed active frazil and has a strong tendency to adhere to metals and other materials with a high thermal conductivitity. It is important to note that the duration of an active frazil ice particle is only a few minutes, after which it becomes inactive and loses this quality of stickiness. It is also possible that continuous supercooling of the water may last for days in the same river reach, and for this reason river rapids are sometimes called ice factories. The location and design of a water intake can be strongly dependent upon these characteristics of frazil ice.

When intakes are subjected to clogging by active frazil ice, accumulations can build up very rapidly and completely choke off the flow in a short time. When the active frazil ice needles reach a set of trashrack bars, they are deposited on the bars and form a matted layer at and near the surface. This layer is somewhat porous and will continue to build and can be as much as 6 inches (0.15 m) or more in thickness. The needles freeze together and to the rack to form a mass that, while not nearly so strong as solid ice, is practically impossible to remove by mechanical means. Figure 5 illustrates the severity of the ice clogging problem. At first the layer of ice forms on the bars only to the depth below the water surface to which the needles have been carried by the turbulence of the water but, as the openings become smaller near the surface, the needles are carried downward by the entering water. Thus, the ice layer on the trashrack is extended downward until the flow is practically cut off. Water draining away through the turbines will cause a drop in head on the downstream side of the trashracks, and the resultant unbalanced pressure may be sufficient to collapse the rack structure. Heating of trashrack bars is effective against this type of clogging when applied before the ice starts to adhere to the bars since active frazil will not adhere to a surface whose temperature is maintained even slightly higher than freezing.

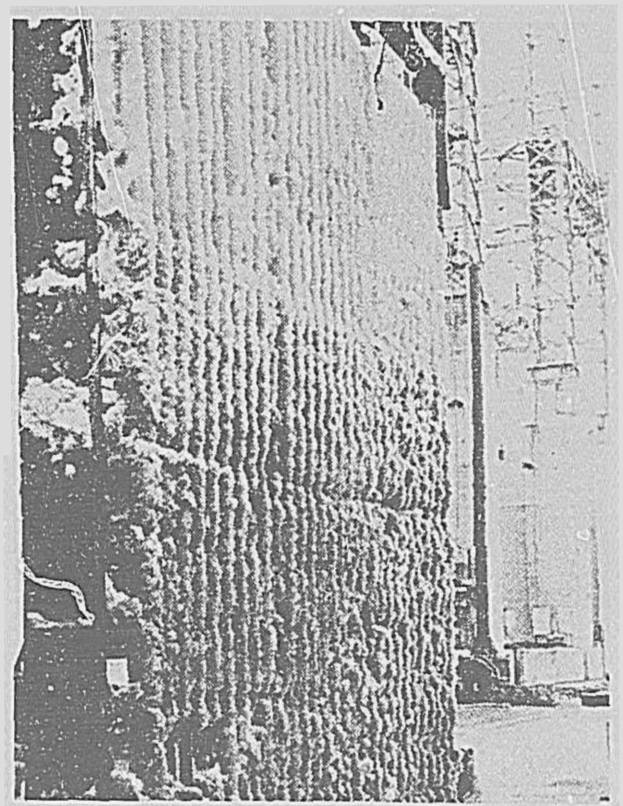

Figure 5. Frazil ice formation on bars of trashrack at Safe Harbor.

B. Inactive Frazil

Water intakes can also be clogged by the action of inactive frazil ice which has little tendency to adhere to objects. When the production front of frazil ice moves far enough upstream of the water intake so that the intake is no longer in danger of active frazil, it will be subjected to ice floes and accumulations of frazil packs. Frazil can then settle and accumulate in zones separate from the flow where velocities are too weak to carry it away. It can also block passages at an obstruction and by arching across at lateral supports. The first effect is not dangerous since it can in fact cause a streamlining of the hydraulic circuit. This type of clogging ordinarily will not be of any serious consequence unless the intake consists of screens of a small size. The maximum buildup of the frazil accumulations is usually only some 2 to 3 inches. Thus, if larger openings can be provided, this type of clogging can often be alleviated. It should be emphasized that heating the trashracks has no advantage in this case since inactive frazil has no tendency to adhere to the intake structure.

C. Clogging of Reservoirs

The property of frazil ice to form flakes and occupy a considerable volume even though only small amounts of actual ice are formed can cause considerable reduction in the efficiency of reservoir operation. While not emphasized in the literature, this condition can be the most dangerous since it may be irremediable.

For example, in 1963, the intake to the Charny Power Station, France, was blocked for an entire winter and lost 4 million kilowatt hours (kWh) of generation [12]. Fist active and inactive frazil passed easily through the hydraulic circuit, then an ice cover settled on the reservoir that had a weak flow velocity through it. Ten days after the formation of the surface ice, the flow stopped abruptly at the water intakes. The rapids above the reservoir had produced enormous amounts of frazil ice which had progressively accumulated downstream, blocking the forebay reservoir almost entirely except for a narrow deep channel. The secondary channel leading to the reservoir was blocked to the very bottom and only a weak flow seeped through the porous mass.

IV. HEATING OF WATER INTAKES

This report discusses the special method of heating trashrack bars to prevent clogging, since this method appears to be the most popular and successful. From a practical standpoint it is extremely important how the heat is applied, but from the standpoint of heat transfer the calculations and assumptions are the same.

A. Theory – Insulating Versus Heating

The concept of heating the trashrack bars is based on the physical law that active frazil ice will not adhere to a surface having a temperature slightly above freezing. The objective is to minimize the heat carried away by the fluid. It is futile to attempt to melt ice by this method when one considers the quantities of energy that would be required and the inefficiency of supplying heat in this manner.

Insulation techniques are used when the objective is to conserve the thermal energy already present in the fluid. Ice covers are the most prevalent utilization of this technique. Covering of intakes is utilized in many instances as an alternative or in addition to trashrack heating. When the trashracks are not completely submerged, it becomes imperative to either cover the intake to reduce the thermal losses to the atmosphere or remove the racks that are not submerged.

The intake channel at Røssaga Powerplant in Norway has been covered with a large roof to prevent cooling by outgoing radiation [5]. A number of electric heaters are also provided to heat the water surface with long-wave radiation. Electrical heating of the trashracks is used to prevent clogging by active frazil ice. Finally, a floating screen with coarse wooden bars is provided to prevent accumulations of floating ice from entering the intake.

B. Methods of Supplying Heat

1. Resistive or induction heating of the metallic components. These methods, which seem to be the most popular, are discussed in detail in this report. The USSR [170a] claims remarkable success with its induction heating designs.

2. Electric heating elements can be embedded in the components to supply the energy. For instance, the trashrack bar could be hollow with a resistance heating element inside.

3. Circulation of heated fluids (air, steam, oil) through the component passages. This method appears popular for gates, penstocks, turbines, surge tanks, valves, etc., but does not appear popular for trashrack heating.

4. Electric radiant or infrared heaters are available and are useful where insulating covers are also used.

5. External application of steam through steam lances.

Whatever method is used it must be compatible with certain requirements. It must be economical with minimum heat losses. It must satisfy hydraulic and structural requirements. It must be reliable and easily maintained, and it must work [36]. A number of methods of applying heat are reviewed in the literature [1, 2, 3, 4, 5, 14, 15, 23g, 28, 33, 35, 40, 41, 170].

Heating the bars by steam has not proved satisfactory but might be advantageous at thermal powerplants. The bars are hollow with pipes conveying steam inserted into them. The arrangement is elaborate; the bars must be thicker than usual, entailing a loss in flow area, and the steam pipes leak whereby the heating of the bars ceases and freezing commences. The thermal efficiency is also quite low. The method has been tried at the Borregaard plant on the Glommen River in Norway [5]. Stream consumption amounted to 13 $kg/hr/m^2$ (2.66 $lb/hr/ft^2$) (based on waterflow area).

The actual heating arrangement selected for a specific installation depends upon a combination of factors and evaluation of alternatives. It is dependent upon the location and configuration of the component, the frequency of frazil occurrence, reliability factors, and availability of energy forms. For example, at a hydroelectric plant where frazil ice occurs occasionally, electric heating of the bars is considered by many to be an economical solution.

C. Recording and Sensing Instrumentation for Predicting Frazil Ice Formation

Bibliography reference [1] describes a method of precise water temperature measurements with an electric resistance thermometer and recorder and its application as a frazil ice warning system for hydroelectric stations. The installations described are at the Holtwood and Safe Harbor hydrostations on the Susquehanna River, Pennsylvania. By precisely measuring and recording the river temperature, frazil ice formation can be predicted and necessary precautions can be taken to prevent operating difficulties.

On the Susquehanna River, it has been found that frazil ice always forms when the river water becomes supercooled and that supercooling occurs only when the rate of cooling is greater than 0.018° F per hour (0.01° C/hr) within the temperature range 32.18° to 32.0° F (0.1° – 0.0° C). Cooling that occurs outside this temperature range is unimportant, and at cooling rates less than 0.018° F per hour (0.01° C/hr), a natural ice cover will form. Furthermore, experience shows frazil ice will not form once the ice cover has formed.

At these stations the severity of the frazil run was directly related to the cooling rate, with the higher cooling rates producing more intense frazil runs. Experience at these plants indicates that when the cooling rate exceeds 0.018° F per hour (0.01° C/hr), the trash screens will be choked with frazil ice 1 hour after the temperature reaches 32.0° F (0° C).

It has also been noted that frazil ice formation does not occur during daylight hours because of the influence of solar radiation (80 $Btu/hr/ft^2$) (252 $watts/m^2$). For example, in the early morning hours after a cold night the rate of cooling of the river is high, say 0.018° F per hour (0.01° C/hr), but with the water temperature at 32.9° F (0.5° C), there will be no need to pull the trashrack screens because it will be 5 hours before the freezing point could be reached—the sun will rise before then which will prevent frazil formation.

V. DEVELOPMENT OF HEAT TRANSFER RELATIONSHIP

The condition as it occurs in a water intake can be idealized as shown in figure 6. Start by assuming a cylinder immersed in a fluid. The surface of the cylinder is maintained at some temperature (T_s) above the fluid which has a temperature (T_f) and a velocity of flow (V_f). This example is widely treated in books on heat transfer.

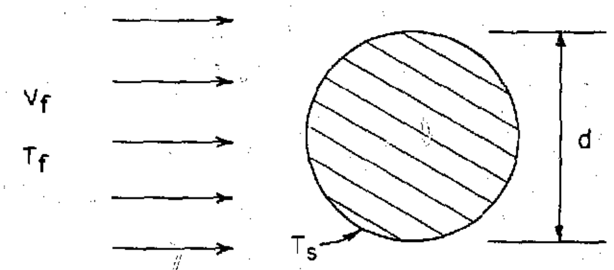

Figure 6. Submerged cylindrical trashrack bar. 101-D-624

The heat transfer from the cylinder to the fluid can be calculated by the convective heat transfer equation:

$$Q_h = h \cdot A \cdot (T_s - T_f) \tag{1}$$

Q_h = energy required to maintain the rack surfaces at a temperature above freezing—Btu/hr or watts

h = average heat transfer coefficient—Btu/hr/ft^2/°F or watts/m^2/°C

A = surface area of the cylinder undergoing heat exchange, ft^2 or m^2

T_s = temperature at which the cylindrical surface of the rack is to be maintained; this temperature need only be slightly above 32° F (0° C)

T_f = the temperature of the supercooled water

The heat transfer coefficient, h, can be calculated using the correlation expressed below [173]:

$$Nu = C(N_R)^n(N\rho)^{m\rho} \qquad (2)$$

where:

$$Nu \text{ (Nusselt number)} = \frac{hd}{k_f}$$

$$N_R \text{ (Reynolds number)} = \frac{vd}{\upsilon}$$

$$N\rho \text{ (Prandtl number)} = \frac{\mu C_p}{k} = \frac{\upsilon}{\alpha}$$

and:

d = bar diameter
h = average heat transfer coefficient
v = velocity of fluid
υ = kinematic viscosity
k_f = thermal conductivity of fluid
μ = absolute viscosity
C_p = specific heat
α = thermal diffusivity

The Prandtl number will be a constant for this example ($N\rho$ = 13.61) since it is dependent on the temperature which will be close to 32° F (0° C) in all important cases of frazil ice formation.

Substituting into equation (2) and rearranging

$$h = \frac{k_f}{d} C \left(\frac{vd}{\upsilon}\right)^n (13.61)^{m\rho} \qquad (2a)$$

Substituting representative values for the constants into equation (2a), the heat transfer coefficient for a typical circular trashrack bar can be calculated.

k_f = thermal conductivity of water at freezing point

$$= 0.32 \frac{\text{Btu}}{\text{hr/ft/°F}} \left(\frac{0.55 \text{ watts}}{\text{m}^2/\text{°C}}\right)$$

υ = kinematic viscosity at freezing point

$$= 20\times10^{-6} \text{ ft}^2/\text{hr } (1.86\times10^{-6} \text{ m}^2/\text{hr})$$

$$\left.\begin{array}{r} NR \approx 10{,}000 \\ C = 0.6 \\ n = 0.5 \\ m\rho = 0.31 \end{array}\right\} \quad n = 0.5,\ m\rho = 0.31 \text{ [reference 172]}$$

Equation (2a) becomes:

$$h = 0.192\sqrt{\frac{10^6 vd}{20}} \quad (2.25)$$

$$h = 100\sqrt{\frac{v}{d}}\ \frac{\text{Btu}}{\text{hr/ft}^2/\text{°F}} = 567\sqrt{\frac{v}{d}}\ \frac{\text{watts}}{\text{m}^2/\text{°C}} \qquad (3)$$

Rewriting equation (1) and substituting equation (3):

$$Q_h = 100\sqrt{v/d}\ (\pi d \ell)\ (T_s - T_f)$$

$$\frac{Q_h}{\ell} = 314\sqrt{vd}(T_s - T_f)\ \frac{\text{Btu}}{\text{hr/ft}}$$

$$= 1782\sqrt{vd}\ (T_s - T_f)\ \frac{\text{watts}}{\text{m}} \qquad (3a)$$

Converting d to inches (meters) and Btu/hr to watts:

$$\frac{Q_h}{\ell} = \frac{314 \quad (1)}{\sqrt{12}\ (3.415)} \sqrt{vd}\ (T_s - T_f)\ \frac{\text{watts}}{\text{ft}}$$

$$\frac{Q_h}{\ell} = 26.5\sqrt{vd}\ (T_s - T_f)\ \frac{\text{watts}}{\text{ft}}$$

$$= 1782\sqrt{vd}\ (T_s - T_f)\ \frac{\text{watts}}{\text{m}} \qquad (4)$$

Equation (4) states that 10.6 watts of energy are required for each lineal foot (0.3 m) of 1 inch (0.025 m) diameter trashrack, when the velocity through the rack is 4 ft/s (1.2 m/s) and the surface of the bar is maintained 0.2° F (0.11° C) above the fluid temperature.

An equation can also be developed that relates energy requirements in terms of bar spacing. This equation is of more use since it is related to energy requirements per square foot of trashrack frontal area (A_f).

$$\frac{Q_h}{A_f} = \frac{318\sqrt{vd}}{s}\ (T_s - T_f)\ \frac{\text{watts}}{\text{ft}^2}$$

$$= \frac{1782\sqrt{vd}}{s}\ (T_s - T_f)\ \frac{\text{watts}}{\text{m}^2} \qquad (5)$$

where:

s = bar spacing in inches (meters)

Only vertical bars are considered in equation (5). For reference purposes if we use $T_s - T_f$ = 0.4° F (0.22° C), a 1-inch (0.025 m) diameter rod, a velocity of 2 ft/s (0.61 m/s), and 4-inch (0.1 m) spacing, then equation

(5) yields 45 watts/ft^2 (485 watts/m^2). Actual field installations show power consumptions of 200 watts/ft^2 (2150 watts/m^2). The value developed here is for idealized conditions and should probably be considered as the minimum attainable for a well-designed system. The values of v, d, and s are known; however, (T_s-T_f) is dependent upon the system design and, as will be shown in the next section, should receive consideration at the design stage.

VI. ANALYSIS OF HEAT TRANSFER RELATIONSHIP

As already mentioned, the development of the heat transfer relationship was for an idealized situation. Conditions at water intakes are not ideal, and large variations in the amount of heat required to prevent icing are to be expected. The deviations from the ideal are related to such factors as bar spacing, bar size, temperature difference between the water and the bar surface, fluid velocity, bar shape, and fluid turbulence. In this section a rough estimate is made to show the effect of these factors on the heat transfer values obtained by using the derived equation (5).

A. Analysis of Factors

1. Spacing and bar size.—The energy required will be related to the surface area maintained above freezing. Thus, as the diameter increases and the spacing decreases, the area being heated increases.

$$Q_{h_2} = \phi\, Q_{h_1}$$

where: Q_{h_1} relates to the reference conditions in equation (5) and ϕ is a multiplier that relates the condition for evaluating Q_{h_2} to the conditions used to evaluate Q_{h_1}.

For instance halving the diameter and tripling the spacing of a given arrangement gives:

$$Q_{h_2} = \sqrt{\frac{d_2}{d_1}}\ \frac{(s_1)}{(s_2)}\ Q_{h_1}$$

$$= \sqrt{\frac{1}{2}}\ (1/3)\ Q_{h_1} = 0.23\, Q_{h_1}$$

and $\phi = 0.23$.

Therefore, only 23 percent of the heat is required under the new arrangement as compared with the reference value.

2. Temperature difference, (T_s-T_f).—The energy consumed is directly proportional to the average temperature difference between the fluid and the trashrack bars, where the temperature of the bar is an integrated average over the entire bar surface area.

A temperature difference of 0.4° F (0.22° C) was used to obtain the reference energy value of 45 watts/ft^2 (485 watts/m^2). The ability to maintain such a small temperature difference is very important for obtaining low power consumption on the bars. The method of heating the bars can strongly affect this value by affecting the temperature variation along the bar. It was not evident from this investigation what degree of variation would be possible for various heating methods; however, induction heating appears to maintain uniform temperature along the length of the bar.

For example, a T_s-T_f = 4° F (2.2° C) will increase the energy consumption tenfold over the base condition of 0.4° F (0.22° C), other factors remaining constant.

3. Flow velocity, v. — The derivation indicates the heat transfer coefficient depends on flow velocity. The hydraulic losses are also strongly related to the flow velocity which is governed by other considerations usually more important than heat transfer. The velocity through the trashrack at most installations is usually between 1.5 – 2.5 ft/s (0.46 – 0.76 m/s).

4. Bar shape.—Equation (5) was derived using a circular bar. The heat transfer coefficient will, however, be related to the shape of the bar. This occurs because the heat transfer rate is related to the flow pattern which is in turn related to the geometry of the bar.

It is shown in heat transfer literature [172] that an expression of the form $Nu = B\ N_R{}^n$ can be used to correlate heat transfer from bars of various shapes. Shown below are appropriate values for the constants B and N for typical bar shapes from streamlined to square.

Ellipse: (e) B = 0.224, n = 0.612
Square: (s) B = 0.092, n = 0.675
Circle: (c) B = 0.536, n = 0.50

By assuming the bar shape is the only characteristic being varied that affects the heat transfer the ratio of the Nusselt numbers will also represent the variation in heat transfer due to bar shape.

$$\frac{h_c}{h_s} = 1.16 \qquad \frac{h_c}{h_e} = 0.86 \qquad \frac{h_s}{h_e} = 0.73$$

The important problem of the direction of the velocity vector has not been considered. In most practical cases, bar shape is governed by considerations more important than heat transfer; for instance, structural needs and hydraulic losses.

It appears then that bar shape has little effect on the heat transfer coefficient in this range of flows.

5. Turbulence.—A well-defined analogy exists between the flow of heat and momentum (Reynolds' analogy) [171]. The analogy developed by Reynolds holds for flow over flat plates; this flow has a well-developed boundary layer. For bars or cylinders, separation occurs and hydraulic energy losses will increase considerably more than the heat transfer losses. With this in mind, flow conditions for intakes are examined, particularly with respect to velocity vector variations. For the ideal situations used in the derivation, the velocity vector was assumed normal to the bar axis.

Using the material presented by Mosonyi [15d], it is noted that trashrack head losses are greatly increased when the flow direction deviates from the normal. For instance, he indicates that for deviations of 10°, 20°, 30°, 40°, 50°, and 60°, head losses increase respectively to 113, 140, 180, 240, 360, and 550 percent. While, as indicated, heat transfer losses are not simply related to these hydraulic losses, they will increase because these losses are reflected as turbulence.

Roughness can also be involved since the cylinder from which the basic equation was derived is smooth, while trashrack bar surfaces would be comparatively rough.

B. Evaluation of Factors

Of all the factors investigated, proper control of the temperature difference (T_s-T_f) is probably the most important. Inproper design of the heating system can lead to values that would be extremely wasteful of energy.

Spacing and bar size also appear to be extremely important and controllable factors. These two factors are closely related to the geometry of the system, the trashrack requirement at a particular site, and the structural design. Removal of part of the trashracks may be possible; increased spacing is another possibility, while the use of two sets of trashracks (summer and winter) needs further investigation. This subject is closely related to hydraulic losses and equipment protection.

The bar shape appears to have a second order effect and could be particularly troublesome to evaluate or change. This is because of the relationship to the velocity vector direction, structural design of the rack, and the importance of reducing hydraulic losses. The USSR [61a], has reported good results on it most recent designs.

Turbulence should receive extra consideration since it is an important item. However, this problem is also intimately related to hydraulic losses in the intake. Even more important, the heating system may operate only a small percentage of the time while the hydraulic losses operate 100 percent of time.

Next, an attempt is made to show that the wide difference between the theoretical value of the energy required and actual values obtained in the field may not really be a discrepancy. The analysis also points out the most fruitful areas for further study. It is possible to indicate in a very crude manner how variations between actual conditions in the intake and those assumed in the derivation will change the heating requirements. Equation (5) $\left(Q/A_f = \frac{318\sqrt{v/d}}{s}(T_s-T_f)\right)$ has been solved for reference conditions of d = 1 inch (0.025 m), v = 2 ft/s (0.61 m/s), s = 4 inches (0.1 m), and T_s-T_f = 0.4° F (0.22° C). Table 1 shows five factors that control the energy requirements for trashrack heating. In Column 1, the reference values are listed, where in Column 2 are listed values that would be more appropriate for an actual trashrack installation. The symbol ϕ is a multiplier with the same meaning stated earlier (see section VI.A.1).

Table 1

FACTORS CONTROLLING HEATING REQUIREMENTS FOR TRASHRACK BARS

	(1)	(2)	(3) ϕ
(1) Spacing	4 in	4 in	1.0
(2) Temperature difference	0.4	1.0	2.5
(3) Velocity	2.0	2.0	1.0
(4) Bar shape and size	circular 1 in	rectangular 0.4x2.8 in	2.0
(5) Turbulence	1.0	2.0	2.0

Thus, the derived equation above will be multiplied by the appropriate factors when they vary from the standard conditions.

Using the ϕ values and equation (5):

$$\frac{Q_h}{A_f} = \left[\frac{318 \quad vd}{s}\right] (1.0)\ (2.5)\ (1.0)\ (2.0)\ (2.0)$$

$$= 450 \text{ watts/ft}^2 \ (4{,}850 \text{ watts/m}^2) \qquad (6)$$

For an intake corresponding to the data of Column 2 and assuming a satisfactory design, it appears this may be a good design guideline. Certainly, if the power consumption is, say, double and triple this value, a problem exists that is related to operation and maintenance or design rather than heat transfer. Sensitivity evaluation of the parameters that affect power consumption leads to the conclusion that control of the bar temperature is the single most important factor. This is associated with the electrical design, a point only briefly discussed in this report. Velocity, rack geometry, and turbulence are intimately associated with the hydraulic design of the intake. Their effect on the heat transfer coefficient can be calculated and cannot cause great deviations from the calculated power consumption.

C. Trashrack Heating Requirements Balanced Against Power Developed

Each pound of water as it enters the intake has a certain power potential. If the power is used to heat the trashrack, the efficiencies of the generator (96 percent), turbine (88 percent), transformer (98 percent), hydraulic circuit (90 percent), and certain other losses must be considered. Therefore, only about 70 percent of the energy potential at the intake can be utilized. By relating the electrical quantity watts to the hydraulic quantities, flow and head, we have:

$$\text{watts} = \frac{Q\,w\,H}{550} \times 746 \times 0.70 \approx 60\ QH$$

where:

Q = discharge (ft^3/s)
w = unit weight of water (lb/ft^3)
H = hydraulic head (ft)

Thus, 1 ft^3/s (0.028 m^3/s) at 1 foot (0.305 m) of head has a heating potential of around 60 watts. Or assuming a 2.0 ft/s (0.61 m/s) velocity through the trashracks, each square foot of rack area has a heating potential of around 120 watts per ft^2 per foot of head (4,250 watt/m^2/m).

D. Actual Values at Hydroelectric Installations

The equations developed in the previous section are intended to help deduce those factors that are most important in determining the power requirements for a heated trashrack. Bibliography references [1, 2, 4, 5, and 14] list a number of values pertaining to installations in Norway, Sweden, Canada, and the United States. Most of the references do not contain enough information about the installation design, power requirements, electrical hookup, and operation of the system to arrive at firm conclusions concerning design of these systems. Where possible, an attempt has been made to analyze the values given in terms of equation (6).

In studying Holtwood Station, Susquehanna River, Pennsylvania, Reference [1] states that 2.4 feet (0.73 m) of head are required to heat the trashracks which has water velocity through the trashracks of 2 ft/s (0.61 m/s) results in an energy consumption of approximately 300 watts/ft^2 (3,220 watts/m^2). With reference to table 1, appropriate ϕ values would be:

$\phi(1)$ = 1.33
$\phi(2)$ = unknown temperature differences for which we are solving
$\phi(3)$ = 1.0
$\phi(4)$ = 2.0, and
$\phi(5)$ = 2.0.

Evaluating equation (6)

$$300 = Q_{h\ ref}\ [(1.33)\ (\phi(2))\ (1.0)\ (2.0)\ (2.0)]$$

$$\phi(2) = \frac{300}{(45)\ (5.35)} = 1.25 \text{ or } 125 \text{ percent.}$$

Since the reference temperature is 0.4° F (0.22° C), this indicates the bar temperature $T_s \approx 32.5°$ F (0.3° C).

At Shawinigan Falls, Quebec, Canada [2], it is noted that 227 watts/ft^3/s (8,000 watts/m^3/s) are required to prevent frazil ice formation at this plant. Assuming the velocity through the rack is 2 ft/s (0.61 m/s) an energy consumption of 550 watts/ft^2 (5,900 watts/m^2) is indicated.

At the Swedish Hydro Installation, Samsioe [4] reports a value of 625 watts/ft^2 (6,730 watts/m^2) for Swedish installations.

At Norwegian Hydro Installations, Ruth [5] reports values between 280-350 watts/ft^2 (3,000-3,800 watts/m^2) at seven Norwegian powerplants. Putting appropriate ϕ values on the data given in the article results in $\phi(1) = 2.7$; $\phi(2) = ?$; $\phi(3) = 1.0$; $\phi(4) = 2.0$; $\phi(5) = 2.0$. Making the proper substitutions yields a $\phi(2) \approx 0.68$. This would indicate a bar surface temperature of 32.3° F (0.16° C). While it is not possible to put exact values on ϕ from the data given, this article states that the spacing is around 1.5 inches between bars (3.8 mm), and 350 watts/ft^2 (3,800 watts/m^2) is a very low value for energy input.

Most of the installations discussed in the literature were either induction or resistive heating, though other techniques have been tried and should be investigated further. The technology of heating appears to be well established and hundreds of such installations are in use. The users consider the power requirements as being low and the reliability and operating history as good. At some installations where trashrack heating systems were used to melt ice, the systems were usually ineffective and the intake would clog regardless of the temperature at which the bars were maintained.

VII. ELECTRICAL HEATING OF BARS

This subject is outside the scope of this investigation; however, as shown in the previous section, the proper design of the electrical system is all important if reasonable power consumption is to be realized. During the investigation, a number of heating systems presented in the literature were reviewed.

In a paper published at the 1972 Leningrad Ice Symposium, reference [61a], investigators from the U.S.S.R. reported great success with an advanced induction heating system for trashracks. They reported that their new design coupled with a drop-shaped trashrack bar permitted normal operation of power units during frazil ice passage. They further indicated that the drop-shaped bar reduces head losses and lends itself well to the heating arrangement. There were not enough details given in the paper to further describe the system. Since induction heating is also used for heating other hydroelectric components, further investigation seems worthwhile. Induction heating was used by the USBR [28] for the drum gates at Grand Coulee Dam. This reference contains considerable information on induction heating.

Reference [5] gives the details of other systems described in the literature; however, for the most part, the heat is generated resistively as contrasted with the induction method. The importance of proper design cannot be stressed too strongly. It has been reported that even trashracks that maintained surface temperatures above freezing, reference [61a], can become severely clogged during heavy frazil runs.

VIII. ECONOMICS

There are a number of alternatives to heating the bars, and when heating is used there are a number of heating designs available. In general, the costs break down into capital costs based on the type of system supplied, the capacity of the system in kilowatts, and those considerations which have been discussed elsewhere in this report. The second consideration is the operating costs of the system based on the amount of power supplied, the time for which it is supplied, and the unit cost of energy in dollars/kWh.

Early in the planning stage consideration should be given to the frequency of system operation. This, of course, will depend upon local meteorological conditions and the hydraulics of the system upstream of the intake. A paper by Schermann [23a] gives insight into a probability method of analyzing this problem for canals or rivers.

For purposes of assigning quantative values to the concepts discussed, assume an intake will need heat applied 2 percent of time and the power requirement is 1 percent of the unit capacity with energy valued at 10 mills kWh for a 50,000-kW turbine:

$$\text{operating cost} \approx 50{,}000 \text{ kw} \times 20 \frac{\text{hours}}{\text{day}}$$
$$\times\, 300 \frac{\text{days}}{\text{year}} \times 0.02 \times 0.01 \times 0.01 \frac{\text{dollars}}{\text{kWh}}$$
$$\approx \$600/\text{year}$$

This operating cost must be considered along with the design and installation costs of the heating system.

IX. CONCLUSIONS

A. General

1. Ice technology as it applies to hydroelectric projects is a well-developed and operational engineering science in many parts of the world. The majority of this technology is available through literature searches. Most problem areas germane to USBR work are described in detail in the literature. Hundreds of powerplants, some built even north of the Arctic Circle, have been constructed and, through proper design, operate efficiently.

2. Icing problems should be considered at the planning or early in the design stage. A number of

alternatives are usually available for any problem; however, these alternatives must be given early consideration. The entire hydraulic circuit should be examined since while the problem may appear to be local (trashracks clogging), the causes (frazil ice production) and effects (loss of power production) are not.

3. It is possible to evaluate the potential icing problems at an installation from a knowledge of the hydrological, meteorological, and topographical conditions which exist at the site.

B. Trashrack Heating

1. Heating of trashracks is of value when frazil ice is in the supercooled, highly adherent state. In its inactive state frazil is not sticky and passes through the system with relative ease.

2. A wide range of required trashrack heating values appear in the literature. It seems reasonable to expect that between 2 and 4 feet of head will be required to supply energy. For typical intakes, this means about 250-500 watts per square foot (2,700-5,400 watts/m^2) of trashrack frontal area. From a discussion elsewhere in this report it can be seen that if energy consumption much greater than the above limits are demanded at operating installations, the problem is likely to be because of inadequate design or faulty operation.

3. Active frazil conditions can be predicted at a given site. Suitable monitoring equipment has been developed so that the heating system need only be energized when conditions indicate active frazil may be formed.

4. Melting of float ice using the trashrack heating system is inefficient and will not prevent clogging.

5. Ice phobic materials are under development; however, investigation is needed to determine their adequacy for trashrack structures.

6. Factors which affect the energy consumption of a trashrack heating system were investigated. Control of the bar surface temperature and turbulence in the intake are two very important factors that should receive further investigation. For this report they were estimated using a practical and theoretical model approach.

7. Apparently little has been done to advance the electrical design of these systems. Investigation is needed in the area since much of the inefficiency may involve improper design of the electrical system.

8. No data are available concerning the surface temperature distribution on the racks or the temperature at which the rack surface is being maintained. Investigations in this area could improve the efficiency of present heating techniques.

X. RECOMMENDATIONS

A. The theoretical minimum energy requirement necessary to supply the heating systems is approximately 10 to 20 percent of that found to be required in actual facilities surveyed. Experiments should be directed toward obtaining this minimum and recognizing that economic benefits may or may not warrant the added expense of an improved system.

B. The Bureau's Ice Research Management Committee should continue to accumulate more knowledge in the field of ice technology and some indepth expertise before embarking on advanced technology. This type of program is quite inexpensively attained and would be of maximum immediate benefit to field offices. If field problems exist, it would be worthwhile to apply available ice technology to their solution.

Further technology studies such as the one just completed would be useful in developing ice control techniques. These studies should include:

1. Power canal heat loss studies

2. Frazil ice production studies

3. Study of western United States to relate meteorology, hydraulics, and topography to occurrence of ice problems

4. Develop hydroelectric problem/solution matrix for ice engineering.

5. Investigate effective use of natural heat balance

6. Design improvements in gates, valves, sluices, penstocks, and hydraulic machinery to prevent ice problems in and around these appurtenances.

C. Develop an ice technology library.

D. Basic research on heat and mass transfer at an air-water interface with emphasis on periods during which frazil ice is being formed.

E. Explore closer cooperative arrangements with others involved in ice studies; that is, U. S. Army, Cold Regions Research and Engineering Laboratory (CRREL).

F. Explore further mechanisms of frazil ice formation on solid boundaries with emphasis on application of ice phobic materials.

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APPENDIX A

Related Technology

A number of other related technologies are discussed in the literature and mention is made of these subjects. Detailed analysis cannot be included.

1. Removal of Racks [2]

A common and obvious method of dealing with frazil ice is to raise the racks and let the frazil pass through the turbines. Since racks are often made in sections, it is usually possible to raise the top section from 3 to 6 feet (0.91-1.8 m). The upper rack will be covered with frazil, but after that the needles are carried down and pass through the opening; the lower part of the rack is then free from ice.

The major objection to raising the racks is that the purpose for which the racks are intended; that is, to keep trash out of the turbines. Trash or large pieces of ice entering the turbines blocks the water passages, reduce output, unbalance the runner which leads to vibration, and can cause damage to the runner and guide vanes. It may be necessary to shut the turbine down frequently for cleaning while the rack is raised. If the frazil ice run time is short, this technique may be useful. In some locations trash is not a problem during the winter months and therefore the racks can be raised without endangering the operation of the structure.

2. Coarse Versus Fine Racks

Another technique has been to remove the fine screens used for summer operation and replace them with a coarse [12-inch (0.3 m)] screen of wood for winter operation. This allows the frazil to pass through the turbines as comparatively loose masses which will not damage the rotating equipment. Large pieces of solid ice could prove dangerous to the turbines. Investigations using this technique are necessary in any particular situation.

3. Streamflow Regulation

The regulation of streamflow by the creation of storage behind weirs and dams decreases the variability of the discharge downstream. Fifty years ago, Swedish and Norwegian engineers [4] recognized that if they could dredge the rapids or form permanent ice covers, they would solve most of their ice problems. The effects of regulation on the ice regime are:

a. Promotion of a stable ice cover with consequent reduction in heat loss,

b. Retention of ice upstream and consequently diminished amounts of ice moving downstream,

c. Reduction of frazil production—warmer water from reservoir depths is sent downstream,

d. Reduction in breakup of newly formed ice sheets by the daily flood wave, and

e. Delay of breakup downstream by attenuation of flood discharges.

The effect should be studied for any particular system. Operating a hydroplant on baseload during ice formation and breakup reduces the variation in discharge.

In some instances if hydroelectric plant output can be reduced for a few hours when frazil is forming the velocity in the forebay or intake channel is reduced, and a stable ice cover can form. However, there is the danger that resumption of normal operation will erode the cover.

Experience with streamflow regulation using a submerged weir in conjunction with a boom to create an ice cover and thus alleviate ice jamming has been encouraging.

4. Special Intake Structures

Several special structures have been designed to help eliminate ice problems at intakes. Special intakes to pass, block, and/or minimize frazil conditions have been designed. Reference [3] describes a raft system which prevents whirl in front of a powerplant and thereby prevents the supercooled surface water from being carried down to the intake.

5. Ice Storage Reservoirs

Low-velocity pools can often be created to provide for storage under a stable ice cover of all or part of the ice formed in a fast-flowing stream. As the reservoir fills with ice, the velocity under the ice increases until the rate at which ice is carried under it equals the rate at which it leaves the reservoir. Such an ice control technique may be more practicable than constructing a facility to decrease the gradients in fast-flowing reaches.

6. Mechanical Raking

In the early days of hydroelectric development, hand and mechanical raking was used to keep the screens free from frazil, literally by brute force. To quote Reference [5], "To start with, hand scrapers were used to keep the screens free from frazil. As many men as could conveniently find a place on the stand above the screens were mobilized at times of frazil ice formation trying with scrapers of different lengths to keep the screen free. As a rule, these endeavors were entirely in vain," the screens clogged and the output was reduced accordingly. Mechanical scrapers of various design have also been tried. These have also proved unsuccessful, the ice formation being so heavy that the flow through the screens was eventually completely stopped.

7. Vibration of Racks

This method has apparently been tried, but little data were available in the literature.

8. Typical Hydroplant Designs with Powerplant Fed by Headrace Canal or With a Large Forebay

Two Norwegian hydroplants, Kykkelsrucl and Vamma, are discussed in Reference [5]. They illustrate the problem and avoidance of the problem of frazil ice. Characteristic of the Kykkelsrucl plant is its long headrace canal which conveys water from the river to the powerhouse forebay. The water velocity in the canal is 6.5 ft/s (2 m/s) and is therefore great enough to exclude formation of surface ice, and as the entire flow of the river passes into the canal, so does all drift, frazil, and solid ice. The solution here has been to provide an ice sluice which when opened creates a surface current alongside the screens. By this means all the drift ice and solid ice are removed.

Only surface ice can be removed in this way, whereas drifting frazil can fill the entire flow section from top to bottom and consequently is not so easy to deal with. This frazil often has a tendency to stick to anything it contacts. The canal intake is often a barrier which the frazil must pass, and ice masses can accumulate at this point. Dynamite has been used at Kykkelsrucl to keep the canal intake free.

By contrast, plants of the Vamma type have a large forebay and employ an ice cover to mitigate ice problems.

In some canals or rivers where velocities have been too high to form an ice cover, it has been possible to place a coarse network of timbers across the channel and thereby promote an ice cover. The theory of promoting ice covers using booms is well covered in the literature and many installations are operating successfully.

It is interesting to note that the early Norwegian, Swedish, and Canadian writers pointed toward damming all the main water-courses as the ultimate solution to the icing problem. It was thought that if an ice sheet could be formed over these areas of frazil ice production, the problem would cease to exist.

9. Combating Frazil Ice

The best method of combating the problem of frazil ice is through proper design of the hydraulic circuit upstream of the rack bars. A large body of quiet water will freeze over quickly and an ice covering of sufficient size will intercept the frazil. If the velocity of approach is low, the racks are at considerable depth; and if, in addition, the bed of the approach channel is smooth and grades down easily to the bottom of the rack, frazil ice problems may be eliminated entirely. Precautions to avoid ice problems must be considered at an early stage in designing the project if an optimum solution is to be found.

GPO 856-047

7-1750 (3-71)
Bureau of Reclamation

CONVERSION FACTORS--BRITISH TO METRIC UNITS OF MEASUREMENT

The following conversion factors adopted by the Bureau of Reclamation are those published by the American Society for Testing and Materials (ASTM Metric Practice Guide, E 380-68) except that additional factors (*) commonly used in the Bureau have been added. Further discussion of definitions of quantities and units is given in the ASTM Metric Practice Guide.

The metric units and conversion factors adopted by the ASTM are based on the "International System of Units" (designated SI for Systeme International d'Unites), fixed by the International Committee for Weights and Measures; this system is also known as the Giorgi or MKSA (meter-kilogram (mass)-second-ampere) system. This system has been adopted by the International Organization for Standardization in ISO Recommendation R-31.

The metric technical unit of force is the kilogram-force; this is the force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 9.80665 m/sec/sec, the standard acceleration of free fall toward the earth's center for sea level at 45 deg latitude. The metric unit of force in SI units is the newton (N), which is defined as that force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 1 m/sec/sec. These units must be distinguished from the (inconstant) local weight of a body having a mass of 1 kg, that is, the weight of a body is that force with which a body is attracted to the earth and is equal to the mass of a body multiplied by the acceleration due to gravity. However, because it is general practice to use "pound" rather than the technically correct term "pound-force," the term "kilogram" (or derived mass unit) has been used in this guide instead of "kilogram-force" in expressing the conversion factors for forces. The newton unit of force will find increasing use, and is essential in SI units.

Where approximate or nominal English units are used to express a value or range of values, the converted metric units in parentheses are also approximate or nominal. Where precise English units are used, the converted metric units are expressed as equally significant values.

Table I

QUANTITIES AND UNITS OF SPACE

Multiply	By	To obtain
	LENGTH	
Mil	25.4 (exactly)	Micron
Inches	25.4 (exactly)	Millimeters
Inches	2.54 (exactly)*	Centimeters
Feet	30.48 (exactly)	Centimeters
Feet	0.3048 (exactly)*	Meters
Feet	0.0003048 (exactly)*	Kilometers
Yards	0.9144 (exactly)	Meters
Miles (statute)	1,609.344 (exactly)*	Meters
Miles	1.609344 (exactly)	Kilometers
	AREA	
Square inches	6.4516 (exactly)	Square centimeters
Square feet	*929.03	Square centimeters
Square feet	0.092903	Square meters
Square yards	0.836127	Square meters
Acres	*0.40469	Hectares
Acres	*4,046.9	Square meters
Acres	*0.0040469	Square kilometers
Square miles	2.58999	Square kilometers
	VOLUME	
Cubic inches	16.3871	Cubic centimeters
Cubic feet	0.0283168	Cubic meters
Cubic yards	0.764555	Cubic meters
	CAPACITY	
Fluid ounces (U.S.)	29.5737	Cubic centimeters
Fluid ounces (U.S.)	29.5729	Milliliters
Liquid pints (U.S.)	0.473179	Cubic decimeters
Liquid pints (U.S.)	0.473166	Liters
Quarts (U.S.)	*946.358	Cubic centimeters
Quarts (U.S.)	*0.946331	Liters
Gallons (U.S.)	*3,785.43	Cubic centimeters
Gallons (U.S.)	3.78543	Cubic decimeters
Gallons (U.S.)	3.78533	Liters
Gallons (U.S.)	*0.00378543	Cubic meters
Gallons (U.K.)	4.54609	Cubic decimeters
Gallons (U.K.)	4.54596	Liters
Cubic feet	28.3160	Liters
Cubic yards	*764.55	Liters
Acre-feet	*1,233.5	Cubic meters
Acre-feet	*1,233,500	Liters

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Table II

QUANTITIES AND UNITS OF MECHANICS

Multiply	By	To obtain
MASS		
Grains (1/7,000 lb)	64.79891 (exactly)	Milligrams
Troy ounces (480 grains)	31.1035	Grams
Ounces (avdp)	28.3495	Grams
Pounds (avdp)	0.45359237 (exactly)	Kilograms
Short tons (2,000 lb)	907.185	Kilograms
Short tons (2,000 lb)	0.907185	Metric tons
Long tons (2,240 lb)	1,016.05	Kilograms
FORCE/AREA		
Pounds per square inch	0.070307	Kilograms per square centimeter
Pounds per square inch	0.689476	Newtons per square centimeter
Pounds per square foot	4.88243	Kilograms per square meter
Pounds per square foot	47.8803	Newtons per square meter
MASS/VOLUME (DENSITY)		
Ounces per cubic inch	1.72999	Grams per cubic centimeter
Pounds per cubic foot	16.0185	Kilograms per cubic meter
Pounds per cubic foot	0.0160185	Grams per cubic centimeter
Tons (long) per cubic yard	1.32894	Grams per cubic centimeter
MASS/CAPACITY		
Ounces per gallon (U.S.)	7.4893	Grams per liter
Ounces per gallon (U.K.)	6.2362	Grams per liter
Pounds per gallon (U.S.)	119.829	Grams per liter
Pounds per gallon (U.K.)	99.779	Grams per liter
BENDING MOMENT OR TORQUE		
Inch-pounds	0.011521	Meter-kilograms
Inch-pounds	1.12985×10^6	Centimeter-dynes
Foot-pounds	0.138255	Meter-kilograms
Foot-pounds	1.35582×10^7	Centimeter-dynes
Foot-pounds per inch	5.4431	Centimeter-kilograms per centimeter
Ounce-inches	72.008	Gram-centimeters
VELOCITY		
Feet per second	30.48 (exactly)	Centimeters per second
Feet per second	0.3048 (exactly)*	Meters per second
Feet per year	*0.965873×10^{-6}	Centimeters per second
Miles per hour	1.609344 (exactly)	Kilometers per hour
Miles per hour	0.44704 (exactly)	Meters per second
ACCELERATION*		
Feet per second^2	*0.3048	Meters per second^2
FLOW		
Cubic feet per second (second-feet)	*0.028317	Cubic meters per second
Cubic feet per minute	0.4719	Liters per second
Gallons (U.S.) per minute	0.06309	Liters per second
FORCE*		
Pounds	*0.453592	Kilograms
Pounds	*4.4482	Newtons
Pounds	*4.4482×10^5	Dynes

Table II—Continued

Multiply	By	To obtain
WORK AND ENERGY*		
British thermal units (Btu)	*0.252	Kilogram calories
British thermal units (Btu)	1,055.06	Joules
Btu per pound	2.326 (exactly)	Joules per gram
Foot-pounds	*1.35582	Joules
POWER		
Horsepower	745.700	Watts
Btu per hour	0.293071	Watts
Foot-pounds per second	1.35582	Watts
HEAT TRANSFER		
Btu in./hr ft^2 degree F (k, thermal conductivity)	1.442	Milliwatts/cm degree C
Btu in./hr ft^2 degree F (k, thermal conductivity)	0.1240	Kg cal/hr m degree C
Btu ft/hr ft^2 degree F	*1.4880	Kg cal m/hr m^2 degree C
Btu/hr ft^2 degree F (C, thermal conductance)	0.568	Milliwatts/cm^2 degree C
Btu/hr ft^2 degree F (C, thermal conductance)	4.882	Kg cal/hr m^2 degree C
Degree F hr ft^2/Btu (R, thermal resistance)	1.761	Degree C cm^2/milliwatt
Btu/lb degree F (c, heat capacity)	4.1868	J/g degree C
Btu/lb degree F	*1.000	Cal/gram degree C
Ft^2/hr (thermal diffusivity)	0.2581	Cm^2/sec
Ft^2/hr (thermal diffusivity)	*0.09290	M^2/hr
WATER VAPOR TRANSMISSION		
Grains/hr ft^2 (water vapor transmission)	16.7	Grams/24 hr m^2
Perms (permeance)	0.659	Metric perms
Perm-inches (permeability)	1.67	Metric perm-centimeters

Table III

OTHER QUANTITIES AND UNITS

Multiply	By	To obtain
Cubic feet per square foot per day (seepage)	*304.8	Liters per square meter per day
Pound-seconds per square foot (viscosity)	*4.8824	Kilogram second per square meter
Square feet per second (viscosity)	*0.092903	Square meters per second
Fahrenheit degrees (change)*	5/9 exactly	Celsius or Kelvin degrees (change)*
Volts per mil	0.03937	Kilovolts per millimeter
Lumens per square foot (foot-candles)	10.764	Lumens per square meter
Ohm-circular mils per foot	0.001662	Ohm-square millimeters per meter
Millicuries per cubic foot	*35.3147	Millicuries per cubic meter
Milliamps per square foot	*10.7639	Milliamps per square meter
Gallons per square yard	*4.527219	Liters per square meter
Pounds per inch	*0.17858	Kilograms per centimeter

ABSTRACT

The phenomenon of ice formation in flowing water and the technology of heating trashrack bars to prevent clogging by frazil ice are reviewed. The report includes: (1) A description of frazil ice formation, (2) development of heat transfer equations for trashrack bars immersed in a fluid, (3) correlation between conditions assumed in developing the theoretical expressions and actual conditions present in a water intake, (4) economics of heating trashrack bars, (5) methods of heating trashrack bars, and (6) recommendations for future studies. Has 64 references.

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DESCRIPTORS—/*frazil ice/ ice/ canals/ floating ice/ ice cover/ open channels/ slush/ intake structures/ *heating/ trashracks/ barriers/ bibliographies

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