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GENERALIZED RIVER MODEL TESTS WITH HEATED EFFLUENT
AT BONNEVILLE HYDRAULICS LABORATORY.

AUTHOR

J.P. Corley

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GENERALIZED RIVER MODEL TESTS WITH HEATED EFFLUENT

AT BONNEVILLE HYDRAULICS LABORATORY

INTRODUCTION

The distribution of the heated effluents discharged by Hanford reactors to the Columbia River has been a matter of interest since the early design stage of the first reactors. The pattern of this distribution is a major factor in determining the extent to which a downstream reactor is affected by those upstream, as well as the localized effects on the ecology of the river. Pollutational characteristics of the effluents are three -- heat load (or temperature increase), chemical content, and radioactivity. The latter has received the greatest attention in connection with potential personnel exposure and effects on river biota; it has been assumed, however, and generally confirmed by sampling that the measure of distribution of any one of these characteristics is the same as for the others. Observed distributions of radioactivity for various river and reactor flow rates are documented in references (1) and (2). Unfortunately, any extrapolation of these observed distributions to altered flow conditions of river regimes is of questionable validity. Mathematical models of the problem have been formulated^(1, 3) but have been of little value due to the necessity of measuring certain parameters under the conditions for which a solution is desired. Even so, calculated distributions provide only general patterns and would not be expected to provide quantitative data where local disturbances intervene, as is the case at the reactor intakes and around many of the river islands. The desirability, or even necessity, of using a river scale model for investigations of potential flow and river conditions has been discussed a number of times in the past several years, particularly in connection with establishing a minimum acceptable river flow for dilution of Hanford effluents. The necessary funds have not been available, however.

In October 1957, the Atomic Energy Commission requested that General Electric Company evaluate the effects of a proposed dam at Columbia River mile 348. In order to do so, certain assumptions had to be made as to the hydrologic effects of damming the river, thereby increasing the water depth and decreasing the velocity⁽⁴⁾. When re-evaluation of a revised dam proposal was requested in April 1958⁽⁵⁾, time again did not permit construction of a model of the Hanford Works portion of the river. However, the Corps of Engineers had become directly interested and testing of the Ice Harbor Dam model had just been completed at their Bonneville Hydraulics Laboratory. Upon inspection, it was apparent that a portion of the modeled river bed could be quickly modified to a generalized representation of the portion of the river within the reactor areas of greatest concern. Use of the model facilities at Bonneville was therefore requested through the Hanford Office of the Atomic Energy Commission and agreed to by the Seattle Office of the Corps of Engineers. It was recognized from the start that quantitatively test runs would not apply to Hanford conditions. It was hoped, however, to be able to demonstrate qualitatively certain effects of the dam and perhaps determine the most important variables, as well as to demonstrate the consistency of results from such a model study.

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SUMMARY

In an attempt to verify some of the assumptions made for a previous report regarding hydrologic effects of the proposed dam, a limited study of the behavior of heated effluents in a generalized river model was performed at the Bonneville Hydraulics Laboratory of the Corps of Engineers. In view of the limited time, no attempt was made to simulate the reach of the river through Hanford Works, although there was a general similarity of slope and width-depth ratio to a portion of the river within the plant boundaries. A series of tests was performed using a scaled outfall line and river pumphouse forebay and intake. Although the lack of similitude to our portion of the river prevents quantitative application of the test results to Hanford plant conditions, certain general effects of dam pooling were readily and consistently demonstrated. Results and conclusions were as follows:

1. All of the variables investigated--river flow, pool elevation, effluent-intake distance, and effluent temperature--showed consistent and presumably significant effects on the fraction of effluent taken in and consequent temperature at the intake.
2. Stratification of the heated effluent became very marked with increasing pool elevation.
3. The meander pattern of the main current stream was affected at all pool elevations, the oscillations from bank to bank being reduced in amplitude and lengthened as the pool level was raised, regardless of flow rate. The effect of this change could be favorable or unfavorable, depending on whether the main current stream were changed to give more or less impingement on the forebay opening.
4. Forebay design appeared to be critical in determining the amount of uptake of effluent where stratification occurred. With a forebay excavated to sufficient depth and sufficient length into the river, the tendency would be to draw colder bottom water into the intake without disturbing the warmer surface layers.
5. Below a certain critical water velocity dependent on both flow rate and pool elevation, severe surface eddying appeared around the outfall location. If this should occur at one or more of the HAPO effluent outfalls as a result of dam pooling, spur dikes or jetties might be required to prevent recirculation of effluent into the forebay of the same area.
6. The net effect of stratification and change in velocity pattern on the plant for any actual river situation cannot be reliably predicted from these test results.
7. The general problem is capable of solution by a model study; given an accurate model of our reach of the river, there is little doubt that the hydrologic effects of a dam could be reliably predicted.

PROCEDURE

The model bed, as modified, had a transverse profile, longitudinal slope, and depth-width ratio approximating that of a typical section of the river between two of the HAPO reactor areas (see Figure 1) at an undistorted linear scale ratio of 1:150.

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To further the similitude, typical effluent lines and an intake structure were modeled to the same scale and inserted at a scaled distance typical of reactor spacing, as well as about half this distance. The primary effect to be investigated was the increase in temperature at water plant intakes. Apparatus for heating the model effluent stream consisting of a steam supply and mixing chamber was therefore provided. (see Figure 2) After starting up each day and reaching stability, an effluent temperature stable to within $\pm 0.1^\circ \text{F.}$ during a test run was maintained. The intake stream was taken off by a proportioning pump from a pump well behind the scaled intake openings (see Figure 3).

River flow was measured through a calibrated orifice and passed over a level sill from an entrance sump in order to obtain uniform velocity distribution at the beginning of the modeled section. Effluent and intake flows were calculated from flows through calibrated V-notch weirs, with heights in the weir-boxes read to ± 0.001 inches by means of verniered bayonet gauges (see Figure 2). These flows were maintained constant throughout the series of test runs at flows approximating typical plant flows properly scaled. Pool elevation was controlled by the outlet sump overflow sill which could be raised or lowered to the desired elevation. Temperatures were read with resistance temperature elements (see Figure 3). Detectors were mounted in the intake, in the river above the effluent, and at surface and bottom at two locations in the stream opposite the intake; a portable detector was used for surface and bottom temperatures at three other locations opposite the intake. Effluent temperature was taken and other temperatures spot-checked with certified hand thermometers. All RTD elements were read at a central amplifier bank both on individual meters and from traces on photo-sensitive paper. Each element was zeroed and checked against a calibration setting just before each reading. Temperatures were read as departures from the base river temperature to $\pm 0.01^\circ \text{F.}$, which approximated the instrument accuracy. Probe placement was quite critical, however, especially where stratification occurred. Partial exposure to the air or contact with the model bed also introduced occasional errors in temperature readings. Dye solutions were furnished for visual observations of dilution patterns. They could be added to the effluent mixing box or spotted at critical locations for more localized observation.

Test procedure was as follows: Water and steam control valves were adjusted to give the proper flows at a stable effluent temperature between 200 and 205°F. Simulated river flow was adjusted by means of the inlet orifice and control valve, and pool elevation set by adjusting the outlet sill height. Intake temperatures were then checked periodically. When effluent and intake temperatures had been stable for at least an hour, all temperatures were recorded. Dry and wet bulb thermometer readings were also taken in the building. The average temperature of the stream at the intake was estimated from the profile points and used to calculate a heat retention factor. An uptake fraction (k) was then calculated using the formula:

$$\rho_1 \cdot Q_1 \cdot (T_1 - T_r) = k \cdot \rho_e \cdot Q_e \cdot (T_e - T_r) \cdot f_q$$

where Q_1, Q_e = intake and effluent flow rates, respectively.
 T_1, T_e = intake and effluent temperatures, respectively.
 ρ_1, ρ_e = intake and effluent densities, respectively.
 T_r = temperature of stream above the effluent.
 f_q = heat retention fraction.

After recording the data, dye was generally injected for visual observation of flow patterns.

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Time did not permit more than simple paired observations. The factors investigated and the arbitrarily selected values were:

- a) River flows - 36,000 and 60,000 cfs
- b) Effluent temperature - 150° F. and 205° F. (maximum stable temperature available)
- c) Distance between outfall and intake - 9000 feet and 17,000 feet
- d) Pool elevation - normal river and 385 ft. MSL (also 400 ft. MSL for $Q = 36,000$ cfs)

DISCUSSION

Table I shows pertinent test data, calculated heat retention factors, temperature increase in the pump intake, and calculated uptake fractions. The degree of reproducibility of the data is indicated by double runs 9 and 10. Uptake fraction is shown graphically for all runs in Figure 4. Degree of stratification is shown in Figures 5, 6, and 7. Due to the limited number of point temperatures measured, the heat balances are of questionable accuracy, but undoubtedly some heat losses did occur. The major source of heat loss was the escape of steam (usually visible) at the effluent line opening, with partial compensation by conduction from the surroundings. The size of the latter correction was found with a cold run to be 70.7° F. with an air-water differential of 15° F. No consistent pattern of heat loss was found either for model test data or air temperature data. The size of the potential error involved is believed to be sufficient to reverse the trends shown in Figure 4 for runs 10 and 11 only.

As stated above, it was not expected that the results of the tests could be used quantitatively. It is noteworthy, however, that at normal river levels practically no thermal stratification was observed, as is actually the case with the prototype. In contrast, Figures 5 - 7 show the pronounced stratification that could occur with sufficiently high pool levels and consequent low water velocities.

Further verification, or at least qualitative demonstration, of prototype behavior was provided by the flow pattern observed in the scaled forebay. Surface circulation in the forebay was observed overlying sub-surface flow into the submerged pump intake. This pattern can generally be observed in existing reactor intake forebays, as demonstrated by results of a recent survey (see Figure 8).

The depth of excavation of the forebay channel and the distance from the forebay opening to the pump well opening appeared to be critical parameters in determining the extent of dye pickup.

Referring to Figure 4, all four variables investigated—river flow rate, pool elevation, effluent temperature, and distance between outfall and intake—seem to be significant. Presumably, flow rates of effluent and intake would similarly be significant variables. The reversal of slope between 36,000 cfs and 60,000 cfs runs is presumably characteristic of the model and may not be duplicated in the prototype, likewise the relative position of the curves for 9,000 feet and 17,000 feet distance. The particular model used (see Figure 1) had a gentle uniform curve between intake

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TABLE I

MODEL TEST DATA

Run	Qr River Flow cfs	Tailwater Elevation Feet-MSL	L Effluent Intake Dist.-Ft.	Prototype Quantities			fq Heat Reten. Factor	Air River ΔT -°F	
				Te Effluent Temp. °F.	(T _i - T _r) Increase in Pump Intake Temp. - °F.	k Uptake Fraction			
1	36,000	376.5 (Nor)	17,000	204.	3.04	0.0109	0.95 (3)	16.4	
2	36,000	385.3	17,000	204.6	2.04	0.0085	0.84 (4)	16.0	
3	60,000	378.9 (Nor)	17,000	200.	0.64	0.0031	0.73 (4)	9.7	
4	60,000	385.7	17,000	204.8	1.40	0.0061	0.79 (4)	15.8	
5	36,000	400.5	17,000	202.	1.51	0.0067	0.78 (10)	4.3	
6	36,000	376.5 (Nor)	17,000	154.	2.72	0.0163	0.86 (10)	5.1	
7	36,000	385.3	17,000	152.	1.84	0.0126	0.77 (10)	5.2	
8	36,000	376.5 (Nor)	9,000	204.5	3.84	0.0139	0.96 (10)	20.2	No upstream eddy
9	36,000	385.3	9,000	204. 204.5	1.96 2.00	0.0086 0.0110	0.73 (10) 0.63 (10)	25.2 18.5	a) Different days b) Eddy upstream-400 ft.
10	60,000	378.9 (Nor)	9,000	A) 204. B) 204.	2.54 2.40	0.0109 0.0084	0.81 (10) 0.99 (10)	13.2 13.1	With and without upstream diffuser
11	60,000	385.7	9,000	206.	2.30	0.0111	0.59 (10)	10.7	
12	36,000	400.5	9,000	204.	0.80	0.0026	1.08 (10)	21.6	Eddy upstream 800 ft.

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and outfall for 9,000 feet separation; at 17,000 feet, however, a reverse curve intervened, giving the river an S-shaped travel between the two points. The effect of the curvature on the meander pattern of the main current and on the degree of effluent dispersal was pronounced. The effect on uptake fractions might well be reversed for any other stream topography.

A literature search on the general problem of thermal stratification in streams and reservoirs had revealed a pertinent study of interest and potential concern by Bata⁽⁷⁾, whose work has demonstrated the possibility of decided upstream movement of heated effluents and consequent recirculation. Such a phenomenon, at present unknown at Hanford, would be of real significance if it occurred. Dye tests made with the model showed that such an occurrence was indeed possible with mean river velocities below a certain critical point. In the model, this point lay between that corresponding to normal river flow and a pool elevation of 385 feet MSL for a flow of 36,000 cfs in Table I. Critical points for the prototype are unknown; the critical distance for any given river flow will be at a different river elevation.

Dr. E. R. Tinney, Head, Albrook Hydraulics Laboratory, Division of Industrial Research, Washington State College, was retained as a consultant for the interpretation of the model tests and assistance in translating the results to the specific Hanford problem under investigation. Pertinent extracts from his report⁽⁶⁾ pertaining to this study are given below, and pertaining to the general problem of using river models for density current investigations in Appendix A.

"III B. Reliability and Adequacy of the Tests

The model studies described above appeared to be consistent within themselves. Furthermore, they indicated, qualitatively at least, the behavior of the hot effluent under several conditions. The model techniques employed followed modern practices. The temperature control and measuring systems were excellent.

Because of the shortage of time only a limited number of tests were made. Nevertheless, the test program was designed to provide a sufficient amount of data to present the significant aspects of the effluent behavior. One shortcoming of the model study was the excessive heat loss from the system during the tests. It can be shown by dimensional analysis that the temperature drop in a model not specially insulated is magnified by a factor of the order of the square root of the linear scale ratio. This temperature drop was noticeable in the model tests. If more time were available provision could have been made for insulation of the model to keep the model and prototype data in closer agreement.

D. Interpretation of the Test Results

Because of the limited extent of the test program, the small scale of model, the large heat loss in the model, and the idealized conditions, it is not possible to make quantitative predictions from these tests. However, some general conclusions can be made.

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1. Increasing the depth of flow permits greater temperature stratification. However, because changes in depth distort the secondary current pattern, it is not possible to state categorically whether or not the temperatures at the bed will be increased or decreased. Indeed, the model studies show increases in some cases and decreases in others.
2. The heat loss from the prototype would probably be slightly increased by increasing the depth. This temperature increase was quite pronounced in the model but it must be remembered that a 1:150 model will exaggerate the temperature drop by a factor of about 12 unless special precautions are taken to insulate the model. Heat balances in the prototype can be best arrived at by a program of computation and field verification.
3. The upstream motion of the effluent is in accord with the description of the recirculation phenomenon described by Bata.⁽⁶⁾

E. Application Test Results to the Prototype

Even though these model studies cannot provide specific answers to the problems at each site, they do serve as a guide for the assessment of the effects of creating a reservoir. If the reach of river is quite uniform and straight, it can be expected that stratification would take place and that the bed temperatures would be decreased. On the other hand, if the river is tortuous the conservative approach would be to assume that a reservoir would alter the secondary pattern and bring higher temperature water to the next intake. Specific answers can only be arrived at by a detailed study of the river configuration at each site.

In locations where the river is sluggish, increasing the depth may lead to upstream currents that will travel several hundred feet. Under such circumstances, water at highly elevated temperatures may re-enter the same plant from whence it originated."

ACKNOWLEDGEMENTS

G. W. Knoeber, HOO-AEC, and R. A. Skrinde, Seattle Office, Corps of Engineers, were co-workers in arranging for and conducting the tests. The cooperation and guidance of H. P. Theus, Director, Bonneville Hydraulics Laboratory, Corps of Engineers, and his staff were of major importance in successfully completing the test program in the time allotted.

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APPENDIX A

EXTRACT - "Consultant Engineering Report - A Preliminary Study of the Effluent Discharge Problem at Hanford", E. R. Tinney, May 31, 1958.

SOLUTION OF THE EFFLUENT DISCHARGE PROBLEM
WITH HYDRAULIC MODELS

"General

A categorical answer as to the effect of a reservoir on effluent circulation cannot be given because of the complex nature of rivers and reservoirs and because of the lack of precise methods of predicting their behavior. The only acceptable engineering procedure existing today for solving river control problems is the use of hydraulic models. The theory of models, the laws of similitude, and the techniques of modelling have been developed over several decades. Despite this wealth of background, a model study must be confined to the finding of a specific item of information for which the model was designed. For example, separate models to find the coefficient of discharge of a spillway, or the erosion at the toe of a dam, or the head loss in a penstock may be readily used but a single general model to investigate these items simultaneously is impossible. Nevertheless, within the known limits of application, models are extremely useful tools.

Model Studies of Density Currents

Every model must be built and tested according to a particular model law. In the case of river models, as in the case of most open channel models, the primary agents affecting the flow pattern are gravity and inertia forces. Under these circumstances the Froude Law, which states that the ratio of the gravity to inertia forces in the model must be the same as in the prototype, is used. This is achieved if the ratios of the discharges in model and prototype vary as the $5/2$ power of the linear scale ratio. However, in doing so, certain other laws are violated. In particular, the effect of viscosity is ignored. Despite this shortcoming, it has been demonstrated repeatedly that river models on a sufficiently large scale give reliable answers.

The model study discussed in this report⁽⁶⁾ was a river model operated according to Froude's Law. However, a further complication was introduced by the addition of the density current phenomenon. The question immediately arises as to whether or not Froude's Law is applicable under these circumstances. On the one hand density currents are the result of gravity and inertia forces so that Froude's Law applies as long as the relative densities of the warm and cool fluid remain the same in the model and prototype. This can be readily accomplished by using the same fluids at the same temperatures. On the other hand, Keulegan has shown that the stability of the interfaces between the warm and cool fluid is a function of viscosity. Since an unstable interface would

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lead to turbulent intermixing of the warm and cool fluids, the question of the correctness of model law is extremely important in the evaluation of the model data. At the present time there does not seem to be a completely satisfactory answer to this problem of model laws. Several recent papers by Keulegan and others show considerable promise, however, for future development of model laws for density currents.

Further Studies

Before final decisions are reached on the remedies to be employed, it is not only desirable but imperative that model studies be undertaken and that adequate field data be obtained to verify the behavior of these models. Two types of model studies should be considered. The first is a small scale (large numerical ratio) general model of the entire reach of river affected by the Hanford plants and the second are large scale (small numerical ratio) local models of particular sites. For the general model, consideration should be given to a small degree of distortion. The local models should be undistorted. Along with these models some basic problems on density currents should be investigated in a glass-sided flume to verify certain aspects of the model laws."

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MODEL PLAN & PROFILE

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FIGURE 2. Model Equipment - Effluent End Looking Upstream

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LEGEND

A. Steam Mixing Box	F. Temperature Sensing Elements
B. Bayonet Gauge	G. Intake
C. V-Notched Weir Box	H. Intake Pump
D. Effluent Line	J. Tailwater Elevation Control
E. Diffusion Dam	Sill

FIGURE 3. Model Equipment - Intake End Looking Downstream

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FIGURE 4

EFFLUENT UPTAKE FRACTION

() - run number

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FIGURE 5
TEMPERATURE PROFILES
RUNS 1, 2, 3, 4, 5
O-Surface
x-Bottom
E-Intake

Temperature Increase - T .

Temperature Increase - T .

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FIGURE 7
TEMPERATURE PROFILES
RUNS 6, 7

○ - Surface
x - Bottom
□ - Intake

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FIGURE 8

TYPICAL FOREBAY FLOW PATTERN

Scale - None

○ No measureable current (< 0.1 Feet Per Second)

1.5-2.5 Indicates approximate range of river flows (surface through bottom), in units of Feet Per Second.

--- ➔ Indicates subsurface current only.

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