Attachment 3

APPENDIX 5A

REPORT

ON

THERMAL PLUME INVESTIGATIONS

FOR UNION ELECTRIC COMPANY'S

CALLAWAY PLANT, UNITS 1 AND 2

BY

BARRY A. BENEDICT, Ph. D.

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Sverdrup & Parcel and Associates, Inc.

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INTRODUCTION

This report presents data developed to study the discharge of waste heat from the proposed Union Electric Company's Callaway Plant into the Missouri River. The waste heat will be contained in the blowdown water from the plant operating with a closed-cycle cooling water system featuring cooling towers.

Table 1 gives the basic data used for the study. Note that values for both mechanical-draft and natural-draft cooling towers are given. When this study was commissioned, it had not been decided which type of cooling tower would be used. Consequently, analyses were made of the most extreme conditions presented by both cooling tower schemes. Since a final decision has now been reached to use natural-draft cooling towers, the results of this study are overly conservative for those cases where mechanical-draft cooling tower data was used.

In the following pages, the mathematical model to be employed for plume predictions will be described and its limitations noted. Then, the results of analyses made using this model to assess the extent of the effect of the proposed discharge will be presented. Areas, volumes, and distances for the 2°F, 3°F, and 5°F isotherms (among others) will be shown.

These results will be reported for extreme winter conditions with the 10-year, 7-day low flow in the river and for extreme summer conditions with the highest anticipated river temperature.

Also presented is an analysis indicating how close the discharge may be placed to the intake without causing entrainment or recirculation of heated water.

TABLE I

BASIC DATA FOR BLOWDOWN DISCHARGES FROM
MECHANICAL-DRAFT AND NATURAL-DRAFT COOLING TOWERS

Month	Average Missouri River Temperature, T_a °F	Mechanical-Draft Cooling Tower Blowdown		Natural-Draft Cooling Tower Blowdown	
		Q_p, gpm	T_o, °F	Q_p, gpm	T_o, °F
January	35	7140	76.0*	6860	65
February	36	7260	76.3	7000	65
March	41	7600	78.7	7540	69
April	55	8140	80.8	8120	76
May	67	8540	85.0	8520	81
June	76	8940	88.8	8920	86
July	81	9140	89.9	9120	88
August	80	9060	89.8	9080	88
September	72	8740	86.3	8800	84
October	61	8260	82.0	8280	78
November	47	7660	78.4	7600	70
December	36	7260	76.4	7000	65

Note: *76.1°F by calculation

Q_p = flow rate of discharge water

T_o = temperature of discharge water

MODEL SELECTION AND DESCRIPTION

In order to predict the extent of the proposed discharge thermal plume, it is necessary to utilize a reliable mathematical model of the discharge phenomenon. In this case, the discharge is fully three-dimensional, and the river (ambient) current is quite strong.

There is no generally available mathematical model for heated discharges shown to be satisfactorily applicable to a fully three-dimensional, heated water discharge into a strong current without use of field data from a similar discharge (1,2). If a similar discharge into a similar flowing environment exists at a similar site, then some three-dimensional models exist to provide adequate predictions. In such case, the model is fitted to the similar site data to evaluate coefficients, and then this information is used to make predictions for the proposed site. Existence of such data makes it possible to place some confidence on predictions from any model. However, for the current case, data for a similar site and discharge on the Missouri River are not available, and hence three-dimensional models are not applicable. For this reason, a model was chosen for a two-dimensional discharge (i.e., one where only lateral mixing occurs, with no vertical mixing). Such a model should yield conservative results, inasmuch as vertical mixing is neglected. In short, while a three-dimensional model would be preferable, a two-dimensional model is more reliable for simulating the discharge phenomenon. Additionally, its conservative properties (predictions of plume behavior is maximized with respect to the area enclosed by an isotherm) lend themselves to establishing design criteria.

The model selected for use is the one developed by Motz and Benedict (3,4) and verified with laboratory and field data. The major model assumptions are shown in Table 2. Using those assumptions, along with the principles of conservation of mass, momentum, and energy, one can formulate a set of six differential equations describing the structure of the jet. These are solved simultaneously (by numerical methods on the digital computer) to find the six unknowns as a function of the distance along the jet centerline axis. The six unknowns are the x and y coordinates of the jet centerline, the angle of the jet axis with respect to the ambient current, the jet half-width, and the jet centerline velocity and temperature rise. The reader is referred to References 3 and 4 for details of the model.

To operate the model, one needs some knowledge of the initial, transition region called the zone of flow establishment (specifically, the length of this zone and the angle and size of the plume at the end of this zone). It should be noted that, due to Assumption 5 on Table 2 (similar profiles), the numerical solution generated applies only to the zone of established flow (ZOEF), or the region where such similar profiles would exist. A zone of flow establishment (ZOFE) also exists. Here, at the point of jet exit from an orifice, the initially uniform profiles are converted to the profiles of the ZOEF by mixing with the ambient receiving waters. As a result, the mathematical solution must start at the end of the ZOFE, which is also the beginning of the ZOEF. Therefore, in order to completely describe the impact of any discharge, one must know the length of the ZOFE and the angle of the jet axis at the end of the ZOFE. This angle will be the one used to initiate the numerical solution in the ZOEF. Reference 3 and 4 present empirical evidence for definition of the angle and length of the ZOFE.

One can define the plume width at the end of the ZOFE rather simply. Application of the principle of conservation of heat flux along the ZOFE yields

$$b_o = 1.60 b_o' \tag{1}$$

in which b_o = jet half-width at the end of the ZOFE

b_o' = jet half-width at the orifice

According to Yevjevich (6), the entrainment characteristics of a square jet approximate the entrainment characteristics of a circular jet if the cross-sectional areas of the two orifices are equal. Use of this assumption and Equation 1 enables one to derive a relationship between the circular diameter, d_o, and b_o.

$$b_o = 0.709 d_o \tag{2}$$

in which d_o = diameter of circular orifice

Therefore, necessary information on the ZOFE can be furnished to the model by finding the length and angle at the zone's end from Reference 3 or 4 and by using Equation 2 to define the half-width, b_o.

To generate a solution for a specific case, other input data are required. A summary of required input data appears in Table 3, which also lists expected output from the numerical solution. One important value

TABLE 2

MAJOR MODEL ASSUMPTIONS

1. All flows are steady.

2. The jet is two-dimensional, i.e., there is no vertical entrainment.

3. Turbulent mixing into the jet can be represented by entrainment, or an inflow velocity across the jet boundary, this velocity being expressed as a coefficient, E, times the vector difference of the jet and ambient velocities.

4. Changes in density along the jet axis are small compared to a reference density. Thus, inertial terms from density gradients are negligible, and mass flux terms can be replaced by volume flux terms.

5. Profiles of the normal jet axis velocity and temperature are similar along the length of the jet axis; the Gaussian profile is chosen for both. Morton (5) states that, assuming similar profiles and the form of the inflow, velocity suppresses analytic solutions of the details of the jet's lateral structure. Therefore, any reasonable shape can be assumed; however, available evidence implies that the Gaussian is more descriptive of the lateral profile.

6. Separation of the ambient flow around the jet can be represented by a drag force expressed by a drag coefficient, C_D, times an appropriate velocity head.

7. Heat loss across the air-water interface can be expressed by an equilibrium temperature format. It is known, however, that such surface cooling has negligible influence on the surface areas within higher excess temperature isotherms, and, hence, surface cooling will be taken as zero in this work.

8. The jet is discharged into a uniform ambient velocity field.

9. The values of E and C_D for any given case will be taken as constant along the entire length of the jet.

not cutput in the computer solution is the volume within a given isotherm. Later discussions will show how the model results can be used to obtain estimates of the desired volumes.

This model has certain limitations, pertinent to the current study, which should be stated at this time. Any model has such limitations, and recognition of them may prevent mistakes in using the model and in interpretation of results. Table 4 summarizes these limitations.

The net effect of the limitations, shown in Table 4 for the cases to be studied herein, will be to make the actual areas smaller than those predicted by the model. Category A factors will be the dominant ones, especially item 2. For the 2°F and 3°F results to be reported, Item 1 will be a major factor also. It is possible that these limitations could mean that the expected area would be less than one-half the area predicted by the mathematical model. This is acceptable since it is conservative.

TABLE 3

REQUIRED INPUT DATA AND
EXPECTED OUTPUT FOR MODEL

INPUT DATA

b_o = jet half-width at end of ZOFE (from Equation 2)

B_o = angle of jet axis at end of ZOFE

U_o = initial jet velocity

$k = U_o/U_a$ = velocity ratio, where U_a = ambient velocity

$C_D' = C_D/4E$, where C_D = drag coefficient

E = entrainment coefficient (see reference 1 and 7 for guidance in selection of E and C_D)

MODEL OUTPUT

Coordinates of jet centerline

Jet half-width as it varies along the jet axis

$\triangle T_c/\triangle T_o$ = jet centerline excess temperature ratio as it varies along the jet axis, where $\triangle T_c$ = excess temperature at any point on axis and $\triangle T_o$ = initial excess temperature

Jet centerline velocity as it varies along the jet axis

Angle between jet axis and ambient current as it varies along the jet axis

Surface area enclosed within selected isotherms

Coordinates to enable plotting of selected isotherms on the surface

Maximum widths of selected isotherms

TABLE 4

MODEL LIMITATIONS

A. FACTORS TENDING TO MAKE AREAS SMALLER THAN THOSE PREDICTED

1. For excess temperatures (plume temperature minus ambient temperature) below about 3°F, the vertical gradient is no longer strong enough to inhibit vertical mixing, and this mixing will cause a more rapid temperature decrease than predicted by the model.

2. For initial jet densimetric Froude numbers (F_j) greater than about 4-5, initial vertical mixing increases greatly (unless limited by a bottom boundary), and, hence, temperature decrease is more rapid than predicted.

3. If the jet is submerged below the water surface at least 1-2 diameters, mixing will be increased because the jet entrains water along its upper surface as well as along its sides and bottom.

B. FACTORS TENDING TO COUNTERBALANCE INCREASED MIXING AND/OR TO INTRODUCE ADDED UNCERTAINTY

1. Bottom interference will counterbalance effects of item A-2 above. This may be a factor if the pipe is placed quite near the river bottom.

2. For lower river velocities (less than about 20 percent of the jet initial velocity), values for the entrainment coefficient employed in the model are less certain.

In these discussions, the term F_j, the initial jet densimetric Froude number, is defined by

$$F_j = \frac{U_o}{\sqrt{g \frac{\Delta p}{p} d_o}}$$

in which p = ambient fluid density
P_1 = initial jet density
$\Delta p = p - p_1$

SPECIFIC CASES STUDIED

Goals for the Callaway Plant thermal plumes analyses are:

1. To assess the possibility of the mixed (average) river temperature being elevated more than 5°F above the ambient temperature and, in addition, to determine the river areas and volumes elevated 5°F, 3°F, and 2°F above the ambient.

2. To determine the possibility that the mixed river temperature will exceed 90°F and to evaluate water areas and volumes that may exist at temperatures greater than 90°F.

An alternate goal involves an assessment of the possible impact of the proposed intake on the discharge plume.

Basic Data for Analyses

There are several basic uncertainties in terms of available data applying to any analyses conducted here. Basic data on river rating curves and channel cross-sections were furnished to this writer by Sverdrup & Parcel as they had been received from the Corps of Engineers. Due to the shifting nature of the river bottom in the Missouri River, the exact cross-sectional area for any given river flow will vary from one time to another. Such uncertainty leads to uncertainty in the ambient river velocity distribution and magnitude, U_a, a major input parameter to the mathematical model. Although this uncertainty may lead to problems in interpretation of results, efforts have been made to bracket expected variations.

Earlier model results for a wide variety of cases led to selection of a 24-inch diameter discharge pipe oriented at a 90° angle to the ambient flow. The runs made represented a number of combinations of pipe diameter, plant discharge, river velocities, and other pertinent parameters. These earlier runs provided a basis for better understanding of the system. On the basis of these findings, this writer was advised (8) to proceed on the basis of analyzing a 24-inch diameter discharge pipe.

For convenience, the basic input data for all three cases studied are listed in Table 5. The basic model input data are derived from the flow rate and temperature information shown in Table 6. The uses and development of these data will be discussed in the following sections.

TABLE 5

BASIC INPUT DATA FOR
ANALYSES OF PARTIAL-DISCHARGE CASES

Case No.	$A=\frac{1}{k}$	U_o, ft/sec	U_a ft/sec	b_o, ft	E	ΔT_o, °F	F_j
1	0.358	5.59	2.0	1.418	0.4	41.1	13.3
2	0.710	5.59	3.97	1.418	0.4	41.1	13.3
3	0.457	7.44	3.4	1.418	0.4	8.0	24.8

Note: b_o = 1.418 ft corresponds to d_o = 24 inches. See Table 3 for other term definitions.

TABLE 6

BASIC TEMPERATURE AND FLOW
DATA FOR PARTIAL-DISCHARGE CASES

Case No.	Q_p, gpm/cfs	T_o, °F	Q_a, cfs	T_a, °F
1	7885/17.6	76.1	8,460	35.0
2	7885/17.6	76.1	8,460	35.0
3	10,500/23.4	95.0	35,000	87.0

Note: T_a = ambient river temperature

T_o = temperature of discharge water

Q_a = ambient river flow rate

Q_p = flow rate of discharge water

Low-Flow Investigations

The first goal of this study is the evaluation of how far above the ambient the Callaway Plant discharge may elevate river temperatures. It will be shown that the affected river water areas and volumes are very small, even for critical conditions.

Critical Conditions - Maximum areal and volumetric extent should occur at times of low river flow. For the analyses, the 10-year, 7-day low flow was chosen. Stage curve data developed by Dames & Moore estimated this flow to be 8460 cfs, giving a water surface elevation of 490.5 ft at River Mile (RM) 115.0.

This low flow is expected to occur during the winter months, and Table 1 shows that the critical plant discharge conditions occur in January. Combining the most extreme flow and temperature data shown for January in Table I, the ambient river temperature, T_a, is 35.0°F, the plant discharge, Q_p, is 7,885 gpm (17.6 cfs), and the plant discharge temperature, T_o, is 76.1°F; this yields an initial excess temperature, $\triangle T_o = T_o - T_a = 41.1°F$. The two unit plant flow rate, Q_p, is the sum of the twice the mechanical-draft cooling tower blowdown shown in Table 1 and all other plant waste flows. These other waste flows are assumed to have the same temperature as the blowdown.

Mixed Temperature - A first check on the discharge effect under these critical low-flow conditions can be made by using a simple heat balance to compute what temperature would result from the complete mixing of the heated discharge water and the ambient river flow. The basic equation for calculating this mixed temperature states that the heat flow upstream from the plant, plus the heat flow from the plant, must equal the heat flow downstream from the plant. Using this relationship, and neglecting density differences (as these will be small compared to temperature differences) one obtains equation 3.

$$T_{mix} = T_a + \frac{Q_p}{Q_a} \triangle T_o \qquad (3)$$

in which T_{mix} = average river temperature after complete mixing

Application of Equation 3 for the current case yields a value of T_{mix} = 35.158°F, or an increase in temperature of only 0.158°F. Therefore, the impact of the projected heat load on the overall river temperature is almost negligible.

The jet model described earlier can be used to predict the thermal plume in these low-flow conditions.

Application of Jet Model - Evaluation of U_a, the ambient river velocity, is necessary for application of the jet model. Planimetering the cross-sectional area from charts furnished (8) with a water elevation of 490.5 ft yields an area of 2,130 ft^2; hence U_a = 3.97 ft/sec. However, due to the shifting bottom of the Missouri River, somewhat different velocities may be expected. Higher values of U_a are not of interest here, as they would imply enhanced mixing. Corps of Engineers personnel indicated they thought the river velocity would not fall below 2 ft/sec. A value of U_a = 2.0 ft/sec for this flow yields a cross-sectional area of 4,230 ft^2. Cases 1 and 2 were studied to determine discharge performance for these two U_a values in the belief that these cases would bracket expected performance. The data used for these cases appear in Tables 5 and 6.

Important results from Case 1 and 2 analyses appear in Table 7 and in Figures 1, 2, and 3. Notice that no figures are included for Case 2, as Case 1 is the limiting condition, and results from Case 2 merely show much smaller areas and volumes (30-40 percent of those in Case 1). There is no reason to expect results for intermediate velocities to differ appreciably because (1) the value of $A=\frac{1}{k}$ is greater than 0.2 for all cases, implying no expected entrainment coefficient (E) change, and (2) A is less than 0.785, implying no major mixing decrease from near shore interference with plume mixing. In addition, the high value of F_j (13.3, shown in Table 5) for these cases means that the predicted areas themselves are conservative, since early vertical mixing in the jet is neglected.

Volume Estimates - The volume estimates and the figures showing isotherms in the river cross-sections (Figures 2 and 3) represent upper-bound influenced volume estimates and are based on a modification of the two-dimensional model output. An exact value, corresponding to the predictions by the Motz-Benedict model, is difficult to obtain. As noted, this model assumes that no vertical mixing occurs. To the extent that vertical mixing does occur, the surface areas are reduced, and it becomes increasingly difficult to define the vertical structure of the jet and hence the volume. If the jet remained truly two-dimensional, then the predicted volume would equal the predicted surface area multiplied by the initial jet thickness (in this case, the diameter of the discharge pipe).

TABLE 7

IMPORTANT RESULTS FROM
LOW-FLOW STUDIES

	Case 1			Case 2		
ΔT_c, °F	S_{max}, ft	A_c, ft^2	Vol., ft^3	S_{max}, ft	A_c, ft^2	Vol., ft^3
8.2	27	177	1151	21	84	546
5.0	53	580	3770	36	230	1495
4.1	68	884	5746	44	315	2048
3.0	99	1750	11,375	61	540	3510
2.0	157	3400	22,100	92	1000	6500

Note: ΔT_c = excess temperature in river

A_c = area within ΔT_c isotherm

S_{max} = distance to end of ΔT_c isotherm measured along jet axis

Both A_c and S_{max} are measured from the end of the zone of flow establishment.

Theoretically, the value of F_j, the initial densimetric Froude number, should not exceed 1.0, if vertical mixing is to be eliminated. As a practical matter, for F_j less than about 3, initial vertical mixing is small enough to be negligible. For Cases 1 and 2, $F_j = 13.3$, therefore, some adjustment must be made to the values calculated on a strict two-dimensional assumption.

No currently available model exists for cases in which there is a strong cross-current. Therefore, the only available approach is to estimate an upper bound on the predicted volumes, using the two-dimensional predictions and available three-dimensional data.

A helpful analysis of currently available data has been prepared by Shirazi (10), who has subjected the data to regression analysis in an effort to discover trends which might be discernible. He presents data for plume half-depth and plume half-width. An estimate of the ratio of the upper bound volume prediction to the strict two-dimensional volume prediction (ratio RV) can be found by reviewing the influence of F_j on the plume width and depth. The product of the width ratio and the depth ratio should be a reasonable estimate of RV. Shirazi shows that the plume half-depth is proportional to $F_j^{0.656}$. It should be noted that this value is obtained from laboratory data taken by two separate investigators, both working with <u>stagnant</u> receiving bodies. For moving receiving water, it is likely that the exponent will be less than 0.656; i.e., for a given increase in F_j, there will be a less extreme increase in the depth of the plume in the moving environment. This ambient current influence is due to the lateral vortex motion set up inside the jet by the cross-current; the motion enhances the mixing and minimizes the importance of the increased vertical mixing occurring when F_j increases.

A review of the proposed discharge indicates that it may mix completely to the river bottom at low-flow conditions. Table 5 shows $F_j=13.3$ for Cases 1 and 2. The 0.656 exponent reported by Shirazi implies that the fully three-dimensional plume ($F_j=13.3$) will reach a depth 5.46 ($=13.3^{0.656}$) times the strict two-dimensional ($F_j=1.0$) plume depth. For a 2.0 ft diameter discharge at the surface, this produces a plume depth of 10.92 ft; however, available river depth at low flow is only about 6.5 ft. Hence, the plume may reach the river bottom.

Since the plume will probably reach the river bottom, an upperbound volume estimate can be obtained merely by multiplying the predicted surface areas by the river depth. The volumes shown in Table 7 were obtained in this way. Note again that these volumes are upper-bound values, since the decreases in width and length of the isotherms (accompanying increased depth) have not been considered.

Even though the volumes listed are upper-bound values, the proportion of the stream cross-section above 5°F is still less than 5 percent (assume a river width of about 600 feet here). A model output review shows the maximum lateral extent of the 5°F excess temperature isotherm to be only 4.3 percent of the river width for Case 1, and 2 percent for Case 2. Therefore, 95.7 percent and 98 percent, respectively, of the stream cross-sectional area is elevated less than 5°F.

Summary of Low-Flow Studies - Studies made for the 10-year, 7-day low flow under January conditions show these results:

1. Average river temperature will be elevated less than 0.1°F.

2. Surface areas within contours of interest are very small.

3. Upper-bound estimates of volumes within the 5°F excess temperature isotherms indicate that more than 95 percent of the river cross-section will be elevated less than 5°F.

Both Cases 1 and 2 were run to show that while the river velocity may drop to 2.0 ft/sec (Case 1), river bottom conditions may vary so as to give higher river velocities (Case 2) and, hence, less extreme conditions, even at the low flow.

High Temperature Conditions

A second goal of this study is the assessment of possible river temperature elevation above 90°F.

Although Table 1 (based on mechanical draft cooling towers) shows that the highest expected discharge temperature (indicating that no part of the river will ever be elevated above 90°F), is 89.9°F, it was decided

(8) to investigate an extreme condition, consisting of the highest recorded ambient temperature (87°F) and a blowdown temperature higher than any expected (95°F). The Corps of Engineers indicates that a navigational river flow is maintained at 35,000 cfs during the time of the year when such temperatures might occur. Corps of Engineers data indicate that this flow corresponds to an ambient velocity, U_a, of about 3.4 ft/sec. Case 3 represents these conditions. The plant flow, Q_p, consists of the blowdown expected in July at the design point of the natural draft cooling towers plus all other waste water flows from the plant. These other waste flows are assumed to have the same temperature as the blowdown.

Results of the investigation show negligible impact on water temperatures even for this extreme case. Flow and temperature data from Table 6 in Equation 3 indicate that the average river temperature is increased only 0.0635°F, yielding T_{mix} = 87.0635°F. Results of the jet model plume analysis are shown in Table 8 and Figure 4. No cross sections of the river are shown for this case, as the areas and volumes involved are so small. The volumes shown in Table 8 are obtained by multiplying the areas by an expected 12-foot average river depth. This follows the reasoning applied in an earlier section, in which the high initial densimetric Froude number (F_j = 24.8) is assumed to cause the jet to mix downward to the river bottom. In this case, distances are so short that this may not be attained, and hence the volumes shown in Table 8 are even more certainly upper-bound values.

Table 8 shows a predicted area of only 28 square feet elevated to or above 90°F. This prediction gives an upper limit to the expected extent, as it neglects the substantial vertical mixing associated with a very high initial F_j of 24.8. A review of the expected lateral extent of the 90°F isotherm shows it to be less than one percent of a 600 foot wide river.

In summary, the high temperature studies show a negligible thermal influence extent even for an extreme, very unlikely postulated condition.

Intake-Discharge Proximity

Upon selection of the intake site, an investigation was conducted to set the proximity limits of locating the downstream discharge point. An alternate goal of the Callaway Plant thermal plume analyses study was to establish a

TABLE 8

RESULTS OF HIGH TEMPERATURE INVESTIGATION (CASE 3)

ΔT_c, °F	T_c, °F	S_{max}, ft	A_c, ft^2	Vol., ft^3
5	92	3	5	60
3	90	9.6	28	336
2	89	18	82	984

Note: ΔT_c = excess temperature in river

T_c = actual river temperature

S_{max} = distance to end of ΔT_c isotherm measured along jet axis

A_c = area within ΔT_c isotherm

distance between intake and discharge that would prevent entrainment of any discharged water by the intake.

The intake flow characteristics were mathematically described to provide the rationale for establishing the separating distance. The flow into the intake is visualized as a reversed plume. That is, the intake appears at the end of a dispersing quantity of water contained in the plume, rather than at the initiating end, as shown in Figure 5. Since the intake plume is initiated at stream flow conditions, the intake flow is determined to emanate from a cross-sectional area of 45.2 square feet (this is based on a 2 fps stream velocity-the lowest anticipated velocity-and a 40,560 gpm, or 90.4 cfs, intake flow). If the full depth of the stream at low flow conditions is 6.5 feet, then the width of the cross-sectional area is approximately 7 feet. Thus, the intake flow begins from a cross-sectional area measuring 6.5 feet x 7 feet some distance out in the stream, upstream from the intake point.

The intake flow is turned from the stream toward the intake as a result of the two acting velocity forces: the 2 fps ambient stream velocity and the assumed 0.8 fps (greater than expected) intake velocity. The resultant of these two velocities acting 90 degrees to each other is a velocity acting at an angle of 21.8 degrees from the stream to the intake at the shore. Based on a plume spreading ratio of 5:1 (longitudinal:lateral) for slot jets discharging into a stagnant environment (Albertson, et al, 9) the centerline distance of the intake plume can be computed. The flow width at the point of initiation is 7 feet (as determined above) and the width at the terminus point (intake), equivalent to the face width of the intake structure, is 22 feet. The 5:1 spreading ratio gives a 22 ft width to a 7 ft width reduction requiring a longitudinal distance of 37.5 ft. This distance is along the plume centerline and is oriented, by the resultant velocity vector, 21.8 degrees toward the shore. Therefore, the distance from the shore to the initiating point (shown as Y_1 in Figure 5) is equal to the sin 21.8° times the centerline distance, 37.5 feet, or 14 feet. The distance from the intake upstream to this point is equal to the cos 21.8° times the centerline distance (37.5 feet) or 34.8 feet.

The calculations produce conservative values, since the intake plume does not truly follow the resultant velocity at the intake, but tends to be curved, thus

resulting in a shorter upstream distance. After a safety factor allowing for uncertainties in river bottom, river current direction, and assumptions of analysis performed is applied, a distance, L_D, between intake and discharge of at least double the upstream distance computed, or 70 feet, is recommended.

To assure that none of the plant discharged water is entrained by the intake, a check was made to ascertain if an upstream heated wedge will develop from the discharge. It has been determined, as a result of several model and field studies, that a disturbance such as a heated discharge cannot propagate upstream if the Froude number is greater than 0.7. To perform this check, one must calculate the ambient flow densimetric Froude number, F_a, from the equation.

$$F_a = \frac{U_a}{\sqrt{g \frac{\Delta p}{p} H_a}}$$

in which: U_a = ambient stream velocity

g = acceleration due to gravity

H_a = ambient river depth

$p = p_o - p_a$

p_a = ambient density

p_o = initial jet density

For the low-flow stream conditions occurring in January, the density difference is based on an ambient temperature of 35°F and a plant discharge water temperature of 76.1 (mechanical draft towers), see Table 1. The ambient stream velocity is 2 fps (see page 12) and the ambient river depth is 6.5 feet (see page 14). The computed Froude number, F_a, for these conditions is 2.63.

For stream flow conditions occurring during the highest monthly stream temperature, the density difference is based on an ambient temperature of 87°F and a plant discharge water temperature of 95°F, the ambient stream velocity is 3.4 fps, and the river depth is 12 feet (see page 16). The computed Froude number, F_a, for these conditions is 4.56.

Both of these Froude numbers are considerably greater than the critical value of 0.7 required to assure that no upstream wedge develops. Therefore, no wedge is expected and, hence, no entrainment and recirculation of heated water. As a result, the 70 ft spacing between intake and discharge discussed earlier on page 19 would continue to be the minimum allowed. A spacing (L_D) greater than 70 feet is recommended, preferably about 100 ft.

CONCLUSIONS

A review of the studies reported herein enable one to report the following findings:

1. The lowest average monthly river temperature (35°F) under 10 year - 7 day low flow conditions (8460 cfs), will be elevated less than 0.2°F. The highest river temperature of record (87°F), under minimum navigation flow (35,000 cfs) and unusually high plant discharge temperature (95°F), will be elevated less than 0.07°F.

2. Surface areas and volumes within the 5°F, 3°F, and 2°F isotherms are very small. Upper-bound volume estimates of the 10 year 7 day low flow (8460 cfs) and lowest average monthly river temperature (35°F) conditions show that less than 5 percent of the river cross-sectional area will be exposed to excess temperature greater than 5°F.

3. Under normal operating conditions, the maximum monthly average river water temperature will not be elevated above 90°F. Even under an assumed extreme occurrence (highest river temperature of record, 87°F; minimum navigational flow, 35,000 cfs; and unusually high plant discharge temperature, 95°F), less than one percent of the river cross-section experiences a temperature elevation above 90°F.

4. No entrainment or recirculation of heated water will take place if the discharge pipe is located about 100 feet downstream of the intake structure.

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