HYDRAULIC LABORATORY

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ICE PREVENTION BY THE AIR-LIFT SYSTEM AT GRAND COULEE

by Thomas G. Owen

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ICE PREVENTION BY THE AIR-LIFT SYSTEM AT GRAND COULEE

Laboratory Investigations Disclose Problems Encountered in Designing Orifices for the Air-Lift Ice-Prevention System for the Grand Coulee Dam, Columbia Basin Project, Washington

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ABSTRACT

A laboratory study of the orifices for the air-lift de-icing system at Grand Coulee Dam was made which embraces testing of single- and multiple-hole arrangements of orifices of the short-tube type, the diverging-tube type, and various combinations of both. Flow patterns were studied with these various orifices discharging upward, horizontally, and downward. Special attention was devoted to the freezing phenomenon and rules for designing a satisfactory nonfreezing orifice have been proposed. An orifice was developed which gave a satisfactory balance between flow pattern, economy of operation, and nonfreezing characteristics.

The formation of ice in front of the trashracks and drum gates of Grand Coulee Dam will be both detrimental to good operation and dangerous to the structure. Temperatures of -28° F. and of several days duration have been recorded at the dam site. The problem confronting the designing engineers was to develop a system whereby the reservoir surface immediately adjacent to the upstream face of the dam could be maintained free of ice. Many methods of accomplishing this result were studied but discarded in favor of the air-lift system because of its simplicity. In the air-lift system compressed air is forced into the reservoir adjacent to the structure at a depth at which the water temperature is at or near that corresponding to maximum density. The stirring and mixing action of the rising air induces the upward flow of relatively warm currents of water, which either melt the ice or prevents its formation.

A typical plan and section of the proposed location of the orifices in front of one trashrack and in front of one drum gate is shown in figure 1. Provision is made to introduce air at three different elevations in front of the trashracks and at two separate levels in front of the drum gates. This feature allows air to be introduced at a depth equal to or greater than 10 feet, which has been found to be the minimum depth for best results, regardless of the reservoir elevation.

The problems of determining the best size, shape, and direction of discharge of the orifice and the cooling effect due to expansion of the air at the orifice exit were studied in a 1 to 1 scale model in the hydraulic laboratory of the Bureau of Reclamation in Denver, Colorado. The laboratory investigation was divided into two parts: First, a preliminary examination of several orifice designs; second, a detailed study concerning the cooling effect due to expansion.

In the preliminary tests the equipment consisted of a glass-

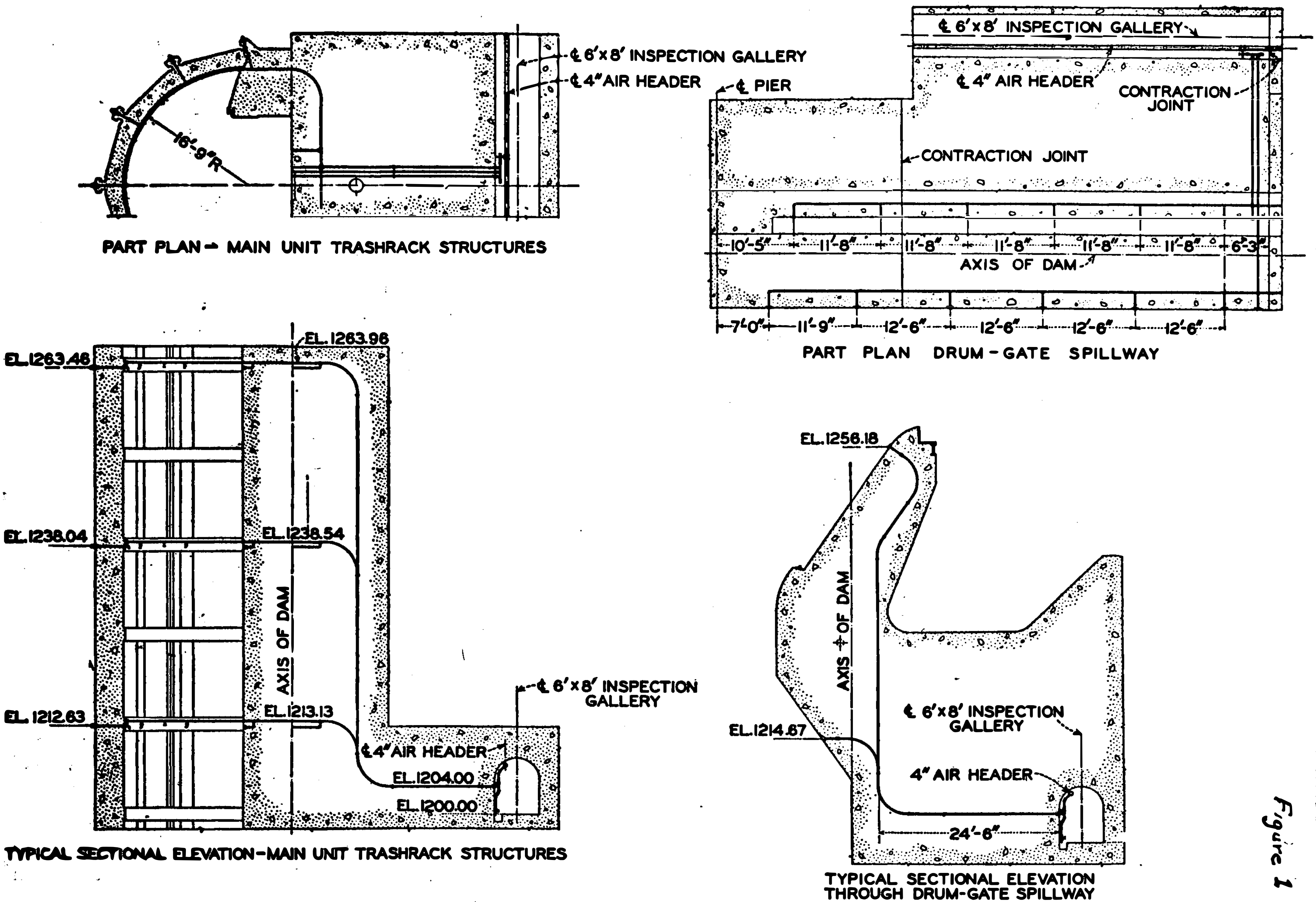
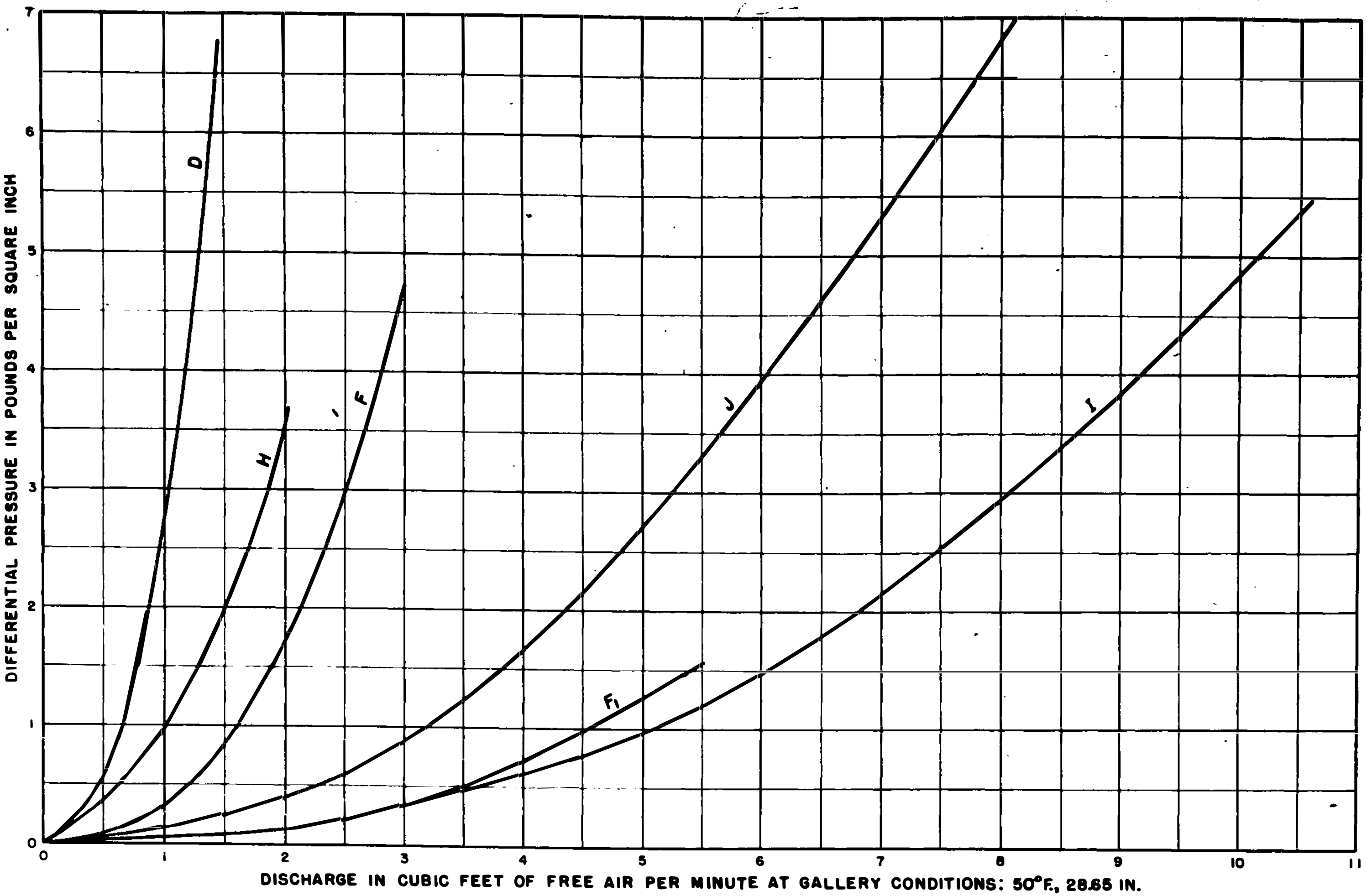


Figure 1

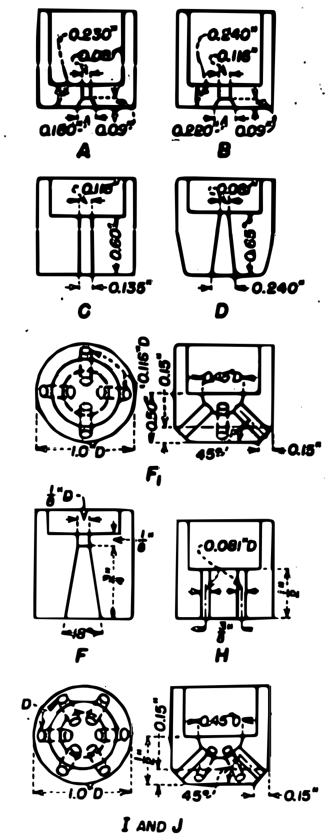
Fig. 1 Typical Orifice Locations in Front of Trash-Rack and Drum-Gate Spillway Structures sided tank, near the bottom of which was located the orifice to be tested. The orifice was connected with a high-pressure air line and a throttling valve was placed in the line to control the pressure. Air-line pressure at the orifice and static water pressure at the orifice elevation were measured by mercury U-tubes, and the difference between these two observed pressures gave the differential pressure across the orifice.

In the experiments on orifices A, B, and C, the tests were purely visual. The general details of these orifices are shown in figure 2 and a typical flow pattern in figure 3. From these tests it was determined that discharge directed vertically downward gave the best flow pattern, the criterion being the largest cross-sectional area of the rising air current and the fineness of division of the air bubbles. It was observed further that an orifice of type C gave a better pattern than type B, which had the same cross-sectional area.

After these initial tests, a gas meter of the displacement type was installed to obtain the discharge characteristics of the various orifices. The flow pattern of orifice D was found to be good but its discharge was too low to establish a strong upward water current. Orifice F produced a good flow pattern and also a good upward circulation of water. The orifices thus far tested had only one hole. The multiple-hole nozzles were then examined. This group embraces orifices F_1, H, I, and J (figure 2). The



A. PRESSURE-DISCHARGE CURVES BASED ON AVERAGE STATIC WATER HEAD ON ORIFICE OF 1.987 POUNDS PER SQUARE INCH AND AVERAGE LABORATORY BAROMETER OF 12.142 POUNDS PER SQUARE INCH



Note: For orifice I, D=0.100"
For orifice J, D=0.081"

B. ORIFICE DETAILS

GRAND COULEE DE-ICING EXPERIMENTS
PRESSURE-DISCHARGE CURVES AND ORIFICE DETAILS

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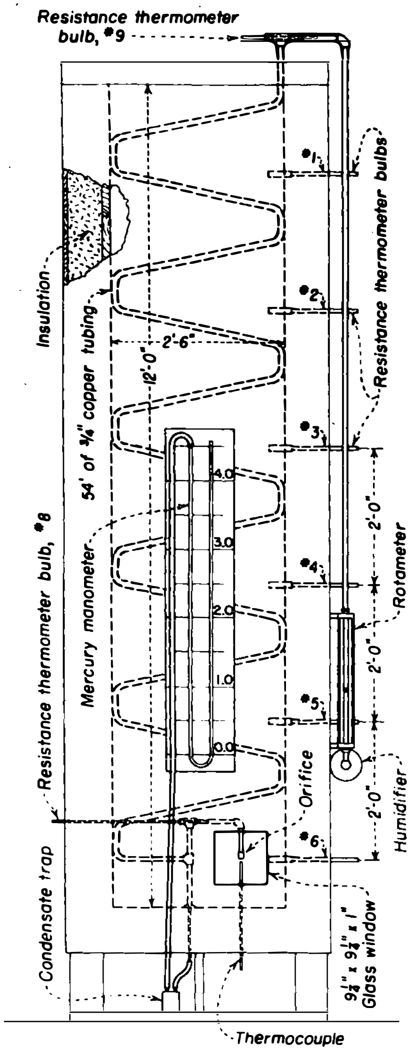
Figure 2

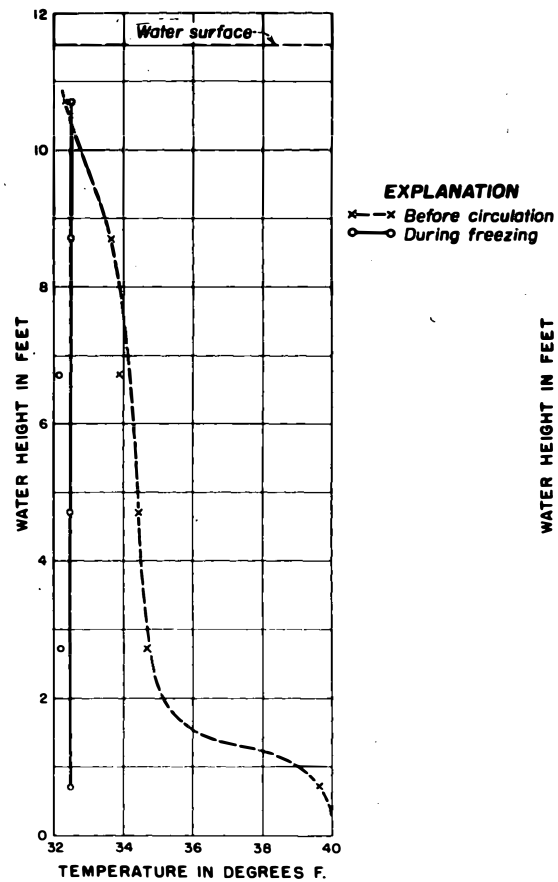
Figure 3 - Typical vertical discharge flow pattern at 3 pounds per square inch differential pressure (orifice C).

flow pattern from nozzle H was no better than F, and the water current it established was inferior. Nozzles F_1, I, and J all gave excellent flow patterns and induced strong water currents but the discharge capacity of each was excessive. It was thought that if the diameters of the holes in these three nozzles were reduced to lower their discharge capacity, the holes would then be so small that they might easily become fouled or plugged by foreign matter.

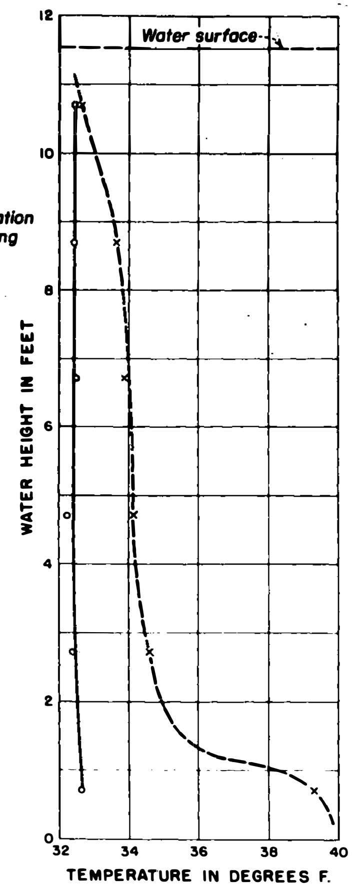
For the detailed investigation a special tank was constructed and equipped with instruments. The tank was made 12 feet deep so that at least 10 feet of static waterhead could be imposed on the orifice. Inside the tank about 54 feet of 3/4-inch copper pipe was placed in coils at the end of which was located the orifice to be tested. In one side of the tank and at the elevation of the orifice a piezometer opening and a resistance thermometer bulb were located. Located in the same side of the tank at two-foot intervals vertically above the thermometer bulb at the orifice level were five other thermometer bulbs to determine the temperature gradient during testing. These details are shown in figure 4-A. The resistance thermometers were connected through a selector switch to a Wheatstone bridge and the resistance balance was indicated by a very sensitive light-beam galvanometer. The temperature of the air before entering the copper coils was measured by resistance thermometer No. 9, and the air temperature



A. DETAILS OF DE-ICING EQUIPMENT



B. TEMPERATURE GRADIENT CURVES, TEST: GIC-11



C. TEMPERATURE GRADIENT CURVES, TEST: GIC-12

GRAND COULEE DE-ICING EXPERIMENTS
DETAILS OF APPARATUS AND TEMPERATURE GRADIENT CURVES

Figure 4

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before expansion through the orifice, by thermometer bulb No. 8. Attempts were made to measure the temperature of the air stream issuing from the orifice by using a small resistance thermometer bulb and also by a thermocouple. However, because of the oscillation of the air jet and the vibration of the thermocouple it was thought that neither the resistance thermometer nor the thermocouple was continuously surrounded by air alone and hence the indicated temperatures were unreliable.

Insulating material was placed between the inner and outer tank walls which were separated by 2- by 6-inch studding. The bottom of the tank was insulated and the top was equipped with a close-fitting removable cover, also insulated. The air pressure was controlled by a system of three valves (figure 5) so arranged that variations in the supply-line pressure would be minimized. The humidity of the air from the supply line was increased by passing the air through the humidifier, consisting of two atomizers which sprayed water on two porous baffles. Mechanically entrained water was removed by a system of three solid baffles (figure 5). From the humidifier the air passed through the air rotameter, a device for measuring rate of flow. The air rotameter (figure 5) consists of an accurately machined glass tube tapered to increase in bore from bottom to top. A spinning metal rotor floats in the air stream and its position, read on a scale on the glass tube, indicates the amount of air flowing. Just above the rotameter, a

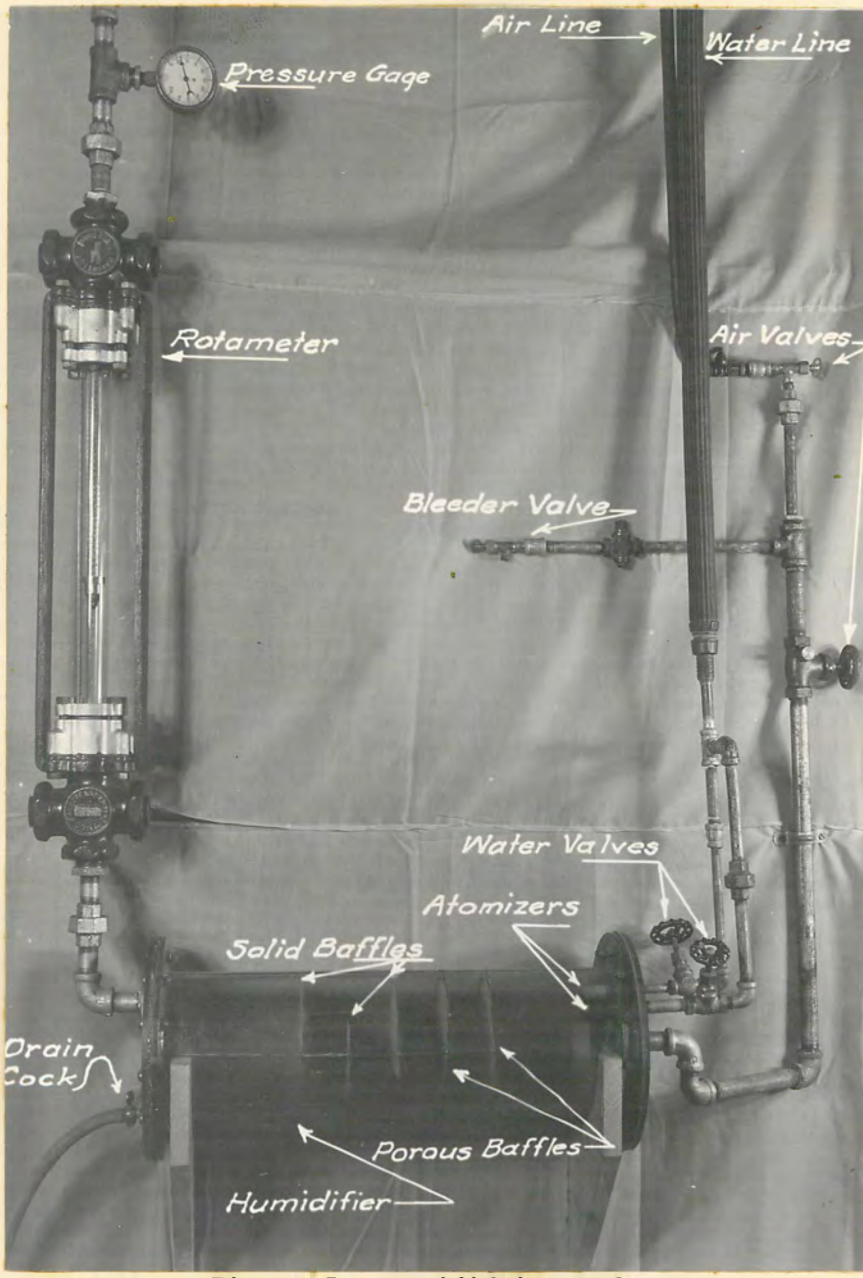


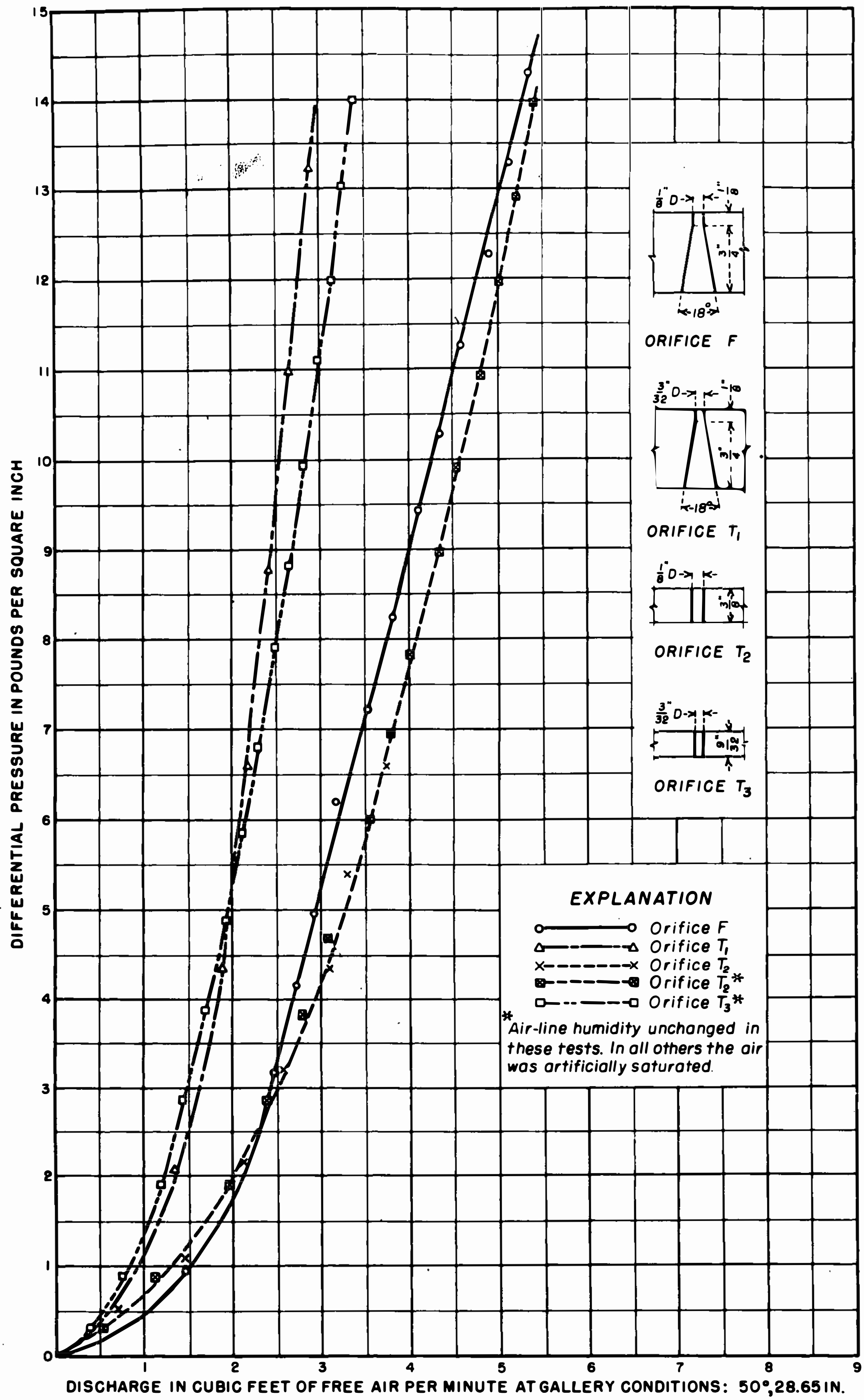
Figure 5 - Humidifying and air-metering apparatus.

Bourdon-type pressure gage was located. For more accurate air-pressure measurements, a mercury manometer was used. For visual observation and photographic recording, two $9\frac{1}{4}$- by $9\frac{1}{4}$-inch glass windows were located on opposite sides of the tank at the orifice level.

Before starting a test, the tank was charged with about 1,200 pounds of ice in pieces of about 25 pounds each. The initial temperature gradient as indicated by thermometer bulbs Nos. 1 to 6, inclusive (figure 4-A) was recorded. Figure 4-B shows typical temperature gradient curves. The static waterhead on the orifice was recorded and then the air flow was started. Water and air temperatures, air pressure, and the quantity of air discharged was observed. The differential pressure across the orifice was progressively increased by increments of about one pound per square inch until the orifice froze or until the pressure limit of the apparatus was attained.

The preliminary tests indicated that orifice F had the most desirable properties. A check calibration was made on this orifice in the new model as shown on the pressure-discharge curve plotted in figure 6. Tests on the cooling effect due to expansion of the air indicated that the orifice would freeze solidly, forming a cone of ice in the tapered exit when the air temperature before expansion was 32.38° F. and the differential pressure was 5.4 pounds per square inch.

Figure 6



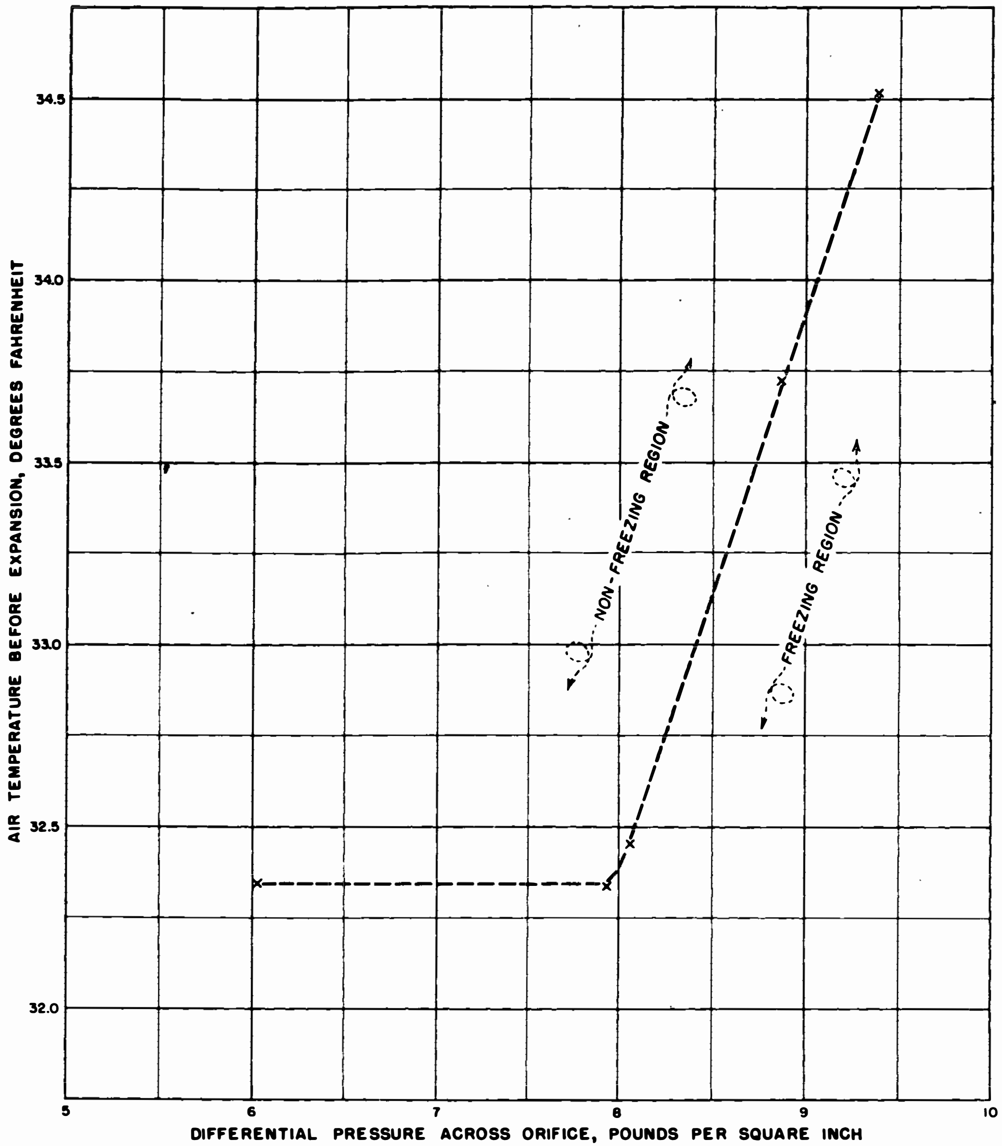
GRAND COULEE DE-ICING EXPERIMENTS
PRESSURE-DISCHARGE CURVES

As an alternative design, orifice T_1 was built. It is the same in every detail as orifice F except that its initial diameter is 3/32 inch instead of 1/8 inch, which makes its area roughly half that of orifice F. The calibration curve for this orifice is shown in figure 6. Temperature tests were made but the range of air temperature before expansion was too high to cause freezing. The highest differential pressure during the test was 17.54 pounds per square inch, and the air temperature before expansion was 35.39° F. No further temperature tests were made on this orifice.

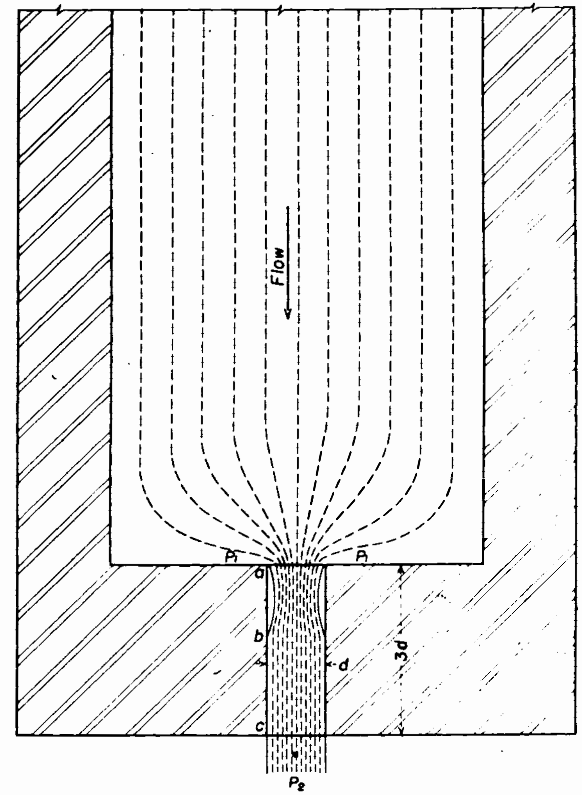
Orifice T_2 was tested because it was believed it would have a lesser tendency to freeze than an orifice having a tapered exit, such as F or T_1. The general dimensions and calibration curve are shown in figure 6, and figure 8 shows orifice T_2 during a freezing cycle.

Orifice T_3 is a short tube similar to T_2, having its length equal to three diameters (figure 6). Its area, however, is approximately half that of T_2. The calibration curve for this orifice is shown in figure 6. At this point in the test program it was decided to adopt orifice T_2 so no further temperature investigations were conducted on T_3.

From data on the freezing characteristics of orifice T_2 a "critical freezing curve" was constructed by plotting air temperature before expansion against differential pressure (figure 7-A).



A. CRITICAL FREEZING CURVE FOR ORIFICE "T_2"



B. SECTION ON ℄ OF ORIFICE "T_2"

GRAND COULEE DE-ICING EXPERIMENTS
CRITICAL FREEZING CURVE AND FLOW DIAGRAM FOR ORIFICE "T_2"

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Figure 7

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This curve passes through the points which lie furthermost to the left and upwards. Thus, it divides the temperature-pressure plane into two regions: one region lying upward and to the left of the curve, in which no combination of initial air temperature and differential pressure will cause freezing; the other lying downward and to the right of the curve, in which all combinations of initial temperature and pressure result in ice formation in the orifice. Ice formation in the orifice is a function of at least the differential pressure across the orifice, the air temperature before expansion, and temperature of the surrounding water; but since the air temperature before expansion is, in turn, a function of the temperature of the surrounding water, the initial air temperature was chosen as one of the coordinates for the freezing curve. In one test the air temperature before entering the cooling coils was purposely raised about 90 degrees (F.) higher than in other tests, but the temperature before expansion was found to be about the same as in other tests. This indicates that the air temperature before expansion will be sensibly the same as that of the surrounding medium, regardless of its initial temperature.

The critical freezing curve (figure 7-A) does not give all the data in regard to the freezing of orifice T_2. While it gives the combinations of initial air temperature and differential pressure at which freezing starts, it does not indicate the degree or seriousness of freezing. In the range of initial air temperatures up to about 33° F., it was observed that it was possible to have the orifice freeze solidly at points lying on the critical freezing curve. However, these instances were exceptions rather than the usual result; generally ice would start to form in the orifice, partially fill it, and then be removed by the passing air. In order to obtain quick freezing and ice cones (such as shown in figure 8) the differential pressure was increased to 19.25 pounds per square inch. In the range of initial air temperature lying above 33° F., freezing of the orifice was not such a serious factor within the differential pressure range tested. The start of freezing in the range above 33° F. became progressively more and more difficult to detect by visual observation of the jet as the differential pressure necessary to produce freezing increased, until in the vicinity of 10 or 11 pounds per square inch it could only be detected by the instruments. When the mercury manometer, indicating the air-line gage pressure, showed an increase in pressure, and when the rotameter showed concurrently a decrease in discharge, it was definitely established that freezing had started. In the region of temperature lying above 33° F., it was observed that the duration of the decreased discharge due to ice formation in the orifice became shorter as the values of temperature and differential pressure necessary to cause freezing became greater. Clearing of the ori-

A. Unobstructed flow prior to ice formation.

B. Deflected and restricted flow due to ice formation.

C. Large dense ice cone completely restricts flow.

Figure 8 - Orifice T_2 discharging at 19.25 pounds per square inch differential pressure; air temperature before expansion was 32.37° F. Thermocouple is seen immediately below orifice.

fice was manifested by a sudden increase in discharge and decrease in differential pressure.

In attempting to explain the phenomenon of ice formation in the orifices, the following interpretation is offered. A theoretical analysis was made for expansion of saturated air through orifice T_2, taking the actual values of initial and final pressure and initial air temperature found in one test. The expansion was considered adiabatic and account was taken of the variation of the specific heat of the saturated air with temperature, and of the heat of vaporization and heat of fusion given to the mixture by the moisture which condensed and froze. Thus, by approximation, the final temperature of the gas mixture was obtained, and found to be about 2.34° F. This analysis has taken no consideration of heat transfer from the orifice to the gas mixture although there must have been some. It will be remembered that this set of values of pressure and initial temperature constituted one point on the critical freezing curve, which means that freezing of the orifice just started under these conditions. The theoretical final temperature of 2.34° F. is far below the freezing point and it is difficult to conceive that the orifice whose temperature cannot be greater than that of the surrounding water (32.48° F.) could raise the air temperature to such a point that freezing just starts under these conditions. Another question rising from a study of the freezing phenomenon is how frozen moisture particles can stick to the walls of the orifice when moving at such a high velocity, approximately 525 feet per second or 358 miles per hour for orifice T_2 at a differential pressure of 6.01 pounds per square inch. A solution which would satisfactorily explain both of these points is proposed and reference will be made to figure 7-B. The mixture of air and water vapor at pressure P_1 expands through the orifice to pressure P_2 following the approximate streamlines as shown in the figure. From point "a" to point "b" the jet contracts, passes through the vena contracta, and then expands again following the walls of the orifice between points "b" and "c". The cold air cools the walls of the orifice between points "b" and "c" to some temperature which is higher than that of the air and lower than that of the water surrounding the orifice. As the saturated air expands the temperature drops, resulting in moisture being removed from the air by condensation. The resulting fluid is then a mixture of moisture particles and saturated air, the air temperature being below freezing. It is conceivable that the particles of moisture do not freeze instantly because there must be a heat transfer before freezing can occur, and therefore, because of the high velocity through the orifice, it could be possible that unfrozen moisture particles could come in contact with the walls of the orifice between points "b" and "c". It will be remembered from studies of refrigeration that a moist finger will stick instantly to a metal surface when that surface is at a temperature of 15 degrees F. or lower. (This is known as the "stick test.") If the walls of the orifice were at 15° F., then the moisture particles would stick instantly upon contact and freezing of the orifice would start. This hypothesis would satisfy both the question of low air temperature and that of the high air velocity. It is of interest to note that for the one point on the critical freezing curve for which the theoretical final air temperature was computed and found to be 2.34° F., the average of this final air temperature and that of the surrounding water is exactly 15° F., which is the highest temperature at which the "stick test" will occur.

By extending this reasoning further it can be explained why freezing is more serious (that is, the orifice may freeze solidly) when it occurs with the temperature of the surrounding water in the region of 32° to 33° F. The orifices tested in the laboratory were made of wrought iron and lead. The thermal conductivity at 64° F. is 20.1 for lead, and 34.9 for wrought iron.[1] For ice, the thermal conductivity[1] is given as 1.26. This means

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[1] Marks' Handbook, Third Edition, First Printing, Tables 1 and 3, pp. 396-397, McGraw-Hill Co., N. Y.

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that a temperature gradient plotted from the surrounding water, through the metal forming the orifice and to the inside wall can be of a relatively flat slope, but from the inside wall through the ice to the cold air stream the temperature gradient has relatively a very steep slope. Therefore, when freezing of the orifice starts with the temperature of the surrounding water in the region of 32° to 33° F., the temperature of the inside wall of the orifice can conceivably remain below the melting point, the bond between metal and ice remain unbroken, and the freezing process continue on to ultimate restriction of air flow. Whereas, with a higher temperature of the surrounding water the freezing of the orifice may start, but as the ice deposit increases in thickness the temperature of the inside wall of the orifice rises until the melting point is reached, the bond between the ice and metal is broken, the flow-restricting ice deposit is removed, and complete freezing of the orifice is prevented.

From this investigation it was concluded that:

(a) The direction of discharge vertically downward from the orifice gave a superior flow pattern.

(b) An orifice with an 18-degree tapered exit similar to type F gave the best flow pattern of all single-hole types tested. The multiple-hole types were at once abandoned because of the high discharge capacity or because of danger of becoming plugged if the diameter of the holes were decreased so that the discharge would be equivalent to the single-hole type.

(c) A discharge of two cubic feet of free air per minute at a differential pressure of two pounds per square inch is sufficient to induce a strong upward water current. This value for discharge is also consistent with practical limits of compressor size required for the Grand Coulee air de-icing system.

(d) An orifice of the short-tube type (T_2) was found to be somewhat superior to the type represented by orifice F as far as freezing is concerned; its flow pattern was not materially worse, and its discharge characteristics about the same. Therefore, this orifice was adopted for use in the Grand Coulee de-icing system.

(e) When freezing in the orifice occurs with the initial air temperature and surrounding water temperature in the range of 32° to 33° F., the orifice may freeze completely thus stopping the air flow. No complete freezing was observed in the tests when the temperatures of the air and surrounding water were above 33° F. and the differential pressure was within the range available with the laboratory apparatus. However, complete freezing may be possible at higher differential pressures.

(f) Freezing of the orifice is a function of the initial air temperature, the differential pressure, the type of orifice, the temperature of the surrounding water, the thickness of the orifice walls, and the thermal conductivity of the material of which the orifice is made. (It is presupposed that the air used has a sufficiently high initial humidity that moisture will be condensed during expansion.)

Where the danger of freezing is imminent, a sharp-edged orifice should be used. If, however, an orifice of the short-tube type is used because of its superior flow pattern, the freezing hazard may be decreased by making the operating differential pressure small, the walls of the tube as thin as possible and of a material of high thermal conductivity such as copper.

The hydraulic laboratory in which these studies were made is directed by J. E. Warnock, Engineer, and is a section of the materials, testing, and control division, supervised by R. F. Blanks and Arthur Ruettgers, Senior Engineers, in the Denver office of the Bureau of Reclamation. Design studies and investigations are made under the direction of J. L. Savage, Chief Designing Engineer. S. O. Harper is Chief Engineer for the Bureau, and J. C. Page is Commissioner of Reclamation.

the results were very satisfactory and materially strengthen the case for the reliability of model tests. The results are shown in detail on Figs. 49 to 60.

Comparisons of the water levels for the various flows with the crest gates down are shown on Figs. 49 and 50. These show very close agreements of the water surface levels, except for a rise in the surface which seems to exist in the 1:20 model near the downstream end. The cause of this is not apparent and unfortunately time was not available ~~for~~ to study it in more detail.

Longitudinal profiles of comparable conditions on the 1:20 and 1:60 models with crest gates raised to various heights is shown on Figs. 51 and 53. Cross sections of the water prism in the channel for the same conditions are shown on Figs. 52, 54 and 55. The 1:100 model had no movable gates, and therefore it was not included in this study. The agreement in these cases was also good. The rise previously mentioned appears in these also.

On Fig. 56 is shown a comparison of the water surface for the same discharge with gates at various elevations, on each model separately. As previously explained, the agreement of the lines on a given model indicates the reliability of the assumption usually used in side channel spillway design that the entire energy of the overfalling water is dissipated without causing longitudinal flow in the spillway channel.

The pressures acting on the weir and in the side channel, as shown by the piezometric observations on the 1:20 and 1:60 models are shown on Figs. 57 to 60. Considering the difficulties of obtaining consistent piezometric readings where high velocities and impacts are involved, the results are very consistent and comparable. In general they show the same pressure concentrations and reductions as the observations previously described on the M-3 model. The pressures on the weir and on the drum gates will be discussed in more detail in Book 4, of this report.

Final Gate Operating Program

A comparison of the action of the three gate operating programs studied in detail is shown on Plates 117 and 122. The similarity of action is shown by the close agreement of the water surfaces in all cases, both in the longitudinal profiles of mean water surface shown on Figure 61 and the cross sections shown on Figure 62. The only point at which the surface levels differ appreciably is at Station 4 + 25 for the 90,000 sec. ft. discharge. In this case the water surface for the program adopted rises somewhat higher than with the two other schemes. This is not believed to be important or especially undesirable.

Flow in the Spillway Transition Sections

The section of the side channel spillways in which the change was made from the trapezoidal section of the side channel to the circular section of the tunnel, referred to in this report as the "transition," was a transition section not only from the standpoint of the shape of the channel but also from the standpoint of direction of flow,