BNWL-208

63-

AEC
RESEARCH
and
DEVELOPMENT
REPORT

AN EVALUATION OF THE USE OF SELECTIVE DISCHARGE
FROM LAKE ROOSEVELT TO COOL THE COLUMBIA RIVER

R. T. JASKE

FEBRUARY, 1966

R. B. Smith

30081-326

APR 12 1966

Don J. J.

W. B. J.

51312-1700D

JUN 8 1966

BATTELLE-NORTHWEST

BATTELLE MEMORIAL INSTITUTE / PACIFIC NORTHWEST LABORATORY

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

PACIFIC NORTHWEST LABORATORY

RICHLAND, WASHINGTON

operated by

BATTELLE MEMORIAL INSTITUTE

for the

UNITED STATES ATOMIC ENERGY COMMISSION UNDER CONTRACT AT(45-1)-1830

3 3679 00060 2229

BNWL-208

UC-2, General, Miscellaneous, and
Progress Reports

FIRST
UNRESTRICTED

TID-4500

DISTRIBUTION
MADE

EDITION

FIRST UNRESTRICTED
DISTRIBUTION MADE

MAR 16 '66

AN EVALUATION OF THE USE OF SELECTIVE DISCHARGES
FROM LAKE ROOSEVELT TO COOL THE COLUMBIA RIVER

By

R. T. Jaske

Environmental Studies Section
Environmental Health and Engineering Department

February, 1966

PACIFIC NORTHWEST LABORATORY
RICHLAND, WASHINGTON

Printed in USA. Price \$3.00. Available from the
Clearinghouse for Federal Scientific and Technical Information,
National Bureau of Standards, U. S. Department of Commerce,
Springfield, Virginia

AN EVALUATION OF THE USE OF SELECTIVE DISCHARGES
FROM LAKE ROOSEVELT TO COOL THE COLUMBIA RIVER

INTRODUCTION

This document is a review of the results of and the general operation of the annual Columbia River cooling program for 1963, 64, and 65.

Commencing with some experimental operation in 1958, Richland Operations Office has authorized cooperative activity directed towards selective releases of cold water from the depths of Lake Roosevelt to reduce the effective Columbia River temperature at the Hanford plant.⁽¹⁻⁵⁾ In 1962 some additional sophistication of the appraisal techniques became necessary. This necessity was partly brought about by the completion of additional impoundments between Hanford and the Grand Coulee Dam.

These impoundments increased the travel time between the Grand Coulee Dam and the Hanford Reservation by a factor of 1.5 or more and introduced the potential formation of density currents. The analysis of Columbia River heating originally conducted by Raphael⁽⁶⁾ was based on hydraulic mixing concepts. These concepts did not appear valid after additional information was derived from field measurements and after supporting hydraulics research was conducted at other sites. Yet, Raphael's work, particularly the concept of the guiding temperature index, gave promise of future development. An effort was initiated to develop a digital computer model of the river reach between Grand Coulee and the Hanford plant. Because of the complexity of the problems and the need for extensive verification, this effort was not advanced to a useful stage until August 1965.

In research operations with the resulting model COL HEAT, an appropriate degree of agreement has been obtained between

model calculations and measured data. Efforts to obtain further generalization are currently in progress.

In addition, the method of handling the heat budget in the impoundments between Grand Coulee Dam and Hanford has involved some questionable assumptions regarding the temperature of the spill. In 1963, the first temperature recorders (frequently calibrated) were installed at strategic locations. Additional efforts were placed on improving the validity of the field data which supported the entire cooling operation. This emphasis has produced a significant improvement in the credibility of input measurements and has made verification of the computer program possible. Further, these measurements permitted development of a rational theory governing the temperature distribution of the spill.

Considerable effort remains to be done to develop a rigorous theory concerning the prediction of temperatures from multiple sources within deep reservoirs. It is hoped that this report can make a contribution to the analysis of complex basin heat budgets and the effects of such large projects as those authorized by the Columbia River Treaty of 1964.

SUMMARY AND CONCLUSIONS

Based on a continuous record of observations since 1958 and supplemented by detailed studies of heat balances and reservoir behavior, the following conclusions appear appropriate.

1. Variations of Columbia River temperature introduced by upstream manipulation or alteration of the natural watercourse persist as far downstream as the Hanford plant. During the high flow period, about 85% of the temperature alteration, either positive or negative, is retained with a tendency towards values of 65% to 75% in the lower flow (less than 100,000 ft³/sec) periods. This evaluation includes the complete

development of the river including Wells Dam and is drawn from the parametric variation of Grand Coulee mixed discharge temperatures in the computer model.

2. A review of the previous effects of the annual river cooling program and the detailed study of the 1963 to 65 control periods leads to the conclusion that the reported effects have been somewhat overstated. This overstatement is due to two primary causes: 1) the incorrect assumption that the spill flow is drawn primarily from the upper 5 to 10 ft of the lake; and 2) an unfortunate accumulation of temperature data inaccuracies emanating from the temporary or expedient installation of data input sources.
3. The existence of density currents and subsurface jet formation cannot be ignored in the development of heat budgets because large errors are introduced by the transition from mixed flow to almost adiabatic flow conditions. This transition occurs for the intermediate size projects, such as Wanapum, during the portions of the year when heat input to the surface is high. The high level discharges from the Chief Joseph Project appear to minimize the transitional nature of the thermal cycles and to retain features more like the natural cycle of events which existed before the dam projects were erected.
4. A high degree of integration among the flood control, power, and cooling water user interests is required to minimize effects on fisheries. Further, the operational plan for the entire river and reservoir system will have a greater effect on the resulting temperature and dissolved chemical level in the

Columbia than is possible by the present scope of the Columbia River Cooling Program. This conclusion is reached from results of both the research reported in this review and contract studies performed for the Bureau of Commercial Fisheries, Dept of Interior.⁽⁷⁾

Both the timing and the rate of draw-down of individual reservoirs in the system contribute to temperature excursions which in turn may affect dissolved gas concentration and other critical parameters. The data in this report support the fact that for short periods of time, minor amounts of river heating have resulted from inadequate coordination of attempts to produce cooling effects.

5. Additional research on the formation and scope of subsurface jet flow in Lake Roosevelt and other large reservoirs in the system is essential to develop an optimal plan which will minimize river temperatures. Statistical studies performed incidental to this program show that the temperature peak from Lake Roosevelt occurs 30 to 40 days after the natural peak of the inflow waters. Erection of large upstream storage reservoirs is expected to lengthen this lag. To properly evaluate the impact of this lag or to develop alternate procedures, extension and refinement of the low level of research effort currently permissible is essential to support an effective Columbia River temperature and optimum flow program.

PHYSICAL BASIS FOR THE EVALUATION

Lake Roosevelt

Physical Characteristics

General characteristics of Lake Roosevelt pertinent to this discussion have been outlined in a previous report.⁽⁸⁾

Since that report, the Bureau of Commercial Fisheries, from whom the original data readings were received, has undertaken additional measurements programs which are unpublished by them at this time. All of this information plus supplementary data collected by H. A. Kramer, by the author in 1963, and by Davidson of the Grant County Public Utility District #2 in 1962 form a basis for a qualitative description of the pertinent features of Lake Roosevelt.

Lake Roosevelt contains approximately 9,000,000 acre-feet of storage at 1030 ft above MSL. At the beginning of the annual cycle of operation on October 1, the lake is full to treaty limits of 1290 ft above MSL. Depending upon water and power needs, the level of the lake is drawn down slowly until just before the spring runoff when further reductions in level are made for flood control purposes. The flood control reductions are accomplished by opening the tubes at 1030 and 1130 ft elevations. Ordinarily the surface is drawn down to about 1230 ft or down some 4.5 million acre-feet. The spring runoff recharges the lake to the 1288 ft level, the maximum controlled level with the existing gates; and the spill is maintained until just before the sharp drop in flow in late July. At this time, the lake is lowered for three or four days for installation of flashboards which permit control of the reservoir at the 1290 ft level. The lake is then raised to the 1290 ft level and held there until the system goes "on seal" for the next water year.

The temperature of the discharge from the project varies from the annual low of 2 to 4 °C in late February to an average maximum mixed discharge of 18.3 °C in September. Early in July, while flows still exceed 200,000 ft³/sec, the first thermal stratification in the lake begins to develop but is not fully developed until around the last week in July.

Stratification persists through August and well into September and depending on the weather, can still exist in early October. Figure 1 illustrates typical flow and temperature during the critical period from July through September. Any time after September 1, the inflow begins to cool rapidly; and the lake begins to fill with cooler water. Figure 2 illustrates the typical condition for this time. A flow jet exists and extends through the isotherm system. Cool water, upon entering, does not develop a density current in the traditional sense. Well into October the discharge from the low level continues to reflect the mean temperature of the downstream end of the reservoir. In effect all of the warm water is discharged from the south end of the lake and successively colder isotherms, tilted perhaps at a 75° angle, persist until early winter. Then "turn-over" occurs and the uniformly mixed condition reoccurs to start another cycle. During the first 6 mo of the calendar year, the reservoir is quite uniformly mixed but slowly increases in average temperature until July 1 when the mixed discharge from the project is about 13°C .

Analysis of the typical cycle shows that the lake conditions can be summarized as follows:

- 1) January through June--Generally mixed, turbulent in late spring due to high flow. Little or no stratification.
- 2) July through September--Poorly mixed with stratification general at the discharge end; although late in the season jet flow persists while cold water enters from the north.
- 3) October through December--Cooling, unmixed with oblique orientation of isotherms persisting until winter storms.

FIGURE 1

Flow and Temperature Expected from Grand Coulee During Critical Season
(Without Columbia treaty dams in Place)

FIGURE 2

Typical* Lake Roosevelt Flow Regime for Early September and Other Reservoir Data

*Adapted from the author's data and previously unpublished data
of the Bureau of Commercial Fisheries.

Figure 3 illustrates the ordinary density current conditions expected in a deep reservoir and verified to some extent by the trough experiments of Debler.⁽⁹⁾ In the actual case the narrowness of the reservoir increases the flow per unit width and modifies the straightforward explanation. Since the edge effects apparently play a large part in determining the elevation of the sheet of flow contained in the flow jet, no existing theory fully explains the diving, distorted shape of the Lake Roosevelt jets. The following observations do, however, appear pertinent:

- 1) The correlation developed by Debler⁽⁹⁾ explains the actual positions of the upper dividing streamlines at Lake Roosevelt provided the computation is done on an iterative basis using the apparent lower dividing streamline as the "bottom." The densimetric Froude number is used as an internal concept.
- 2) Observation of the temperature records indicates that the lower dividing streamline can be generally described by a temperature discontinuity. Additional current measurements are needed to verify this observation and to develop a generalized theory.
- 3) The turbine intakes derive their flow from a distributed strata of elevations generally above the 1030 ft elevation. This is apparently due to the vertical orientation of the inlet bar screens and to the distribution of viscosity and temperature profiles.
- 4) The spill flow contains water from depths considerably below the surface because the velocity profile expands as the distance from the spill nappe increases.

The resulting hydraulics are quite complex and are currently undergoing additional examination.

FIGURE 3
Expected Current Pattern

Heat Balance

The critical factor in appraising the effects of a cooling program is the measurement of the effective temperature of the spill. Because of the variable depth and the high velocity of the currents, measurements are quite difficult to obtain and often are not reproducible. For this reason the temperature of the spill is calculated from a heat balance taken throughout the dam. This approach is valid if the following assumptions are satisfied:

- 1) There is complete mixing below the dam.
- 2) Relatively little temperature differential exists transversely from the right to left bank.
- 3) Negligible amounts of heat are lost to evaporation in the spill or are counter balanced by the slight heat gain from release of potential energy.

Temperatures taken over a 4 yr period verify the first two assumptions completely. Temperature traverses taken across the pool behind the spill gates and on the bridge below the dam reveal no persistent lateral segregation in excess of 0.2 °C. Calculation of potential heat transfer to the air reveals no quantities large enough to introduce errors beyond the size of the temperature measurement. All temperatures are standardized against certified thermometers and recording instruments are restandarized every 2 to 3 weeks during the critical months of August and September.

Some variation of turbine discharge temperature occurs due to shifting of loads and resulting variation of the vertical recirculation apparently occurring at the face of the dam. Continuous recording of the temperature at the 5 and 20 ft depths shows this variation to be limited to about 0.30 °C. Errors which could be introduced from this source are minimized by timing the measurements on a programmed basis.

The following temperature and flow records are used in preparation of the heat balance:

- 1) $\bar{Q}_r$ Mixed River flow below the dam (at Lone Pine)
- 2) $\bar{Q}_g$ Generator flow from plant records
- 3) $\bar{Q}_t$ Special tube flow from 1130 and 1030 ft elevations
- 4) $\bar{Q}_s$ Spill flow: defined as all releases not producing electricity
- 5) $\bar{Q}'_s$ Spillway flow: calculated by difference

$$\bar{Q}'_s = \bar{Q}_s - (\bar{Q}_t + \bar{Q}_g)$$
- 6) T_r Average temperature of river below dam (at Lone Pine)
- 7) T_g Average temperature of generator discharge
- 8) T_t Average temperature of tube flow (taken as T_g)
- 9) T'_s Average computed spill temperature
- 10) k Conversion factor for weight and specific heat

The heat balance around the dam can be calculated as follows using $T = 0$ as an internal energy base.

$$k\bar{Q}_r T_r = k\bar{Q}_g T_g + k\bar{Q}_t T_t + k\bar{Q}'_s T'_s$$

or

$$T'_s = \frac{\bar{Q}_r T_r - (\bar{Q}_g + \bar{Q}_t) T_g}{(\bar{Q}_s - \bar{Q}_t)}$$

Values of T' calculated from this procedure represent the average temperature of the spill, usually calculated on a daily basis. These values are then compared with the vertical temperature profiles, taken at periodic intervals, of the reservoir immediately adjacent to the dam. Comparison of these calculated temperatures and the depth of the water mass corresponding to this

temperature yields an estimate of the depth of average water mass being discharged over the spillway. Calculations made over a 3 yr period have been plotted in Figure 4. The resulting curve is essentially linear within the range of spill flow up to 80,000 ft³/sec; beyond this flow not enough measurements exist for a valid representation although withdrawal from considerable depth appears a reasonable conclusion.

Figures 5, 6 and 7 are included in this section to illustrate the interim step in the procedure from which Figure 4 is derived. They show a consistent pattern of withdrawals from depths somewhat greater than previously supposed probable. The year 1963 was relatively warm; 1964 was cool; 1965 started quite warm but, because of late summer storms which are statistically predictable for the last week in August, failed to produce the record river temperature expected earlier. The figures illustrate the progress of the mean streamline representing the average spill temperature T'_s for the 3 yr for which reliable data are available.

The evidence supports the conclusion that the mean depth of withdrawal from the Lake Roosevelt is a function of the total spillway flow. Further it appears that the derived relationship, while empirical, is consistent enough to permit use of this relationship on a generalized basis until additional analytical work, now planned at Battelle-Northwest, is completed. The net output of this research proposed for FY 1967 is expected to produce a mathematical model of the three dimensional flow regimen immediately adjacent to the dam.

Verification of these effects appears to be of vital interest in determining an optimal operating plan for the Columbia Treaty Projects in conjunction with the third power house at Grand Coulee. Should essential substantiation be achieved, it appears that a good argument can be made for

FIGURE 4
Estimated Mean Depth of Reservoir
Contributing to Spill as a Function of Spillway Flow

FIGURE 5

Isotherm Map for August Through September, 1963
at Eden Harbor, Lake Roosevelt

FIGURE 6

Isotherm Map for August Through September, 1964 - Plum Point, Lake Roosevelt
 (The data used to establish the isotherms were from previously unpublished records
 of the Bureau of Commercial Fisheries)

FIGURE 7

Isotherm Map for 1965 at Eden Harbor, Lake Roosevelt
 (Some data used in this chart adapted from previously
 unpublished records of Bureau of Commercial Fisheries
 and supplemented by the author)

location of the turbine intakes at a high rather than a low location for minimal effects of the downstream average water temperature. River cooling under these circumstances would be effectively done by favoring the discharge from the high intakes of the dam during the warming season; thus retaining the greater portion of Lake Roosevelt full of colder water until later in the year when this inventory can be used to offset the lag storage effect. Other specific operational recommendations directly related to the Hanford program are listed later in this document. The tabulated computations for this section appear in the Appendix B.

Downstream Reservoirs

Some general observations regarding each of the reservoirs and their effect on the temperature downstream is discussed below.

Chief Joseph

The Chief Joseph project was completed in March 1955. The dam height is 230 ft above the foundation and the spillway is about 950 ft wide. Rufus Woods Lake behind the dam contains 480,000 acre-feet of storage when full with a mean depth of 67.2 ft calculated over the total length of 51 miles. Levels vary less than 5 ft in routine operation.

The intakes to the turbines draw water from the higher elevations of the pool. Temperatures below the dam are generally within 0.1 to 0.2 °C of the Grand Coulee discharges except during the months of June through September when the differential gradually increases about 0.6 °C during the latter part of August. Short term differentials due to reservoir and generator manipulation occur, but are generally limited to about 1.0 °C differential. Since the surface-to-volume ratio is quite low by comparison to the other downstream projects and the warmed water is not stored but continuously drawn off, the effects of this project upon the river temperature are minimal.

Some stratification does occur, and it is conjectured that a density current exists in the middle reaches of the reservoir during the hot water season although no specific studies have been made in this area. Time of travel studies indicate relatively continuous passage of thermal spikes through the project. (Additional discussion of time of travel applying to the computer model appears below in "Theoretical Basis for Evaluation."

Wells Project, Rocky Reach, Rock Island, and Priest Rapids

These dams are discussed as a group because they have basic similarities as to size, depth, and reservoir volume. Temperature measurements taken in the reservoirs over a number of years indicate little or no stratification except as a thin skin of surface water. The vertical position of the turbine inlets appears to have little effect on the reservoir heating; however, extended forebays create some stratification during reduced generator flow. Figure 8 shows the results of a temperature traverse series taken at Rocky Reach on July 21, 1965. In August a differential of about 0.7 °C exists in the top 6 in to 1 ft of the surface and enters into the surface interchange calculations performed in the computer program.

Some reservoir regulation occurs in the winter months; however, during July to September the river flow usually exceeds 65,000 ft³/sec. The surface area changes are relatively minor compared to other variables. The most significant effect of the low head reservoirs taken as a group is to increase the travel time and, to some extent, decrease the average turbidity. However, short term manipulations of the reservoirs during the critical river heating period can contribute to heat spikes of from 1 to 2 °C which could be avoided.

FIGURE 8

Typical Temperature Traverses, Rocky Reach Project
July 21, 1965

Wanapum Project

Wanapum Dam impounds a reservoir volume of 638,000 acre-feet at the low flow of 50,000 ft³/sec when filled to level of 575.00 ft above MSL. While the height of the dam is not substantially greater than Priest Rapids, the reservoir is quite wide at the downstream end below Quilomene Rapids. Approximately 75% of the reservoir volume is in the lower reach. Stratification commences with the hot season late in July and exists through September, depending on the total flow. Since the tendency to stratify is a function of the geometry and the rate of heat input, the operational scheme of low weekend flow and favorable geometry both work to produce densimetric Froude numbers⁽⁹⁾ below 0.26 through the period.

As a consequence, during the critical period of July through September, water moves through the Wanapum reservoir as a submerged density current, essentially in an adiabatic condition. A series of temperature profiles obtained in and around the Wanapum project (Table I) further confirm that the flow is largely adiabatic.

TABLE I

TEMPERATURE PROFILE AT WANAPUM PROJECT

(Temperatures recorded with a calibrated RTD probe)

Depth Meters	Location - Aug. 16, 1963		
	Vantage Bridge	Wanapum Left Bank- Thalweg	Wanapum Right Bank- Power House Pool
Surf	19.1	19.3	19.3
1	18.6	19.5	19.1
2	18.4	19.8	19.1
3	18.2	19.3	19.0
5	18.2	19.1	19.0
10	18.1	18.5	18.9
20	18.1	18.3	18.8
30	18.1	18.2	18.8
35	--	18.2	18.8

Variations of 5 ft in reservoir height are common, but have little or no effect on the density flow. The existence of these density currents serves to reduce the effects predicted by Raphael.⁽⁶⁾

Table II illustrates that the density currents produce adiabatic flows. The data was collected by the author in 1963.

TABLE II
MEAN TEMPERATURES AT SELECTED
DATES AND LOCATIONS--1963

<u>Location</u>	<u>July 26</u>	<u>Aug 3</u>	<u>Aug 9</u>	<u>Aug 16</u>	<u>Aug 27</u>
Below Grand Coulee	16.0	16.4	16.4	16.3	16.0
Rocky Reach	16.3	17.4	18.2	17.7	17.5
Vantage Bridge (Wanapum)	16.8	17.4	18.3	18.1	17.5
Below Priest Rapids	17.3	17.8	18.6	18.7	17.6

The discovery of these density currents was the primary factor in determining the necessity of a computer program for simulation of the river temperature regimen because hand calculation methods were too time consuming and were based on questionable theory.

THEORETICAL BASIS FOR EVALUATION

Summary of Previous Investigations

The study of energy budgets has its origin in efforts to account for evaporation. In the landmark publication summarizing the Lake Hefner studies,⁽¹¹⁾ Anderson states, "Since 1915, when Schmidt first attempted to utilize the (thermal) energy budget to obtain estimates of the annual evaporation from the oceans, applications of the energy budget have been restricted because of the difficulty of evaluating certain terms, such as reflected solar

radiation, atmospheric radiation, reflected atmospheric radiation, longwave radiation from the body of water, advected energy, energy conducted to or from the body of water as sensible heat, and the change of energy storage in the body of water.

"In addition, difficulty has been experienced in evaluating the conduction of sensible heat to or from the body of water. From the energy budget equation it is possible to obtain the sum of energy conducted as sensible heat and energy utilized by evaporation. During the early use of the energy budget for obtaining evaporation rates, the ratio of these two terms was estimated to be around 0.1 or 0.2. Later investigations showed that the ratio varied considerably. Bowen (1926) theoretically examined the ratio and developed an expression for it in terms of easily measured quantities. Considerable controversy, however, still exists over the meaning and validity of Bowen's ratio.

"The principal objective of the energy budget investigation at Lake Hefner was to determine the utility of the energy budget as a method for computing evaporation from natural bodies of water. This made it necessary to improve our understanding of certain terms in the energy budget, for example, reflected solar radiation, change in energy storage, the Bowen ratio, and effective back radiation."

No breakthrough in analytical procedure beyond the point reached in Paper No. 269 has taken place, but determined investigators have used the energy budget method because they lacked a suitable substitute.

In 1962, Raphael summarized the application of the energy budget to rivers and reservoirs.⁽⁶⁾ In his work he used the basic energy budget terms evaluated in the Lake Hefner studies and applied them to a transient expression which sought to account for the change in internal energy in a reservoir. For purposes of providing background, and because of the large extent

to which the original work was used as a basis for the COL HEAT program, Raphael's work is reviewed below in some detail.

The process used by Raphael involved the computation of the surface exchange using the heat budget equation:

$$Q_t = \Sigma(Q_s - Q_r) - Q_t - Q_e - Q_h + Q_v$$

where

Sum = net incoming radiation less reflected short wave radiation. This is expressed Q_i

where

(Net insolation) $Q_i = (1 - 0.0071 C^2)(Q_s - Q_r)$ BTU/ft²

C is cloud cover in tenths of sky covered

(Back Radiation) $Q_b = 0.070 \sigma(T_w^4 - \beta T_a^4)$ BTU/ft²

σ is Stefan Boltzmann radiation constant
 1.714×10^{-7} BTU/hr-ft²

Q is atmospheric radiation factor

T_w is absolute water surface temperature

T_a is absolute air temperature

(Evaporation) $Q_e = 12U(e_w - e_a)$ BTU/ft²

U is wind speed in knots

e_w is vapor pressure of water in inches of Hg

e_a is partial pressure of vapor in inches Hg

(Conduction) $Q_h = 0.00407 UP(t_a - t_w)$ BTU/ft²

U is wind speed in knots

P is total pressure of air in inches Hg

t_a is air temperature

t_w is water surface temperature

Q_v advected heat; considered as zero in Raphael's Columbia River studies.

The heat balance function derived by Raphael is summarized by the following expression:

$$t_w = \frac{1}{V_1} \left[\frac{Q_t A \theta}{62.5} + V_i (t_i - t_w) \right]$$

where

V_1 is mean lake volume in acre-feet,
 A is mean lake area in acres,
 θ is time variable in hours,
 V_i is inflow volume in acre-feet for time θ ,
 t_i is mean temperature of inflowing water,
in degrees Fahrenheit, and
 t_w is mean temperature of water in lake in
degrees Fahrenheit.

Using Equation 2, he calculated the temperature rise of batches of water representing a 3 hr incremental flow. This was done in Monte Carlo fashion to arrive at new values of t_w for correction of the surface exchange rates. Summation of these increments produced a net calculated temperature rise for the selected river reach.

To evaluate the term Q_t , several assumptions were required. The important observation that boundary layer effects were minimal⁽¹¹⁾ led Raphael to the use of the Larson Air Force weather data as a single point source to represent air temperature, vapor pressure, and cloud cover for the entire reservoir area in question (50 to 75 mi of reservoir). Also despite Anderson's conclusion⁽¹¹⁾ Raphael calculated the net insolation using the method of Mosby and Kennedy. Lacking actual measured values, little alternative was available.

The calculated values^(12,13) of temperature increase determined by Raphael's studies for the reaches studied were twice the measured values. Since the Hanford project was involved in the River Cooling Program, an evaluation of Raphael's technique

appeared justified to determine if it could be adapted for use. Other observations pertinent to the heat budget technique are summarized in the Proceedings of the Twelfth Pacific Northwest Symposium on Water Pollution Research⁽¹⁴⁾ held in November 1963. The Conference Proceedings including the summary of heat model work by Zeller⁽¹⁴⁾ and Raphael's open literature description of his method⁽⁶⁾ form the basis for the COL HEAT computer model.

Heat Budget Work at Hanford

A great deal of supporting investigation has been performed by the author in evaluation of the Columbia River cooling program and by J. P. Corley in his research. Two basic approaches are utilized: 1) Research into interfacial and diffusion transport mechanisms and 2) generalized systems approaches with heavy dependence on data analysis. In addition, Battelle-Northwest operates extensive meteorological research activities which are of invaluable assistance in deriving support for various heat budget studies. As many as seventeen remote weather stations have been operated on a real time comparison basis in order to predict the instantaneous behavior of atmospheric contaminants. Weather records at varying altitudes are routinely taken and analyzed and continuing research into plume dispersion is conducted.

One basic problem in using the heat budget approach is the matter of interfacial reactions. Most investigators agree that wind direction and speed play important roles in interfacial reactions, as do surface absorption and reflection. A better definition of these factors requires increasing amounts of data until the problem becomes one of defining the micrometeorological limits to which the investigator can afford to go. Corley^(*) has determined that wide variations exist among weather parameters near the Columbia River and those measured at some distance from it. Having determined the size of an acceptable unit river

* Personal communication

surface area, the relation of this unit area to other river areas reopens the question of experimental design; seemingly without a short term solution short of a multiplicity of weather stations.

The alternate approach favored by the author is similar to that used by McAdams and other classical developers of chemical engineering heat transfer relationships. If a large enough system to permit measurement of bulk effects exists, the compensating errors from inadequately developed mechanisms may cancel out or not require definition.

Analysis of integrated local weather data collected over 15 yr at Hanford appears to justify the original assumption by Raphael that a single point weather data station can be used to represent rather broad land areas if the objective of the study is to develop generalized courses of action. With this concept in mind, the following observations were developed as a guide in the program development:

- 1) The empirical relations used by Raphael to define the bulk surface exchange of internal energy were substantiated by the Lake Hefner project to the extent that they were acceptable to provide inputs in the range of 5 to 10% accuracy.
- 2) The availability of routine radiometer readings at Hanford enabled elimination of the calculation of short wave insolation and the errors introduced by varying definition of cloud cover.
- 3) Since the model objectives included the entire series of reservoirs with travel time of 10 to 15 days or more, the use of daily averages to describe input variables was adopted to minimize data processing in the model. Statistical analysis supporting this concept showed

that the mean driving forces could be described to within 3% when compared to the summation of events derived from integration of hourly or shorter periods.

- 4) The transport model used by Raphael was entirely inadequate to describe the actual events. A model using realistic transport of water masses is essential. Further, the existence of density currents on a seasonal basis requires adjustment of the flow model if representative areas are to be used in interfacial calculations. A two region flow model based on realistic current distribution reduced to dimensionless form was selected with provisions to adjust the ratio of the inner to outer region during verification operations. Since the solutions of the resulting difference equations involved multiple iterations, the digital computer was selected as the appropriate instrument.

Model Development

A series of velocity traverses observed over a period of years within the Hanford reservation is compared to the data which was reported by Wasley in 1961⁽¹⁵⁾ and which correlates model experiments on turbulent channel flow. The results of the comparison indicate that the river current velocity distribution is similar to that of the model channels.

Calculations using commonly accepted scaling ratios appear to permit extension of Wasley's conclusions and observations to straight river sections. In the Stanton diagram of Wasley's paper, very little change in the friction factor occurs for large changes in Reynolds number. From this observation it is assumed that wherever supercritical flow conditions exist, either Larson's or Wasley's expression for current distribution would apply to a dimensionless representation (neglecting curb shear). The velocity distribution diagrams (Figure 9) were developed from this concept.

From Matalas and Conover⁽¹⁶⁾

$\bar{U} = k \bar{U} \left(\frac{Y_1}{Y_0} \right)^{2/3}$ From Larson⁽¹⁷⁾

*Not Corrected for Vertical Distribution

FIGURE 9
Velocity Distributions

The cross sectional representation of Figure 10 was used to develop ratios of surface area to volumes in the theoretical stream. For example the average velocity contour $\bar{U}$ in Figure 10 can be used to define two regions as follows:

- 1) All water traveling at velocities greater than $\bar{U}$ is represented by an average $\bar{U}$ which is equivalent to $1.37 \bar{U}$. This portion contains 53% of the stream cross section (volume) and 48% of the associated area.
- 2) All water traveling at velocities lower than $\bar{U}$ is represented by a $\bar{U}$ which is equivalent to $0.60 \bar{U}$ in a region with 47% of the cross section (volume) and 52% of the associated area.

Other regions could be described, but in general the illustrations show the concept of a fixed ratio of percentage area associated with a percentage volume being close to unity. This permits ready mathematical description and variation of the region by simple substitution of varying coefficients.

The use of this concept the actual model assumes the intermittent transport, mixing, etc. of water in terms of the ratios of the mean velocities of the two regions. The total volume considered in each mass is calculated by the program as that associated with a single day's travel time. Hence the number of days of exposure to the surface interaction is a function of the system volume divided by the travel time of each region. The fundamental difference Equation (2) is applied to each region and the internal energy changes computed.

Figure 11 is a representation of the region concept as applied to the transport instant for one half day. The length of the volumetric mass is a function of the outlet flow rate from the system and the geometric configuration selected to represent the reservoir or river reach in question. Since storage under normal

FIGURE 10

Theoretical Velocity Contours Used in Development of Model Flow Regions

1. l varies as reservoir geometry and flow and represents a reservoir length for that region one flow day in length
2. $W = 2 \left(\frac{W'}{4} \right) + \frac{W}{2}$ when B the volume fraction of the center trough = 0.5 or $W = 2 (1-B)W' + BW$ for any value of B

FIGURE 11

Graphic Representation of Flow Transport Model at Translation Instant

conditions is minimal, the flow out of the downstream dam in the series is used to calculate the effective travel time for the system by dividing the reservoir volume by a rolling mean daily average flow. The resulting value, to the nearest integer, is used to determine the surface exposure days.

Each addition or reduction of heat as internal energy changes the temperature of the surface and, thus, changes the resulting air-water interface reactions. This situation requires the use of iterative computation since the model heat balance involves the internal energy of the outlet stream. This can only be computed by accurate evaluation of temperature and atmospheric factors involved in continuous evaluation of Q_t (Equation 1). An individual difference equation exists in the computer processing routine for each region, and for each volume associated with a day's travel. Since the latter value is outlet flow dependent, no fixed increments of volume are used; the actual values are determined in the computation by the flow from the downstream dam.

The resulting model solves the general equations resulting from the very general expression:

$$T_{nk} = (1 - B)^{k-1} T_{\ell} + \sum_{m=\ell}^{n-1} (1-B)^{n-1-m} \left[A_{kx} \bar{Q}_{mkx} + B \left\{ T_{mkx-1} + A(S_{kx-1} \bar{Q}_{mk-1} - S_{kx} \bar{Q}_{mkx}) \right\} \right]$$

where

- n = actual number of days
- k = river sections as defined (see Table III)
- ℓ = $i + mQ - 1$ number of travel days in region (nearest integer)
- $kx = m + 2 - (kQ) - i$ a derived subscript wherein (kQ) is an index of flow days sections affected, or $kQ = 1Q - nQ$
- $(\ell Q) = \frac{\text{number of river sections} + 1}{2}$ to largest integer

$(nQ) = n - k + i$ where i = first day under study or integer 1

B = Fraction of water in central through

S = Surface area of affected section

A = A derived constant related to reservoir parameters of volume dimensions and thermal conversion factors

$\bar{T}$ = 24 hr average temperature at any point defined by subscript

$\bar{Q}$ = 24 hr average heat input to a given area (Equation 1)

Since density currents can cause appreciable error in the heat budget calculation, the overall system heat budget must include analysis of this effect where applicable. Density currents in the rapidly flowing river are only stable when reinforced by heat input which produces a density gradient greater than that required for maintenance of a densimetric Froude number of 0.28 or less.⁽⁹⁾ Accordingly the existence of density currents must be verified constantly. The verification is done in the COL HEAT model by the process delineated in the notes of Figure 12. In the actual model the additional subroutine, SMATCH, is used to correlate and match the appropriate water masses as they pass through the reservoir reach in question.

Application of the density current concept has solved transient errors within the accuracy intended of the program. Additional research is planned for nonlinear density gradients which are more typical of actual, especially deeper reservoirs, and more precise determination of the critical values of Froude numbers other than 0.28 for signaling area reductions.

The actual COL HEAT program requires iterative handling of the intermediately generated data required for solution of the generalized equation; thus, running times on the IBM 7090 average about 2 min for each month of data submitted. Longer times have been required for lower flows, and current efforts involve reduction of the program complexity to permit better use of machine

IWANX Density Current Subroutine

$$\text{from } F_i = \frac{Q}{D_o^2 W_o} \sqrt{\frac{\rho_o}{g\beta}}$$

where $\beta = \frac{\Delta e}{\Delta d}$ Reference (9)

1. Assume stratification will take place for any value of $F_i > 0.28$
2. Calculate $\frac{\Delta e}{\Delta d}$ for F_i of 0.28
3. Compare to input for that day obtained from unit heat flux Q_R for d_o in reach ℓ_R'
4. If Step 3 ratio 1.0 or greater reject area A_R associated with travel length ℓ for that region for that day only.

ℓ_R = one day flow mass length for Region R

$V_R = \sum \ell_R \cdot \bar{W}_R \cdot \bar{d}_i$ for each flow mass length

$A_R = \sum \ell_R \cdot \bar{W}_R$ for each flow mass length

FIGURE 12

Graphic Representation of Flow Transport Model at Translation Instant

time. The exponents (k-1) and (n-1-m) applying to the water fraction ratio can be limited by controls without detracting from the overall program accuracy.

Input data consists of the following:

1. Temperature at the inlet end (Grand Coulee in this case)
2. Discharge flow from Priest Rapids (24 hr average)
3. Wind velocity at 1000 ft above MSL
4. Air temperature at 1000 ft above MSL
5. Sky cover in tenths averaged over visible sky period
6. Dew Point (24 hr average)
7. Short Wave Radiation (integrated over 24 hr period)
8. Reservoir dimensions (volume and surface areas are derived)

The program is arranged to be addressed by data cards for each calendar day with computed output for the same day. The varying reservoirs and trough sections of the river are also submitted with each data run and can be varied easily by substitution of as many as 100 reservoir sections depending on the accuracy of the study. Twenty sections are programmed for the current simulation efforts reported.

TABLE III
RESERVOIR SECTIONS PROGRAMMED

Name	Type	Number of Sections
Chief Joseph	Rectilinear using average depth	one
Wells	" " " "	two
Rocky Reach	" " " "	three
Rock Island	" " " "	one
Wanapum	Trapezoidal-Parallel sides	seven
Priest Rapids	Trapezoidal-Nonparallel sides	six

During the interval of interest, the travel time can vary from as little as 5 days to as many as 30 days or more. Data cards for a sufficient number of days to fill the memory banks to permit calculation on a real time average basis from the outlet structure must precede the desired date.

A typical comparison between computed and actual data measured at Priest Rapids is illustrated in Figure 13. The correlation appears quite good, generally oscillating ± 0.2 °C about the measured data except where there is a sudden decrease in river temperature from local winds or sharply falling local temperatures. Since this is a data averaging program, short term transients are not seen in complete detail. This averaging process is vital to the success of the program and permits the use of inputs measured over a 24 hr period.

With this approach, the use of single point weather data originally attempted by Raphael appears defensible within the accuracy of the output desired. The computed results bear out this contention (Figure 13).

The Battelle-Northwest Atmospheric Sciences section makes continuous correlations of regional weather in respect to the Hanford weather station. These correlations indicate that within the region of interest covered by the model, single point measurements are an effective index for those factors which have dominant effect on the model. These are high level winds, air temperature, short wave radiation, and to a lesser extent, the dew point.

Superimposed on the calculated data of Figure 13 are the output calculations performed to check the longitudinal diffusion characteristics of the model. Since conventional diffusion equations were not used in the model development, this test was of interest in order to determine to what extent generalization could be achieved. Three spikes occurring naturally on July 7th,

FIGURE 13

Comparison of Measured and Computed Temperatures at Priest Rapids - 1965 Season

August 8th, and August 27th in the Grand Coulee mixed discharge were arbitrarily increased by 5 °C. The output spikes produced in the calculated output match relatively well the travel time of the natural spikes at Priest Rapids. Both forward and backward diffusion are evident, and the longitudinal spread is similar to that expected in the prototype. The distribution of the spikes is encouraging, and additional tests of diffusion performance on a controlled basis are planned.

Figure 13 also indicates that the computer model produces rate action a little sooner than the prototype does. While this is acceptable for parametric studies of environmental prediction, improved performance for diffusion studies would be necessary. Since the program allows for parametric adjustment of model flow time and the mixing ratio, optimization for this purpose appears quite feasible. In addition, with some reprogramming which is currently underway, the model can be generalized further to include advected heat with and without flow change and the optional use of hourly data submissions.

Also, efforts to enlarge the model scope both in area and variety of stream inputs are planned. This enlarged scope will include parametric studies of dissolved oxygen and nitrogen. The temperature model is basic, however, in that the density currents which appear require simultaneous treatment of both the chemical and temperature parameters in order to preserve hydraulic simulation. Ultimately, it appears feasible to program an entire river basin on a model of this type and to synthesize the entire environmental cycle on a real time basis to generate appropriate policy instructions during the actual sequence of events.

Calculated Downstream Effects from Parametric Inputs

Verification of the COL HEAT computer model permitted the running of a great number of parametric studies of the effects

of the input parameters on the calculated output. Of interest to this specific evaluation is the answer to the question of how effective a cooling program would be independent of the limits imposed by the current power and flood control operating plans.

To answer this question, a series of cases were run through the computer model in which the Grand Coulee mixed discharge temperatures actually measured were biased upward and downward in 1 °C increments. This experiment was designed to determine the following:

- 1) To what extent the varying degrees of cooling or heating of the natural discharge from Grand Coulee is reflected in expected conditions at the Hanford plant.
- 2) To what extent this effect is flow or seasonal dependent.

The results of the computer runs are indicated in Figures 14 and 15. The changes as far downstream as the Priest Rapids discharge justify the following conclusions:

- 1) Any control program which changes the mixed discharge temperature from the Grand Coulee project is about 65 to 85% effective in retaining the indicated effect in the reaches under study.
- 2) The efficiencies indicated above are highest during the flow period exceeding 150,000 ft³/sec and tend to the lower values as the flow decreases and the longer interfacial contact time permits approach to equilibrium with atmospheric exchange parameters.

The general conclusion can be drawn that the temperature differential resulting from the passage through the series of low head dams is relatively low and that the primary determinant of the actual temperatures which could be expected below the Priest Rapids Project is the mixed discharge of the Grand Coulee dam.

FIGURE 14
Comparison of Temperatures at Priest Rapids
with Varying Cooling or Heating - 1965

FIGURE 15

Loss or Gain of Imposed Artificial Temperature Differential - Real Time Basis

Qualitative examination of the temperature record (published weekly by the USGS) of the Columbia River at the Canadian border indicates that under the present circumstances the peak temperature of the inflow to Lake Roosevelt occurs about the same time as the peak temperature below Priest Rapids and approximately at the same time at Rock Island as indicated by measurements taken before the erection of the Grand Coulee project. Since the data supporting this study show that the peak temperature of the mixed discharge from Lake Roosevelt currently occurs about 30 days later than the inflow peak, it suggests that the accumulation of additional storage above the Canadian border deserves additional study in terms of the seasonal effects on conditions in the United States.

In any event, the identification of the discharge from the Grand Coulee project as the significant parameter in determination of temperatures as far downstream as the Hanford plant appears to be one of the most significant results of this study.

Description of additional parametric studies conducted with the COL HEAT are beyond the scope of this report and will be reported separately. The model permits independent variation of all of the wind, air temperature, dewpoint, cloud cover, and input radiation factors as well as artificial manipulation of the flow and water temperatures. Provided suitable data were available to permit calculation of the discharge temperature from the Canadian projects, it appears quite feasible to estimate the temperature of the Columbia at any point downstream for which valid weather data are available.

MEASURED EFFECTS AT HANFORD

General Program

The Columbia River cooling program originated in 1958 when observations of hourly river temperatures at the various plant

intakes showed a high degree of dependency on the extent of generator usage at the Grand Coulee plant. Detailed studies by Kramer identified, to the extent possible at the time, the time of travel and the degree of benefit obtained. His observations appeared to justify his calculation procedure which assumed that all spill flow was drawn from the top 5 ft of the reservoir, and this assumption is the cornerstone of the succeeding five evaluation reports.⁽¹⁻⁵⁾

At the time this program was initiated, only Chief Joseph and Rock Island Dams were in place and the transport of water masses was relatively easily visualized. The average power generation at the Grand Coulee powerhouses was relatively low, on the order of 1200 MW and went as low as 850 MW on weekends. With an installed capacity of some 2000 MW available, considerable opportunity was seen to exist for a cooperative program involving the Bureau of Reclamation, the Bonneville Power Administration, and the Atomic Energy Commission.

Lake Roosevelt has been shown to develop a stratification pattern with a maximum differential of from 5 to 7 °C.⁽¹⁻⁵⁾ If, starting at some correct time period, all flow from the surface as spill could be stopped and water drawn only from the bottom, water at the lower levels would provide a significant temperature reduction. Further, as new water flowed into the reservoir, the possibility appeared that a density underflow would be created, and leave the trapped warm water at the reservoir surface to reach equilibrium with the atmosphere at a much later time without contributing to the river temperature immediately below the dam. The Hanford production reactors, until January 1964, were all of the once-through type that operated against a fixed upper temperature limit. Therefore, a reduction of river temperature at the intake represented an opportunity to increase the total temperature rise available and at the same time to reduce the temperature effect of the entire Hanford operation. This is true

because the Hanford reactors utilize only a fraction of the total river flow. On the basis of the assumptions and observations, river temperature reductions up to 2.5 °C were estimated for a period of from 2 to 4 weeks during the critically high temperature period.

In order to implement this plan the following arrangements were concluded on an annual basis:

- 1) Arrangements were made with the Department of Interior for Hanford to accept the fee from special gate operation for a time period set by the Atomic Energy Commission.
- 2) A request was made with Bonneville Power Administration to assign extra generation to the Grand Coulee project for a given time period.
- 3) Authorization was extended to the General Electric Company as prime contractor for the AEC to call the appropriate signals as conditions developed.
- 4) Weekly temperature measurements were made immediately behind Grand Coulee in order to inventory the stratification and permit estimation of appropriate timing.
- 5) Special arrangements for temperature data collecting were made at the Chief Joseph Project, Rocky Reach, Rock Island and other locations on the system of interest (some of the locations evolved into continuous data collecting stations). Where manned stations were impractical, seven day thermographs were employed.

When conditions indicated, all excess flow going over the spillway of Grand Coulee was converted to low level tube flow. It was recognized that some loss of effectiveness might result from the need to flow water over the spillway for tourist interest and other intangibles related to coordination and available control equipment at Grand Coulee Dam.

As additional dams were constructed, the conditions which formerly permitted prompt observation of cause and effect were largely obscured. Additional observations of reservoir behavior gave some reason to suspect that the inventory and density current behavior assumptions were not entirely applicable. Commencing with the 1963 program, a series of reservoir observations were conducted.⁽¹⁴⁾ These observations were supplemented by additional joint and independent observations in 1964 and 1965 by G. R. Snyder, Fish Passage Research Program, Bureau of Commercial Fisheries.

The accumulated data, while far from complete enough to develop a general theory, have led to the following tentative conclusions of interest to the Hanford program.

- 1) The correlation of the upper boundary predicted by Yih and demonstrated by Debler in trough experiments is sufficiently correct to describe the position of the upper dividing streamline under a wide variety of flows.
- 2) The bottom of the submerged flow jet, created in Lake Roosevelt by discharge from a point below the surface, does not necessarily remain below the elevation of the point of discharge. Rather, because of the conditions imposed by turbulence and boundary effects, the flow jets form sheets of flow which undulate through the system in general conformance with the location of the upper dividing streamline and rise above the discharge point if necessary to maintain equilibrium.
- 3) It is quite apparent that Lake Roosevelt does fill by displacement from the north and does not develop a cool density current regime of any significance. Discharge operations involve transport from both surface and deep locations, and the mean temperature of the resulting discharges is determined by the dynamic equilibrium rather than purely gravitational forces.

The above factors seriously affect the possibilities of success of a program of the type presently conducted. In addition, other factors inherent in the nature of the facilities cause difficulties. Among these are the following:

- 1) Since the cooler water supply is fixed and not replenished by density underflows, the scope of the program is limited to the inventory in existence when the decision to start is made.
- 2) The need to provide a display of falling water for the tourists seriously hampers, if not eliminates, the chances for this type of a program. Heat balances show that unless spill flow is essentially zero, the resulting transport of the thin, hottest layer at times, actually raises, rather than reduces, the river temperature below Grand Coulee.
- 3) The annual reduction of the Lake Roosevelt level for flood control seriously depletes the cooler water supply and causes a seasonal imbalance by forcing the storage of the hottest incoming water at the poorest possible time. This situation is aggravated by the annual installation of flashboards which require sudden lowering of the lake and refilling with relatively warm water. These actions have not always taken cognizance of the river cooling program and have at times, operated to the disadvantage of the Hanford managed efforts.
- 4) Throughout the reservoir system, there is a tendency to perform maintenance operations in the period just before the annual "on seal" period. This period coincides with the peak temperature period and, because of the random raisings and lowerings of reservoirs, introduces transients which unfavorably affect the temperature.

At this point, a detailed examination of the operation of the program in the years 1963-65 is meaningful. As a background for this discussion, Figures 16, 17, and 18 are included as a representative record of upstream and downstream temperatures and flow.

THE 1965 PROGRAM

At the onset of the critical season, temperatures measured at Priest Rapids remained slightly below the four year rolling mean. Reservoir inventories conducted during July, however, indicated unusual conditions in that the reservoir was both unseasonably warm and the inflow from Canada was also somewhat above average. The 30 day weather outlook for August published in July by the U. S. Weather Bureau indicated that the next 30 days would be unseasonably warm and dry. The river flow outlook was for continuation of the below median flows experienced in July. The appropriate preliminaries for the official program were concluded, and the calculations of timing were initiated.

Because of the serious drop in the Grand Coulee discharge, installation of the flashboards began with the opening of 26 high tubes on July 23. The work continued for five days during which extremely high air temperatures were experienced. These operations caused some warm water to be drawn from the surface resulting in a 0.3 °C warming of the average. Upon notice of this activity, additional computations were made to determine if the Hanford program should dovetail into the termination of this installation. Tube operation at the initiative of Grand Coulee continued until July 29.

On August 3, the Hanford program was started, more in order to minimize surface spill than by actual plan. By August 10, the spill flow had been reduced to the point where the bottom discharge was producing a net benefit. During the period between July 23 and August 10, the river had been heated an average of

FIGURE 16
 Grand Coulee Mixed Discharge - 1963, 1964, and 1965
 on the 1944 Through 1956 Computed Mean

FIGURE 17
 Comparison of 15 Day Rolling Mean Temperatures at Priest Rapids
 with Actual Daily Mean

FIGURE 18

Normal (a) Columbia River Hydrograph and Daily Records (b)
for the Years 1963, 1964, and 1965

(a) From USGS weekly records at Trinidad. (b) From USGS record at Priest Rapids.

0.5 °C averaged over the 18 day period. On August 22, the weather turned quite cool and remained below average for the rest of the control period. The program progressed quite normally until its termination on September 10 when the generation plant required "on seal" operation. Figure 19 provides a historical progression of the actual events.

Cooling efforts for the period August 10 through September 7 produced net cooling at the Hanford plant averaging about 0.25 °C for a 28 day period. The net benefit of the entire program to Hanford was minimal for 1965; probably the heating just about balanced the cooling.

The specific causes for this marginal performance appear to be:

- 1) Lack of integrated purpose among the involved agencies. Delays resulted from the lack of factual basis for planning.
- 2) Continued heavy electrical generation at Grand Coulee which placed the burden of water control on the tube operation. Generation before, during, and after the period averaged in excess of 1500 MW (60,000 ft³/sec) with little hourly fluctuation.
- 3) Continuation of tourist flow which defeated the purpose of the tube discharge program until the flow was minimized on August 10.

Overall, the 1965 results point out the need for close cooperation and a tightly integrated plan. Such a plan is discussed later herein under Recommendations.

THE 1964 PROGRAM

With the exception of a few weeks in April, water temperatures measured at Priest Rapids were below the average for 1961, 62, and

63. Reservoir inventories conducted in July indicated colder than normal conditions and little or no stratification. By July 21, weather conditions warmed considerably and plans were made to initiate the cooling program during the next cold spell or storm in order to minimize warm surface withdrawal. During this period and after, the river flow was 10 to 20% greater than the 25 yr average, and an extended period of tube operation was planned for. The onset of a cooling trend on August 1 permitted coordination of the flashboard operation with the Hanford releases; and on August 3, 17 tubes were opened to permit this installation. Tube flow was continued without interruption until September 18. Spill flow was minimized, but tourist flow was held at relatively high levels until August 20 when it was reduced to optimal levels.

Effective cooling at Grand Coulee was produced during the period August 20 until September 15, and the resulting temperature decrease at the Hanford plant averaged 0.25°C during the period August 25 until September 20. Some inadvertent heating also resulted from high spill flow, averaging about 0.20°C during the period August 16 to August 25.

On balance the program produced about 8 degree days of net effect at the Hanford plant (Figure 20). Considering the resources available, this performance is marginal. Because of the higher river flows, the water management for power purposes was less critical and the beneficial results were more easily obtained.

Later in the season, from September 28 through October 20, after the cooling program was complete, tube discharges were again started in order to test the theory that such flows could assist in the formation of submerged flow jets. With continuation of 2 to 3°C stratification at the lower end of the lake, the expected flow jets were confined to the stratified downstream

portion while the upper end of the lake continued to fill with cool water. By the time the maximum Grand Coulee discharge temperature (16.4 °C) was recorded on September 28, the inflow temperatures at the international border were 14 °C. The temperature at the international border dropped 4 °C below the Grand Coulee discharge temperature by the time tube flow was stopped. Intermediate records of temperature measured by G. R. Snyder of the Bureau of Commercial Fisheries confirmed this analysis. Our mathematical analysis of the Bureau of Commercial Fisheries information indicated that the upper dividing streamline location predicted by the Debler correlation did in fact describe the prototype.

THE 1963 PROGRAM

As the critical period of 1963 approached, conditions were in general quite average in almost every respect. River averages, reservoir conditions, and air temperatures followed this trend. River flows, however, had been quite low and had crested at around 300,000 ft³/sec at the Hanford plant. From that time on, flows were at or below median and forecasts indicated early recourse to "on seal" operation of the Coulee project. Wanapum Dam had just been filled in May, and the additional time delay in water transit time through the project was noted significantly for the first time. The prediction of an above average weather forecast for the month of August indicated a season of higher than normal river temperatures.

By the time the flashboard installation was started on July 21, the river flows were quite low. While it was desirable to time this installation with the onset of the Hanford program, retention of the majority of the cooler water was selected as the desirable alternative; and the starting of the cooling program was held off until August 4. The advance preparation time in this case permitted very close coordination of the resulting tube and spillway operation, and the spillway flow was held to

the absolute minimum. Tourist flow was only continued during the noon to midnight hours with "on seal" operation for the balance of the time. Lake inventory was balanced between overdraft and underdraft.

Despite these precautions, some heating occurred in mixed discharge between August 4 and August 10, averaging about 0.20 °C for the period. Beginning on August 10, even tighter controls were applied; and the results are apparent in Figure 21. When the low tube flow available was considered, cooling effects averaging 0.40 °C were developed at the Hanford plant during the period August 18 through September 14. This represented a net gain of about 11 degree days (Figure 21).

During this 1963 cooling program period, this author began the investigation of the factors effecting the program with an extensive reservoir inventory. Weekly vertical temperature probes were made at the dam site, Keller Ferry, Spokane River, Gifford Ferry, and the Kettle Falls Bridge.

These data gave the first indication that because of the relatively high flow through Lake Roosevelt some of the concepts governing the cooling program needed rather extensive review. While only incompletely developed, the following hydraulic concepts became apparent from my 1963 notes.

- 1) The reservoir isotherms are highly tilted. Warm water flows horizontally quite readily, but cooler water caused tilted isotherms. No significant cool underflow from Canada was detected.
- 2) The cooler flow of the Spokane River appears to make a contribution to the cooling program by a density underflow to the 1030 ft discharges.
- 3) The turbine inlets at Grand Coulee while nominally at the 1030 ft level, affect the upper water all the way

FIGURE 21

Isotherms on Reservoir Axis
August 18, 1965, 2-3 p.m.

to the surface, probably due to the pressure drop in the bar screen inlets. This means that the 1030 ft discharges will contain a relatively broad inventory of water and will average higher in temperature than the level position would indicate. The average 1030 discharge temperature is always somewhat higher than a vertical temperature map taken at Eden Harbor 1 mi upstream. (See Figure 22 for a 1965 confirmation of this effect.)

Based on the performance calculations possible in 1965 using the COL HEAT program, the results of the 1963 program were quite good compared to following years. At the time no serious evaluation of the results were possible with the manual calculation methods of Raphael or others. Development of the analytical technique and improvements in temperature records permitted the analysis in this report.

RECOMMENDATIONS FOR FUTURE PROGRAMS

While the research supporting the definition of current jets in Lake Roosevelt is far from adequate and if a degree of speculation is permitted, two general courses of action for the near future take shape. Since the Canadian Treaty dams and the third power house at Grand Coulee are involved, ultimately, the scope of these recommendations relates only to those efforts which can be accomplished in the next 3 to 5 yr. In this limited period, the opportunity exists to develop the basis for a cooperative program which will lay a foundation for the post-treaty and post-third powerhouse conditions.

The data in this report indicate that within the present scope the Columbia River cooling program is a feasible operation which can produce downstream benefits only if the following conditions can be brought about:

- 1) That the cooling effort be conducted as a truly multi-agency operation with technical inputs from all significantly affected parties.

- 2) That once the decision to proceed with the program is established, the full cooperation of affected parties is necessary. This involves assessment of related commitments to the power fishery, flood control, and park and recreation impacts of the program, in addition to those of the Atomic Energy Commission.
- 3) That within this framework, a supporting technical plan based on current input data, be adopted and continuously updated as water and weather conditions of interest are available. This would include continuing assessment of the water quality impacts of the day to day power and maintenance operations on the reservoir and river systems.

In the absence of this degree of integrated planning and operation, the potential benefits of the program are either incapable of attainment or of negligible value. Since all of the agencies involved currently have staffs and experience in some phase of integrated operation of the Columbia River, it would appear that effective coordination could be achieved and that the integrated plan could be drafted onto the present communications network supporting the Northwest Power Pool.

The following course of action is suggested for consideration as the cooling plan for the immediate future.

Proposed Water Quality Program

- 1) Affected agencies would meet not later than May 1, 1966 to review individual plans which may affect water quality.
- 2) On the basis of available flow and weather forecasts, adjust the timing and actual release of flood control water space to minimize potential temperature and dissolved gas content fluctuations. It appears desirable, that to the extent possible, that the reservoir

remain in the drawn down condition just before the flood control season in order to conserve the inventory of cooler water lost by sudden drainage later. This appears to offer opportunity for spring maintenance operations.

- 3) During the period immediately after the end of flood threat, the generation and low tube discharge at Grand Coulee should be minimized in order to conserve cooler water. Since other projects have large capacity flexibility at this high flow period, this type of operation appears feasible.
- 4) The installation of flashboards should be accomplished with a minimum of drawdown and as early as possible in the season as hydraulics and manpower permit. The schedule for this operation would be set by the permitted spill flow. This would occur at or near mid-July during the time when power generation would be temporarily reduced. After completion of installation, no tube flow and a minimum of generator flow would be scheduled.
- 5) Low releases would commence on the basis of optimal conditions for affected agencies. Technical support would be provided by agencies with computer facilities in order to minimize policy delays. Generation would return to normal. The onset of low releases for cooling would involve strict regulation of tourist flow to fixed hours of the day. This would permit the flow of an appropriate number of acre-feet at the high rate in order to take advantage of the linear mixing characteristic of Figure 4. This may be of benefit to the tourist program by permitting short planned programs of maximum water release instead of a continuous thin trickle. Low releases should be continued until the

"on seal" operation begins at which time the cooling program would terminate for the year.

- 6) Concurrently with these operations 1 through 5, all affected agencies with data to offer would make it available on a routine basis. The existing weather network of Battelle-Northwest and the teletype facilities of the Northwest Power Pool would provide ample data channeling to be supplemented by other communications as appropriate. The existing power optimization programs of the Bonneville Power Administration and the COL HEAT program described in this report would provide a technical basis for daily operation.
- 7) Summary reports of the resulting operation would be prepared on a joint basis with responsibility delegated by participation. Publication could be under the auspices of the Columbia Basin InterAgency Committee or a special subcommittee or task-force of the committee. Affected agencies would make independent appraisals as desirable to describe independent interests beyond the scope of the Water Quality Control Program.

Adoption of this Program appears desirable from three major standpoints:

- 1) It will provide invaluable experience in the development of a functioning water quality plan for future years.
- 2) It will meet the immediate needs of fisheries and the production goals of the Atomic Energy Commission by reduction of water temperatures during the critical early fall season.

- 3) It offers immediate benefits to research in the potential reduction of the "super-saturated gas problem" by reducing the sudden flow of cool water in the spring.

ACKNOWLEDGEMENT

No program of the scope of the Columbia River Cooling Program can be performed without the assistance of a great number of persons and agencies. To all who have provided data and helpful suggestions, our thanks. To those listed below, special thanks for the continuing contribution of time and constructive criticism:

- G. R. Snyder and A. J. Novotny of the Fish Passage Research Program, Bureau of Commercial Fisheries who permitted use by the author of previously unpublished data. A cooperative information exchange has continued for some time, and has resulted in benefits to programs of both the BCF and Battelle.
- R. F. Peterman, Head, Operations Section, Grand Coulee Dam who arranged for special gate operation, equipment installations and data collection in support of the annual cooling program. Also to Duer Johnson, formerly Assistant Power Superintendent at Grand Coulee, for his assistance in 1963 and prior years.
- J. H. Schrengohst, Power Superintendent, Rocky Reach Dam, who has installed special equipment and furnished daily data submissions to the program.
- James Green, Project Engineer, Chief Joseph Dam, who has installed special equipment and furnished daily data submissions to the program.
- H. A. Kramer, now with Culler, Gale, Martell, Norrie and Davis, for his thoughtfulness and inspiration in originating the Columbia River cooling program and setting up many of the original procedures.
- Don Jenne, J. P. Corley and others of the Battelle-Northwest staff who have assisted through the years in furnishing data and thoughtful comments in support of the program.

- L. B. Brinkman, Douglas United Nuclear, who assisted the author in the collection of data on many occasions.
- R. A. R. Kent, currently of Hofmann Electronics, who assisted the author in the development of the COL HEAT program and who provided timely mathematics consultation.

REFERENCES

1. H. A. Kramer. Artificial Cooling of the Columbia River by Dam Regulation - 1958 Program - Part I, HW-60285 PTL. General Electric Company, Richland, Washington. May 25, 1959.
2. H. A. Kramer. Artificial Cooking of the Columbia River by Dam Regulation - 1959 Program - Part I, HW-65767. General Electric Company, Richland, Washington. June 20, 1960.
3. H. A. Kramer. Artificial Cooling of the Columbia River by Dam Regulation - 1960 Program - Part I, HW-68337. General Electric Company, Richland, Washington. February 15, 1961.
4. H. A. Kramer. Artificial Cooling of the Columbia River by Dam Regulation - 1961 Program - Part I, HW-73707. General Electric Company, Richland, Washington. June 15, 1962.
5. H. A. Kramer. Artificial Cooling of the Columbia River by Dam Regulation - 1962 Program - Part I, HW-76887, General Electric Company, Richland, Washington. March 7, 1963.
6. J. M. Raphael. "Prediction of Temperature in Rivers and Reservoirs," J. of Power Division, Proceedings ASCE, no. 3200, pp. 157-181. July, 1962.
7. R. T. Jaske. "Prediction of Columbia River Temperatures Downstream from Grand Coulee Dam for Wide Extremes of Flow and Weather Conditions," Contract Report to Bureau of Commercial Fisheries, September, 1965.
8. R. T. Jaske. The Density Flow Regime of Franklin D. Roosevelt Lake, BNWL-20. March 15, 1965.
9. W. R. Debler. "Stratified Flow Into a Line Sink," J. Engr. Mechanics Div., Proceedings of ASCE, vol. 2093, July, 1959.
10. W. V. Burt, et al. "Preliminary Study on the Predicted Water Changes of the Lower Snake River Due to the Effects of Projected Dams and Reservoirs," Contract Report to Bureau of Commercial Fisheries, November, 1963.
11. "Water-Loss Investigations: Lake Hefner Studies," Technical Report, Geological Survey Professional Paper no. 269.
12. J. M. Raphael. "The Effect of Wanapum and Priest Rapids Dams on the Temperature of the Columbia River," Contract Report to PUD no. 2 of Grant County, September, 1961.

13. J. M. Raphael. "The Effect of Wells and Rocky Reach Dams on the Temperature of the Columbia River," Contract Report to PUD no. 2 of Grant County, January, 1962.
14. "Water Temperature Influences, Effects, and Control," Proceedings of the Twelfth Pacific Northwest Symposium on Water Pollution Research, USPHS, Corvallis, Oregon, November 7, 1963.
15. R. V. Wasley. "Uniform Flow in a Shallow, Triangular Open Channel," Proceedings, Hydraulics Div., ASCE, September, 1961.
16. N. C. Matalas and W. J. Conover. Water Resources Research, vol. 1, no. 2, Second Quarter. June, 1965.
17. C. L. Larson. "Transverse Distribution of Velocity of Flow in a Shallow Triangular Channel," Thesis: University of Minnesota, 1940.

APPENDIX A

Columbia River System

(Comments prepared by J. L. Spurgeon
of Computer Sciences Corporation, Richland, Washington)

General

The Columbia River Studies system comprises a computer program simulating the flow and mixing of water in order to predict the temperature of water leaving the river system. The model used divides the river into longitudinal sections whose lengths are roughly 1 day's flow, and into lateral sections such that water in a central trough flows faster than water at the edges of the river.

Twelve hours is the shortest unit of time employed. The model takes into account such factors as heat gained from solar radiation, losses and gains from evaporation and condensation, and other variables affecting the temperature, such as vapor pressure and barometric pressure.

The system was written in FORTRAN IV and is currently being run on the UNIVAC 1107 at Richland, Washington for investigation of the Columbia River between the Grand Coulee and the Priest Rapids dams.

Definition of Terms and Symbols

V_w : Volume of one flow day of water, ft^3

Flow day of water: Average of water entering and leaving the system in one day.

Δt = Time interval used by the program. In the present model, $\Delta t = 12$ hr. This span of time is either 12:00 AM to 12:00 noon, or 12:00 noon to midnight.

Water Density: 62.5 lb/ft^3

A: $t/(62.5 \times V_w)$

$\underline{v_2}$: Volume of water in the central trough of one river section.

$\underline{V_2}$: Total volume of water in the inner trough of the river bed.

$\underline{B}$: V_2/V_w = fraction of the water in the inner trough.

$\underline{S_k}$: Surface area of river section k (ft^3)

$\underline{Q1_{i,k}}$: Algebraic sum of heat added to the k^{th} river section in the morning of the i^{th} day.

$\underline{Q2_{i,k}}$: Algebraic sum of heat added to the k^{th} river section in the second half of the day.

$\underline{\Delta T_{i,k}}$: $AS_1 Q1_{i,k}$ = Algebraic change in water in the morning of the i^{th} day.

$\underline{T2_{i,k}}$: Temperature of the water in the second half of the i^{th} day in the inner trough of the k^{th} river section.

Trough: The river is divided into two troughs. The assumption has been made that the water in the inner trough moves at twice the speed of the water in the outer trough.

$\underline{T_{i,j}}$: The average temperature of the water in river section J at the start of the i^{th} day.

Method

Water Transport Equation

The Columbia River model used Equation (A-1)

$$T_{i+1,k+1} = (1-B)[T_{i,k} + \Delta T_{i,k}] + B[T_{i,k-1} + \Delta T_{i,k-1} + \Delta T2_{i,k}] \quad (A-1)$$

where $T_{0,0} = T_{i,0}$

$$\Delta T_{i,0} = 0.0$$

to transfer water into section $(k + 1)$ on the $i + 1$ st day. The outer trough of river section k with temperature $T_{i,k}$ receives the

temperature change $\Delta T_{i,k}$ as the result of being in river section k during the entirety of the i^{th} day. The inner trough of river section (k-1) receives the temperature change $\Delta T_{i,k} - 1$ from being in section (k-1) during the morning of the i^{th} day, and $\Delta T_{i,k}$ from being in the inner trough of section k during the second half of the i^{th} day. Thus on the $(i+1)^{\text{st}}$ day the above two troughs of water are moved into the $(k+1)^{\text{st}}$ section and are mixed.

The application of Equation (A-1) to determine the temperature of a flow day of water as it leaves the system requires an extensive accounting system. An example will best illustrate the use of Equation (A-1). We will display the equations necessary to determine $T_{5,5}$ for the system in Figure A-1. The determination of the temperature $T_{5,5}$ requires the calculation of

- (1) $T_{5,5} = (1-B)[T_{4,4} + \Delta T_{4,4}] + B[T_{4,3} + \Delta T_{4,3} + \Delta T_{4,4}^2]$
- (2) $T_{4,4} = (1-B)[T_{3,3} + \Delta T_{3,3}] + B[T_{3,2} + \Delta T_{3,2} + \Delta T_{3,3}^2]$
- (3) $T_{4,3} = (1-B)[T_{3,2} + \Delta T_{3,2}] + B[T_{3,1} + \Delta T_{3,1} + \Delta T_{3,2}^2]$
- (4) $T_{3,3} = (1-B)[T_{2,2} + \Delta T_{2,2}] + B[T_{2,1} + \Delta T_{2,1} + \Delta T_{2,2}^2]$
- (5) $T_{3,2} = (1-B)[T_{2,1} + \Delta T_{2,1}] + B[T_{2,0} + \Delta T_{2,0} + \Delta T_{2,1}^2]$
- (6) $T_{2,2} = (1-B)[T_{1,1} + \Delta T_{1,1}] + B[T_{1,0} + \Delta T_{1,0} + \Delta T_{1,1}^2]$
- (7) $T_{2,1} = (1-B)[T_{2,0} + \Delta T_{2,0}] + B[T_{2,0} + \Delta T_{2,0}^2]$
- (8) $T_{1,1} = (1-B)[T_{1,0} + \Delta T_{2,0}] + B[T_{1,0} + \Delta T_{1,0}^2]$
- (9) $T_{2,0}$ measured temperature of incoming water on the second day
- (10) $T_{1,0}$ measured temperature of incoming water on the first day.

FIGURE A-1
Water Transport Through
a Five-Flow Day River System

temperatures $T_{4,4}$ and $T_{4,3}$ which in turn require the calculation of temperatures $T_{3,3}$, $T_{3,2}$, and $T_{3,1}$ which themselves require the calculation of temperature $T_{2,2}$, $T_{2,1}$, and $T_{2,0}$. Figure A-2 shows the network of antecedent calculations.

FIGURE A-2

Direct Temperature Calculation Dependency

In addition to the dependency shown in Figure A-2, the temperature $T_{i,k}$ must be known before $\Delta T_{i,k}$, $\Delta T1_{i,k}$, or $\Delta T2_{i,k}$ can be calculated.

Heat Exchange Equations

The change in the internal heat energy of the system is equal to the enthalph-in minus the enthalph-out, plus the heat transferred at the surface. From Equation A-2 developed in Raphael, the heat exchange equation used by the computer program is developed.

$$m_w c T_w = M_i c T_i - m_i c T_w + QA$$

$$m_w T_w = \frac{Q_T A}{C} + m_i (T_i - T_w)$$

$$\frac{dt_w}{dt} = \frac{Q_T A + \frac{dm_i}{dt} (T_i - T_w)}{m_w}$$

$$T_w = \frac{Q_T A t + m_i (T_i - T_w)}{m_w}$$

$$T_w = \frac{Q_T A t + V_i 62.5 (T_i - T_w)}{62.5 V_w}$$

$$T_w = \frac{Q_T A t}{62.5 V_w} + \frac{V}{V_w} (T_i - T_w) \quad (A-2)$$

1. Net gain or loss of heat energy.

$$Q_t = (Q_s - Q_r) - Q_b + Q_n - Q_e \quad \text{Btu/ft}^2$$

2. Net heat gain from solar radiation

$$(Q_x - Q_r) = 3.6869 q_s \quad \text{Btu/ft}^2$$

where Q_i = the solar radiation for a 24 hr period in langleys.

3. Back radiation (longwave radiation from the water)

$$Q_b = (24 \text{ hr}) (1.66 \times 10^{-9} \text{ Btu/ft}^2 \cdot \text{hr} \cdot ^\circ\text{R}^4)$$

$$[T_w + 460.]^4 - (T_i + 460.)^4] \quad \text{Btu/ft}^2$$

4. Heat lost through evaporation and gain through condensation.

$$Q_E = (24 \text{ hr}) \frac{U}{(1.1508 \text{ mi/knot})} (e_w - e_a) \text{ Btu/ft}^2$$

where: U = wind speed, mi/hr

e_a = vapor pressure of water in the atmosphere in inches of mercury

5. Heat conduction from the water to the air

$$Q_H = (24 \text{ hr}) (0.00407) \frac{U}{\left(1.1508 \frac{\text{mi}}{\text{knots}}\right)} P (T_a - T_w) \text{ Btu/ft}^2$$

U = wind velocity

T_a = air temperature

T_w = water temperature

P = barometric pressure in inches of mercury

The Density Current

The density current model was developed from the theory advanced by Debler.⁽⁹⁾ The interested reader should consult Mr. Debler's article for a concise development of the theory.

Theory

The model's criteria for the existence of a density current in a dam basin is that the calculated densimetric Froude number F_2 be less than or equal to $F_c = 0.26$, which is the critical Froude number for a density current. The value 0.26 is conservative. For the application of this criteria, the following variables can be selected to define the problem:

q = volumetric discharge, ft^3

d_1 = height of zone in which flow is concentrated, ft

d_2 = depth of dam basin, ft

ρ_o = density of water at the basin bottom, lb/ft³

W_o = width of basin, ft

g = gravitational constant = 32 ft/sec²

$\Delta\rho = \rho_o - \rho_2$ = density difference between water at the bottom and at the surface of the basin, lb/ft³

$\Delta\rho_c$ = Computed critical $\Delta\rho$. Values of $\Delta\rho \geq \Delta\rho_c$ imply $F_2 \leq F_c$, lb/ft³

The selected variables can be combined to form

$$F_2 = \frac{\left(\frac{q}{W_o}\right)}{d_2^2} \sqrt{\frac{\rho_o}{g \Delta\rho}} \quad (A-3)$$

in which $\Delta\rho$ is the variable to be determined. The required expression becomes

$$\Delta\rho = \frac{\rho_o}{F_2^2 d_2^3 g} \left(\frac{q}{W_o}\right)^2 \quad (A-4)$$

The required critical density is found by replacing F_2 by $F_c = 0.26$, thus giving

$$\Delta\rho = \frac{\rho_o}{(0.26)^2 d_c^3 W_o^2} q^2 \quad (A-5)$$

as the critical density gradient for existence of a density current.

The density difference $\Delta\rho$ between the incoming water and the dam basin water depends principally on their temperature gradient. For test purposes it is assumed that there does exist a density current, and the depth ($d_2 - d_1$) of the stagnant water is

calculated from the equation

$$\left(\frac{d_1}{d_2}\right)^2 = F_c \pi \quad (A-6)$$

which in its more convenient form is

$$(d_2 - d_1) = (1 - \sqrt{\pi \cdot 26}) d_2. \quad (A-7)$$

The temperature of the stagnant water with depth $(d_2 - d_1)$ is computed from the incremental surface exchange of heat. Now the density ρ_0 of the incoming water and the density ρ_2 of the basin water can be computed as a function of their respective temperatures.

The test for a density current can now be applied. If $\Delta\rho = (\rho_0 - \rho_2) \geq \Delta\rho_c$, then the density current does exist.

Effect of the Density Current

The effect of the density current is that the water leaving the dam is essentially the same temperature as it was when it entered the dam basin.

Programatic Information

The Columbia River Studies Computer Program comprises a system of an executive program and five subprograms in the simulation of water systems for temperature calculation.

The Executive Program

The executive program manages the program flow. It sets up the river geometry, communicates necessary information between itself and its subprogram, and determines the incremental flow of water through the river system. In addition, it does the accounting necessary to maintain proper control of program flow.

OVALUE

From the information supplied by the executive program, OVALUE determines the incremental heat exchanges and resulting temperature for each flow-day body water.

TROUGH

This subprogram aligns the flow-days of water in their river sections to determine the program surface area for each flow-day.

SMATCH

For density current calculations, the flow-days of water, and portions thereof, in the density current basin are determined in SMATCH.

SLESS

The test for density currents are made in SLESS. If the computed densimetric Froude number is less than the critical Froude number, the dam basin has a density current. The surface areas of the flow days of water in the basin is adjusted to account for the density current.

BEVA

From the input weather data, BEVA calculates the coefficient for the longwave radiation from the water surface.

APPENDIX B

Data and Solutions to Heat Balance Equation

Internal Energy Balance:

$$kQ_R T_R = kQ_6 T_6 + kQ_T T_g + kQ'_S T'_S$$

where Q_R = flow below dam, 10^3 ft³/sec

Q_g = flow through generators, 10^3 ft³/sec

Q_T = flow through tubes, 10^3 ft³/sec

$Q_S = Q_T + Q'_S$, 10^3 ft³/sec

Q'_S = flow over spillway, 10^3 ft³/sec

T_R = temperature below dam (mixed), °C

T_g = temperature through generators (1030 ft), °C

T'_S = effective spill temperature, °C

k = conversion factor

then:

$$T_R = \frac{(Q_g + Q_T)T_g + Q'_S T'_S}{Q_R}$$

where Q'_S is estimated from isotherm maps and depth chart (Figure 4).

$$T'_S = \frac{Q_R T_R - (Q_g + Q_T)T_g}{Q'_S}$$

where actual data are available.

TABLE B-I

MEASURED AND CALCULATED HEAT BALANCE DATA
1965 COLUMBIA RIVER COOLING PROGRAM
(Units defined in text)

July, 1965	MCFS (a)					Actual, °C T_R	Actual, °C T_g	Calculated, °C T'_s	Tube Flow MCFS (a) Q_T	Surface Spill Flow, MCFS (a) Q'_s	Effective Discharge Depth, meters D	From Isotherm Records, °C (see text) T'_s	Actual, °C T_g	Estimated Mixed Discharge, °C T_R
	Q_R	Q_s	Q_g	$Q_T^{(b)}$	Q'_s									
	Actual Conditions													
1	248	183.9	64.1	0	183.9	13.4	13.2	13.6	Assumed Zero	183.9				13.4
2	243	180.6	62.6	0	180.6	13.6	13.3	13.8		180.6				13.6
3	236	175.9	59.0	0	175.9	13.7	13.3	13.8		175.9				13.7
4	225.4	170.2	55.2	0	170.2	13.7	13.3	13.9		170.2				13.7
5	221.1	163.8	57.3	0	163.8	13.9	13.4	14.1		163.8				13.9
6	224.3	160.5	63.8	0	160.5	14.0	13.5	14.2		160.5				14.0
7	233.5	169.3	64.2	0	169.3	14.1	13.5	14.4		169.5				14.1
8	235.6	172.3	63.3	0	172.3	13.8	13.6	13.6		172.3				13.8
9	235.8	173.0	62.8	0	173.0	14.0	13.6	14.2		173.0				14.0
10	237.7	178.0	69.0	0	178.7	14.2	13.6	13.6		178.6				14.2
11	244.9	192.3	52.6	0	192.3	14.0	13.7	14.2		192.3				14.0
12	244.9	187.3	57.4	0	187.3	14.1	13.8	14.3		187.3				14.1
13	245.0	179.3	65.7	0	179.3	14.3	13.9	14.5		179.3				14.3
14	237.6	171.5	66.1	0	171.5	14.6	13.8	14.9		171.5				14.6
15	223.1	156.5	66.6	0	156.5	14.4	13.8	14.7		156.5				14.4
16	222.2	155.3	66.9	0	155.3	14.4	13.8	14.7		155.3				14.4
17	220.0	156.1	64.0	0	156.1	14.7	13.9	15.0		156.1				14.7
18	203.0	143.3	59.8	0	143.5	14.4	14.0	14.6		143.5				14.4
19	198.6	137.4	61.2	0	137.4	14.5	14.1	14.8		137.4				14.5
20	196.8	136.0	60.8	0	136.0	14.7	14.1	15.1		136.0				14.7
21	196.7	134.3	62.4	0	134.3	14.7	14.2	15.1		134.3				14.7
22	204.0	146.0	57.8	0	146.0	15.0	14.3	15.3		146.0				15.0
23	204.1	145.6	58.5	122	23.6	15.2	14.3	20.8		145.6	25	15.3	14.3	15.0
24	197.2	133.7	63.5	103.5	30.2	15.3	14.4	19.9		133.7	25	15.3	14.4	15.0
25	180.9	119.0	61.9	94.0	25.0	15.4	14.5	19.4		119.0	25	15.3	14.5	15.0
26	163.3	102.8	60.5	84.7	18.1	14.8	14.6	16.7		102.8	25	15.3	14.6	15.1
27	161.1	100.5	60.6	75.3	25.2	14.9	14.5	16.9		100.5	25	15.3	14.5	15.1
28	140.7	82.1	58.6	18.8	63.3	15.4	15.0	15.8		82.1	25	15.4	15.0	15.2
29	127.1	65.9	61.2	14.1	51.8	16.0	15.0	17.4		65.9	21	15.5	15.0	15.3
30	119.2	59.4	59.8	0	59.4	16.4	15.0	17.4		59.4	19	15.8	15.0	15.4
31	118.3	59.0	59.3	0	59.0	16.5	15.1	17.9		59.0	19	16.2	15.1	15.7

(a) MCFS = 10^3 ft³/sec

(b) Tube flows vary somewhat from stated values because fractional flows are occasionally dropped.

B-2

BNWL-208

TABLE B-I (contd)

	MCFS(a)					°C			MCFS(a)		m °C			
	Q _R	Q _S	Q _g	Q _T	Q' _S	T _R	T _g	T' _S	Q _T	Q' _S	D	T' _S	T _g	T _R
August, 1965	Actual Conditions								Revised for Zero Tube Flow					
1	118.6	60.1	58.6	0	60.1	16.5	15.0	18.0	60.1	19	16.4	15.0	16.0	
2	123.7	65.7	58.0	18.4	47.3	16.8	15.1	19.6	65.7	21	16.3	15.1	15.8	
3	132.5	73.4	59.1	18.4	55.0	16.8	15.1	19.1	73.4	23	16.3	15.1	16.0	
4	134.3	73.1	61.2	26.4	46.7	16.7	15.0	20.1	73.1	23	16.5	15.0	15.9	
5	155.7	90.5	65.2	41.4	49.1	16.6	15.1	19.9	90.5	28	16.3	15.1	16.0	
6	139.3	73.1	66.2	41.4	31.7	16.5	15.4	20.3	73.1	23	16.7	15.4	16.1	
7	138.4	79.6	58.8	41.4	38.2	16.9	15.2	21.7	79.5	25	16.6	15.2	16.0	
8	137.9	81.2	56.7	41.4	39.8	17.1	15.4	21.1	81.2	25	16.7	15.4	16.2	
9	135.3	71.5	63.8	41.4	30.1	16.6	15.4	20.9	71.5	22	17.2	15.4	16.4	
10	133.6	64.5	69.1	51.3	13.1	16.2	15.5	22.3	64.5	21	17.4	15.5	16.4	
11	130.7	61.1	69.6	39.9	21.2	16.4	15.6	20.5	61.1	20	17.6	15.6	16.6	
12	132.6	63.5	69.1	45.6	17.9	16.6	15.7	22.9	63.5	21	17.6	15.7	16.5	
13	135.3	69.2	66.1	51.3	17.9	16.5	15.6	21.7	69.2	22	17.7	15.6	16.7	
14	135.0	65.1	65.1	51.3	18.6	16.4	15.8	19.9	69.9	22	17.9	15.8	16.9	
15	132.5	68.4	64.1	51.3	17.1	16.5	15.8	21.5	68.4	21	17.8	15.8	16.8	
16	138.3	75.3	63.0	57.0	18.3	16.8	15.8	22.9	75.3	24	17.9	15.8	17.0	
17	137.3	73.3	64.0	62.7	10.6	16.7	16.1	22.6	73.3	24	18.0	16.1	17.1	
18	132.0	71.7	60.3	62.7	9.0	16.9	16.2	23.9	71.7	22	18.2	16.2	17.3	
19	116.3	61.6	54.7	57.0	4.6	16.9	16.2	23.9	61.6	20	18.4	16.2	17.4	
20	118.3	52.7	65.6	45.6	7.1	16.9	16.4	20.2	52.7	17	18.7	16.4	17.4	
21	115.1	47.2	67.9	39.9	7.3	17.0	16.5	23.7	47.2	15	18.8	16.5	17.5	
22	108.4	44.1	64.3	39.9	4.2	16.8	16.7	21.9	44.1	13	19.2	16.7	17.7	
23	106.2	46.1	60.1	34.2	11.9	16.8	16.7	21.8	46.1	13	19.2	16.7	17.9	
24	110.7	50.2	60.5	39.9	10.3	16.9	16.6	21.5	50.2	16	19.1	16.6	17.8	
25	112.1	48.0	64.1	34.2	13.8	17.0	16.6	21.0	48.0	16	19.1	16.6	17.7	
26	114.1	44.0	70.1	34.2	9.8	17.3	16.8	22.7	44.0	13	19.4	16.8	17.8	
27	116.5	50.7	65.8	39.9	10.8	17.6	17.0	23.5	50.7	16	19.2	17.0	17.9	
28	115.5	43.2	71.7	34.2	9.0	17.6	17.2	23.5	43.2	13	19.5	17.2	18.0	
29	115.0	46.9	68.1	39.9	7.0	17.5	17.2	22.1	46.9	15	19.5	17.2	18.1	
30	111.0	40.9	70.1	34.2	6.7	17.6	17.2	23.7	40.9	12	19.6	17.2	18.2	
31	112.0	47.4	69.6	34.2	8.2	17.8	17.5	21.9	42.4	13	19.6	17.5	18.3	
Assumed Zero														
September, 1965														
1	99.8	29.9	69.9	11.6	18.3	17.9	17.5	19.7	29.9	9	19.6	17.5	18.1	
2	88.5	19.6	68.9	11.6	8.0	18.0	17.6	22.0	19.6	6	19.5	17.6	18.0	
3	87.3	18.2	69.1	5.8	12.6	18.0	17.8	18.9	18.2	5	19.4	17.8	18.2	
4	86.2	17.5	68.7	11.6	6.1	18.1	17.9	20.0	17.5	5	19.3	17.9	18.2	
5	85.6	18.3	67.4	11.6	6.7	18.0	17.9	18.7	18.3	5	19.2	17.9	18.2	
6	83.5	14.3	69.2	5.8	8.5	18.0	17.9	18.8	14.3	4	19.1	17.9	18.1	
7	81.6	13.8	67.8	5.8	8.0	18.1	18.0	18.8	13.8	4	19.0	18.0	18.2	
8	75.5	4.7	70.8	0	4.7	18.2	18.1	19.3	4.7	2	18.9	18.1	18.1	

End of Program

(a) MCFS = 10^3 ft³/sec

B-3

BNWL-208

TABLE B-II

MEASURED AND CALCULATED HEAT BALANCE DATA
1964 COLUMBIA RIVER COOLING PROGRAM
(Units defined in text)

	MCFS (a)					°C			MCFS (a)					m °C		
	Q _R	Q _S	Q _g	Q _T (b)	Q _S '	T _R	T _g	T _S '	Q _T	Q _S '	D	T _S '	T _g	T _R		
July, 1964	Actual Conditions								Tube Flow Revised to Zero							
20	282.8	227.2	55.6	0	227.2	14.4	14.2	14.5	Assumed Zero	No Tube Operation This Period						
21	261.3	307.6	54.3	0	207.6	14.6	14.5	14.6								
22	245.8	192.1	53.7	0	192.1	14.6	14.5	14.6								
23	237.0	187.2	49.8	0	187.2	14.7	14.6	14.7								
24	228.7	179.5	48.2	0	179.5	14.9	14.7	15.0								
25	214.5	166.5	48.0	0	166.5	15.0	14.8	15.0								
26	206.3	158.6	47.7	0	158.6	14.9	14.7	15.1								
27	199.3	146.5	52.7	0	146.5	15.0	14.9	15.0								
28	167.9	113.8	54.1	0	113.8	15.1	14.9	15.2								
29	160.7	107.9	52.8	0	107.9	15.1	14.9	15.2								
30	161.6	108.9	52.7	0	108.9	15.1	15.0	15.1								
31	180.0	127.14	52.6	0	127.14	15.1	15.0	15.2								
August, 1964									Assumed Zero							
1	187.1	137.9	49.2	0	137.9	15.2	15.1	15.4								
2	177.0	128.1	48.9	0	128.1	15.2	14.9	15.3								
3	157.0	106.4	50.6	0	106.4	15.1	15.0	16.1								
4	154.2	108.5	45.7	80	28.5	15.1	15.2	15.1								
5	143.4	100.2	43.2	32.9	67.3	15.1	15.1	15.1								
6	110.9	67.8	43.1	14.1	53.7	15.4	15.1	15.6								
7	100.9	57.9	43.0	28.6	29.3	15.5	15.1	16.4								
8	118.8	68.9	49.9	28.6	40.3	15.3	15.1	15.7								
9	137.4	83.9	53.5	28.6	55.3	15.3	15.2	16.0								
10	131.3	78.2	53.1	28.6	49.6	15.4	15.2	15.7								
11	121.8	70.4	51.4	28.6	41.8	15.6	15.3	16.2								
12	118.3	67.2	51.1	28.6	38.6	15.7	15.3	16.5								
13	117.7	68.8	48.9	28.6	40.2	15.8	15.4	16.5								
14	140.5	97.3	43.2	28.6	58.7	16.0	15.4	19.5								
15	129.3	84.4	44.9	28.6	55.8	16.3	15.5	17.4								
16	128.3	83.5	49.8	28.6	54.9	16.2	15.5	17.2								
17	121.3	73.0	48.3	28.6	44.4	16.2	15.5	17.4								
18	114.2	62.8	51.4	22.8	40.0	16.2	15.6	17.3								
19	113.4	63.2	50.2	51.4	11.4	15.8	15.5	18.4								
20	113.0	62.0	51.0	51.4	10.6	15.7	15.6	17.1								
21	109.4	57.9	51.5	51.4	6.5	15.7	15.6	18.3								
22	112.3	67.1	45.2	62.8	4.3	15.9	15.6	23.2								
23	109.0	67.9	41.1	62.8	5.1	15.8	15.6	20.2								
24	111.3	67.6	43.7	57.0	10.6	15.9	15.7	21.5								
25	99.3	53.6	45.7	45.7	7.9	15.8	15.6	18.4								
26	86.1	33.5	52.6	22.9	10.6	15.8	15.7	17.0								
27	92.5	32.8	59.7	28.6	4.2	15.8	15.7	17.6								
28	95.0	39.9	55.1	28.6	11.3	15.8	15.7	15.9								
29	84.3	24.3	60.0	22.9	1.4	15.8	15.7	21.2								
30	80.3	24.1	56.2	22.9	1.2	15.8	15.7	15.9								
31	88.8	30.0	58.8	28.6	1.4	15.8	15.7	17.2								
September, 1964									Assumed Zero							
1	86.7	26.9	59.8	25.4	1.5	15.8	15.7	22.7								
2	75.1	16.7	58.4	11.4	5.3	15.8	15.6	22.5								
3	63.6	7.3	56.3	5.7	1.6	15.9	15.6	22.5								
4	65.5	8.8	56.7	5.7	3.1	15.8	15.8	19.7								
5	63.5	8.2	55.3	5.8	2.5	15.9	15.9	--								
6	65.2	12.5	52.7	11.4	1.1	15.9	15.9	--								
7	69.2	17.1	51.1	5.7	11.4	16.0	15.9	18.0								
8	65.9	7.1	58.8	5.7	1.4	15.9	15.8	20.0								
9	72.9	11.1	61.8	5.7	5.4	16.0	15.8	17.5								
10	72.4	11.9	60.5	11.4	0.5	16.0	15.8	21.0								
11	78.3	18.5	59.6	11.4	7.1	16.1	15.8	17.4								
12	68.2	11.6	56.6	10.7	0.9	16.0	15.8	18.9								
13	69.2	13.9	55.3	11.4	2.5	16.1	15.9	21.2								
14	66.7	7.3	59.4	0	7.3	16.1	16.0	17.3								
15	63.3	0	63.3	0	0	16.1	16.0	--								
									Assumed Zero							
	26.9	8	17.8	15.7	16.4											
	16.7	5	17.7	15.6	16.1											
	7.3	3	17.7	15.6	15.9											
	8.8	3	17.8	15.8	16.1											
	8.2	3	17.8	15.9	16.2											
	12.5	4	17.8	15.9	16.3											
	17.1	5	17.8	15.9	16.1											
	7.1	3	17.8	15.8	16.0											
	11.1	3	17.8	15.8	16.1											
	11.5	3	17.8	15.8	16.1											
	18.5	5	17.7	15.8	16.2											
	11.6	4	17.7	15.8	16.1											
	13.9	5	17.7	15.9	16.3											
	7.3	3	17.7	16.0	16.2											
	0	0	17.6	16.0	16.2											

(a) MCFS = 10^3 ft³/sec

(b) Values estimated from operating records

TABLE B-111

MEASURED AND CALCULATED HEAT BALANCE DATA
1963 COLUMBIA RIVER COOLING PROGRAM
(Units defined in text)

	MCFS (a)					°C			MCFS (a)		m °C				
	Q _R	Q _s	Q _g	Q _T	Q' _s	T _R	T _g	T' _s	Q _T	Q' _s	D	T' _s	T _g	T _R	
July, 1963	Actual Conditions								Revised to Zero Tube Flow						
10	216.1	150.1	66.0	0	150.1	14.4	14.2	14.5	No Actual Tube Operation						
11	212.0	146.1	65.9	0	146.1	14.4	14.2	14.6							
12	201.8	135.3	66.5	0	135.3	14.4	14.2	14.6							
13	208.2	143.1	65.1	0	143.1	14.5	14.2	14.6							
14	202.8	138.9	63.9	0	138.9	14.5	14.2	14.6							
15	199.1	132.3	66.8	0	132.3	14.6	14.3	14.8							
16	204.1	137.3	66.9	0	137.3	14.7	14.3	14.9							
17	212.0	144.3	67.7	0	144.3	14.9	14.4	15.2							
18	215.7	147.6	68.1	0	147.6	15.0	14.6	15.2							
19	209.1	139.1	70.0	0	139.1	15.1	14.6	15.3							
20	198.5	130.1	68.4	0	130.1	15.1	14.7	15.3							
21	190.3	124.2	66.1	54	70.2	15.1	14.8	15.7	124.2	28	16.1	14.8	15.7		
22	179.3	110.9	67.4	54	56.5	15.1	14.8	16.2	110.9	28	16.2	14.8	15.6		
23	173.9	104.5	69.1	54	50.5	15.1	15.0	15.4	109.5	28	16.3	15.0	15.8		
24	165.9	95.8	70.1	54	41.8	15.5	15.1	16.6	95.8	28	16.4	15.1	15.9		
25	133.0	63.4	69.6	0	63.4	15.4	15.2	15.7	No Actual Tube Operation						
26	121.3	52.2	69.1	0	52.2	15.6	15.4	16.7							
27	125.1	57.1	68.0	0	57.1	15.8	15.4	16.5							
28	126.2	59.6	66.5	0	59.6	16.0	15.3	16.8							
29	125.0	54.9	70.1	0	54.9	16.3	15.6	17.2							
30	124.9	54.3	70.6	0	54.3	16.2	15.6	16.9							
31															
August, 1963										Assumed Zero					
1	121.8	52.5	68.3	0	52.5	16.3	15.7	17.3	No Actual Tube Operation						
2	119.4	50.1	69.3	0	50.1	16.4	15.6	17.4							
3	118.4	52.5	66.9	0	52.5	16.4	15.5	17.3							
4	112.2	49.7	62.5	0	49.7	16.5	15.5	17.8							
5	105.4	44.2	60.8	28.5	15.7	16.4	15.7	21.8	41.2		14	17.1	15.7	16.2	
6	110.3	44.5	65.8	28.5	16.0	16.5	15.7	21.2	44.5		14	17.1	15.7	16.3	
7	109.8	42.5	67.3	28.5	14.0	16.5	15.7	21.8	42.5		14	17.1	15.7	16.2	
8	104.1	32.8	71.3	22.8	10.0	16.4	15.7	22.0	32.8		11	17.6	15.7	16.3	
9	104.7	34.8	69.9	22.8	7.0	16.4	15.7	22.0	34.8		12	16.9	15.7	16.1	
10	103.4	35.0	68.4	22.8	12.2	16.4	15.7	21.8	35.0		12	17.2	15.7	16.2	
11	101.0	33.5	67.5	22.8	10.7	16.4	15.7	23.5	33.5		11	18.3	15.7	16.7	
12	100.7	30.8	69.9	22.8	8.0	16.4	15.9	21.6	30.5		10	19.2	15.9	16.9	
13	99.3	28.8	70.5	22.8	6.0	16.4	15.9	23.8	28.8		9	19.9	15.9	17.1	
14	115.8	44.6	71.2	22.8	19.8	16.4	15.9	20.3	44.6		14	18.7	15.9	17.0	
15	113.8	42.9	70.9	34.2	8.7	16.2	15.8	20.9	42.9		14	18.8	15.8	17.0	
16	112.9	42.2	70.7	34.2	8.0	16.3	15.8	22.4	42.2		14	18.9	15.8	17.0	
17	106.6	39.0	67.6	34.2	4.8	16.2	15.8	25.0	39.0		13	19.5	15.8	17.2	
18	111.8	41.9	66.9	34.2	10.7	16.5	15.8	23.2	44.9		14	19.6	15.8	17.3	
19	107.3	37.9	69.4	34.2	3.7	16.1	15.8	23.8	37.9		12	20.0	15.8	17.3	
20	110.3	39.0	71.3	23.8	5.7	16.2	15.8	20.7	39.0		12	20.1	15.8	17.2	
21	108.5	36.7	71.8	28.5	8.2	16.1	15.7	21.0	36.7		12	20.1	15.7	17.2	
22	103.6	30.4	72.1	28.5	3.0	16.1	15.8	20.6	30.4		10	20.9	15.8	17.3	
23	105.0	34.7	70.3	28.5	6.2	16.0	15.8	20.8	34.7		11	20.6	15.8	17.4	
24	101.0	31.7	69.3	28.5	3.2	15.9	15.8	19.1	31.7		10	20.6	15.8	17.4	
25	88.5	22.9	67.6	17.1	5.8	16.0	15.8	20.9	22.9		7	20.9	15.8	17.5	
26	85.8	15.1	70.7	11.4	3.7	16.0	15.8	20.9	15.1		5	20.8	15.8	16.7	
27	82.0	11.0	71.0	5.7	5.3	16.0	15.8	19.7	11.0		3	20.8	15.8	16.5	
28	79.5	6.7	72.8	0	6.7	16.1	15.9	18.1	(b)		3	20.8	15.8	16.5	
29	76.6	4.7	71.9	0	4.7	16.2	16.0	19.4	(b)						
30	78.6	9.0	69.6	0	9.0	16.4	16.2	18.3	(b)						
31	75.7	11.3	64.4	5.7	11.3	16.4	16.2	19.2	11.3	3	21.1	16.2	16.9		

(a) MCFS = 10³ ft³/sec

(b) No actual tube operation

APPENDIX C

$$F_i = \frac{Q}{W_o D_o^2} \sqrt{\frac{\rho_o}{g \left(\frac{\Delta l}{\Delta d} \right)}}$$

COMPUTATIONS FOR FIGURE 22

Station	A	B	C	D
D _o , ft (Depth to 16.0° Isotherm)	260	230	204	197
W _o , ft (Width @ D _o)	3000	2400	3000	2200
Q, CFS	132,000			
T _o , °C (at D _o)	16.2 °C	16.0	16.0	16.0
D _o ²	6.75 x 10 ⁴	5.18 x 10 ⁴	4.16 x 10 ⁴	3.88 x 10 ⁴
(Y) = $\frac{Q}{W_o D_o^2}$	6.52 x 10 ⁻³	10.6 x 10 ⁻³	10.6 x 10 ⁻³	15.4 x 10 ⁻³
Ts- °C (Surface Temperature)	24.3	23.4	22.9	23.4
l _o	62.365	62.368	62.368	62.368
$\frac{l_s}{\Delta l}$, ft ³	$\frac{62.255}{0.110}$	$\frac{67.264}{0.104}$	$\frac{62.274}{0.095}$	$\frac{62.255}{0.113}$
$\frac{\Delta l}{\Delta d}$, #/ft ²	42 x 10 ⁻⁵	45.2 x 10 ⁻⁵	46.3 x 10 ⁻⁵	57.2 x 10 ⁻⁵
$\frac{l_o}{g \left(\frac{\Delta l}{\Delta d} \right)}$	4560	4280	4180	3360
(Z) = $\sqrt{\frac{l_o}{g \left(\frac{\Delta l}{\Delta d} \right)}}$	68.4	65.4	64.6	58.0
F _i = (Y) (Z)	0.043	0.069	0.060	0.090
$\frac{d_o}{d_o}$ (Debler, Reference (9))	0.43	0.53	0.50	0.60
o/o Depth (from Surface)	0.57	0.47	0.50	0.40
Depth, ft	148	108	102	79
Depth, meters	46	33	31	24

ONSITE DISTRIBUTIONCopy NumberDouglas United Nuclear, Inc.

1	T. W. Ambrose
2	L. B. Brinkman
3	R. E. Dunn
4	S. M. Graves
5	R. T. Jessen
6	O. C. Schroeder
7	W. W. Windsheimer

General Electric Company, Richland

8	R. L. Dickeman
9	M. F. Leverett
10	GETA File Copy

Isochem, Inc.

11	H. P. Shaw
----	------------

Pacific Northwest Laboratory

12	J. P. Corley
13	C. C. Coutant
14	G. M. Dalen
15	R. F. Foster
16	J. J. Fuquay
17	J. B. Goebel
18	F. P. Hungate
19	E. R. Irish
20-49	R. T. Jaske
50	D. E. Jenne
51	R. L. Junkins
52	R. E. Nakatani
53	J. M. Nielson
54	H. M. Parker
55	D. W. Pearce
56	W. B. Silker
57	C. J. Touhill
58	F. W. Van Wormer
59	E. E. Voiland
60	F. W. Woodfield
61-65	Technical Information Files
66-67	Technical Publications

ONSITE DISTRIBUTION (contd)Copy NumberRichland Operations Office

68	R. L. Plum
69	S. M. Rhyneer
70	R. K. Sharp
71	R. D. Wildman
72	Technical Information Library

OFFSITE DISTRIBUTION (Special)No. of Copies

1	American Society of Civil Engineers Technical Publications Department 345 East 47th St. New York, N. Y. 10017
1	AEC Division of Biology and Medicine Attn: Dr. John Wolfe, Chief, Environmental Sciences Branch
2	Atomic Energy Commission, Washington Division of Reactor Development and Technology Environmental and Sanitary Engineering Branch Attn: W. G. Belter, Chief Harold Bernard
1	Bonneville Power Administration P. O. Box 3621 Portland, Oregon 97208 Attn: F. A. Limpert
1	British Columbia Hydro and Power Authority 970 Burrard Street Vancouver 1, B. C., Canada Attn: T. F. Daggs
1	Bureau of Reclamation 6728 Pomona Boise, Idaho Attn: J. C. Peterson
1	Bureau of Reclamation Grand Coulee Dam Grand Coulee, Washington Attn: R. F. Peterman
1	Chelan County Public Utility District Box 1231 Wenatchee, Washington Attn: J. H. Schrengohst

OFFSITE DISTRIBUTION (Special)(contd)No. of Copies

1	Grant County Public Utility District No. 2 Box 878 Ephrata, Washington 98823 Attn: R. R. Ries
1	Illinois State Water Survey Champaign, Illinois Attn: William C. Ackermann
1	Johns-Manville Research and Engineering P. O. Box 159 Manville, New Jersey Attn: C. R. Vander Linden
1	New York State Department of Conservation Albany, N. Y. Attn: N. L. Barbarossa
1	Tennessee Valley Authority 410 Edney Bldg. Chattanooga, Tennessee Attn: Milo Churchill
1	U. S. Army Corps of Engineers, North Pacific Division 417 Custom House Portland, Oregon Attn: David M. Rockwood, Portland District Office
1	U. S. Army Corps of Engineers, North Pacific Division Walla Walla District Office Walla Walla, Washington Attn: Melvin Ord
1	U. S. Corps of Engineers Ohio River Division 550 Main Street Cincinnati, Ohio 45202 Attn: Glenn H. Von Gunten
1	U. S. Department of Interior Bureau of Commercial Fisheries P. O. Box 4332 Portland, Oregon 97205 Attn: L. E. Perry

OFFSITE DISTRIBUTION (Special)(contd)No. of Copies

1	U. S. Department of Interior Bureau of Commercial Fisheries Bldg. 67 Sand Point Naval Air Station Seattle, Washington Attn: G. R. Snyder
1	U. S. Department of Interior Office of Water Resources Research Washington, D. C. Attn: Eugene D. Eaton, Deputy Director
1	U. S. Geodetic Survey Water Resources Division 1305 Tacoma Ave., South Tacoma, Washington 98402 Attn: W. D. Simons
1	Washington State Department of Conservation 335 General Administration Bldg. Olympia, Washington Attn: M. G. Walker
1	Washington State Pollution Control Commission Public Health Bldg. Olympia, Washington Attn: A. T. Neale
1	Washington State University Albrook Hydraulics Laboratory Pullman, Washington Attn: E. Roy Tinney
1	Water Pollution Control Administration Robert A. Taft Center 4676 Columbia Parkway Cincinnati, Ohio Attn: J. M. Symons
1	Water Pollution Control Administration Columbia Basin Project 570 Pittock Block Portland, Oregon 97205 Attn: W. W. Towne
1	Water Resources Research Institute Oregon State University Corvallis, Oregon Attn: Malcolm H. Karr