

MATHEMATICAL MODELLING OF THERMAL-PLUME INTERACTION  
AT WATERFORD NUCLEAR POWER STATION

CONF-810545--8

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## ABSTRACT

The Waldrop plume model was used to analyze the mixing and interaction of thermal effluents in the Mississippi River resulting from heated-water discharges from the Waterford Nuclear Power Station Unit 3 and from two nearby fossil-fueled power stations. The computer program of the model was modified and expanded to accommodate the multiple intake and discharge boundary conditions at the Waterford site. Numerical results of thermal-plume temperatures for individual and combined operation of the three power stations were obtained for typical low river flow (200,000 cfs) and maximum station operating conditions. The predicted temperature distributions indicated that the surface jet discharge from Waterford Unit 3 would interact with the thermal plumes produced by the two fossil-fueled stations. The results also showed that heat recirculation between the discharge of an upstream fossil-fueled plant and the intake of Waterford Unit 3 is to be expected. However, the resulting combined temperature distributions were found to be well within the thermal standards established by the state of Louisiana.

## 1. INTRODUCTION

The Louisiana Power and Light (LP&L) Company is constructing the Waterford Nuclear Power Station, Unit No. 3 (Waterford 3), near the Mississippi River at a point approximately 25 miles (40 km) northwest of New Orleans and approximately 50 miles (80 km) SSE of Baton Rouge, Louisiana (Figure 1). The station is designed to employ a pressurized water reactor to produce a maximum thermal output of 3560 MWt and a maximum net electrical output of 1165 MWe. Because of the low thermal efficiency (32 to 40 percent) of steam-electric power plants, a large amount of waste heat must be disposed. The waste heat produced at Waterford 3 will be removed by a once-through cooling system which will withdraw a design flow rate of 2235 cfs (63.3 m<sup>3</sup>/s) from the Mississippi River. The cooling water will be passed through the condenser and various heat exchangers and then returned to the Mississippi River through a surface discharge canal. When the Waterford 3 station is operated at maximum power level, the cooling water temperature rise at the point of discharge will be about 16.1°F (8.9°C).

The discharge of a large quantity of waste heat from the Waterford 3 station into the river raises many environmental concerns regarding possible large-scale modification of the thermal regime of the water body and the resultant potential effects on aquatic ecosystems. These potential effects are of even greater concern because the Waterford 3 station is located near

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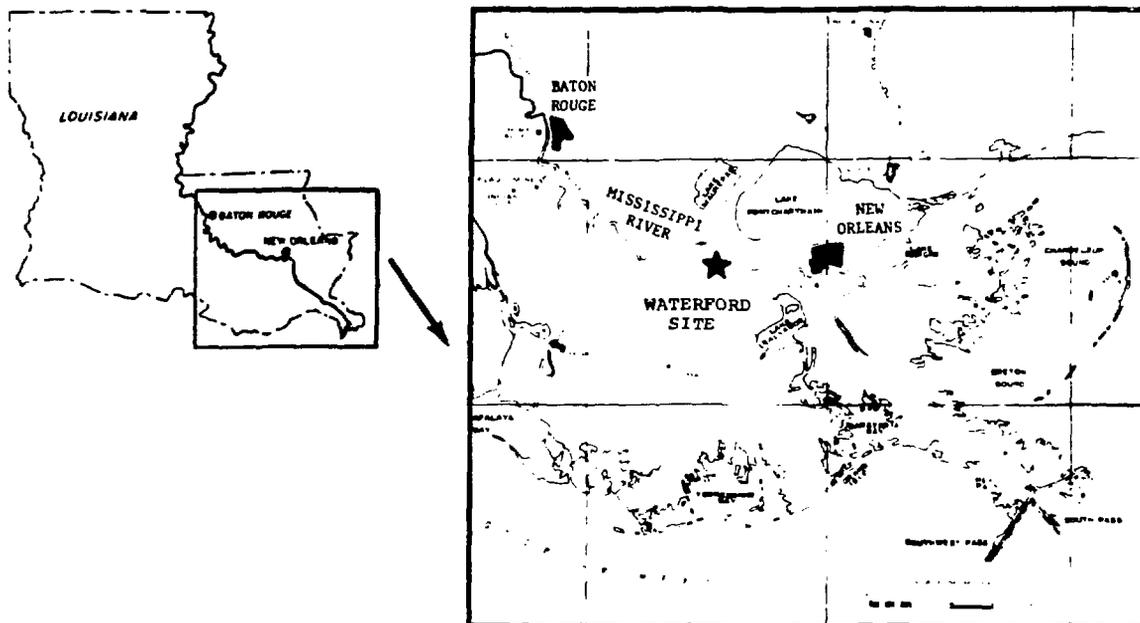


Fig. 1. Map Showing Location of Waterford Nuclear Power Station, Unit No. 3

two existing fossil-fueled power stations (Figure 2). The location of Waterford 3 is approximately 0.5 miles (0.8 km) downstream from the Waterford Units 1 and 2 Station (882 MWe), on the same side of the river, and is almost directly across the river from the Little Gypsy Station (1229 MWe). Depending on river flow conditions and on station operating modes, the thermal plumes produced by the simultaneous operation of all three power stations might interact with one another and create a thermal block that could inhibit the passage of free-swimming and drifting organisms. Furthermore, as indicated in Figure 2, all three stations are located on a river bend. Because of the centrifugal force effect, the river flows around the bend in a complex pattern that can significantly influence the mixing process of the discharged effluents in the river.

The combined thermal plume distributions produced by the operation of all three power stations are required to meet the temperature standards established by the state of Louisiana [1]. The standards specify that for the rivers, the mixing zone is limited to no more than 25 percent of the cross-sectional area and/or volume of flow at any river cross section, and the maximum temperature rise outside the mixing zone is 5°F (2.8°C). Therefore, the objective of this study was to mathematically simulate the merging of the three thermal plumes by considering the river bend effects in order to obtain three-dimensional temperature distributions needed for environmental impact assessment.

## 2. BASIC EQUATIONS OF THE THERMAL-PLUME MODEL

The Waldrop plume model [2,3] was used to analyze the hydrothermodynamics of the Mississippi River in the vicinity of the Waterford site. This model numerically solves the three-dimensional continuity, energy, and momentum equations for velocity and temperature and includes the effects of the curvature of the river. The following descriptions of the model were abstracted from Reference 3.

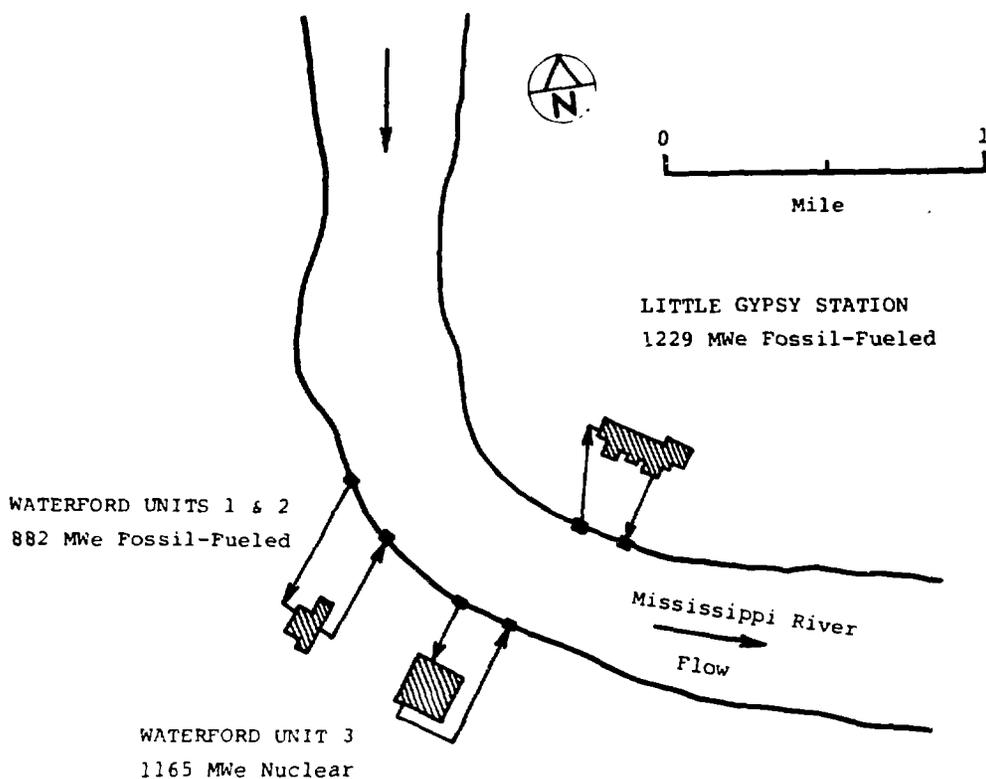


Fig. 2. Relative Location of the Three Power Stations

Assuming that the water is incompressible and that the vertical component of velocity is small, the governing equations of the model in the general orthogonal curvilinear coordinate system are:

continuity equation:

$$\frac{\partial u}{\partial x} + \frac{u}{(R+x)} + \left(\frac{R}{R+x}\right) \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad (1)$$

conservation of thermal energy equation:

$$\begin{aligned} \frac{\partial T}{\partial t} = & - \left[ u \frac{\partial T}{\partial x} + \left(\frac{R}{R+x}\right) v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z} \right] + \alpha_H \left[ \frac{\partial^2 T}{\partial x^2} + \frac{1}{(R+x)} \frac{\partial T}{\partial x} \right. \\ & \left. + \left(\frac{R}{R+x}\right)^2 \frac{\partial^2 T}{\partial y^2} + \frac{Rx}{(R+x)^3} \frac{dR}{dy} \frac{\partial T}{\partial y} \right] + \alpha_V \left[ \frac{\partial^2 T}{\partial z^2} \right] \end{aligned} \quad (2)$$

x-momentum equation:

$$\begin{aligned} \frac{\partial u}{\partial t} = & - \left[ u \frac{\partial u}{\partial x} + \left(\frac{R}{R+x}\right) v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} - \frac{v^2}{(R+x)} \right] - \frac{1}{\rho} \frac{\partial p}{\partial x} \\ & + \epsilon_H \left[ \frac{\partial^2 u}{\partial x^2} + \frac{1}{(R+x)} \frac{\partial u}{\partial x} + \left(\frac{R}{R+x}\right)^2 \frac{\partial^2 u}{\partial y^2} - \frac{u}{(R+x)^2} - \frac{2R}{(R+x)^2} \frac{\partial v}{\partial y} \right. \\ & \left. + \frac{R}{(R+x)^3} \frac{dR}{dy} v + \frac{Rx}{(R+x)^3} \frac{dR}{dy} \frac{\partial u}{\partial y} \right] + \epsilon_V \left[ \frac{\partial^2 u}{\partial z^2} \right] \end{aligned} \quad (3)$$

y-momentum equation:

$$\begin{aligned} \frac{\partial v}{\partial t} = & - \left[ u \frac{\partial v}{\partial x} + \left( \frac{R}{R+x} \right) v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} + \frac{uv}{(R+x)} \right] - \left( \frac{R}{R+x} \right) \frac{1}{\rho} \frac{\partial p}{\partial y} \\ & + \epsilon_H \left[ \frac{\partial^2 v}{\partial x^2} + \frac{1}{(R+x)} \frac{\partial v}{\partial x} + \left( \frac{R}{R+x} \right)^2 \frac{\partial^2 v}{\partial y^2} + \frac{2R}{(R+x)^2} \frac{\partial u}{\partial y} - \frac{v}{(R+x)^2} \right. \\ & \left. + \frac{Rx}{(R+x)^3} \frac{dR}{dy} \frac{\partial v}{\partial y} - \frac{Ru}{(R+x)^3} \frac{dR}{dy} \right] + \epsilon_V \left[ \frac{\partial^2 v}{\partial z^2} \right] \end{aligned} \quad (4)$$

z-momentum equation:

$$0 = - \frac{1}{\rho} \frac{\partial p}{\partial z} - g \quad (5)$$

where:

x, y, and z are orthogonal curvilinear coordinates as shown in Figure 3; u, v, and w are scalar components of the velocity in x, y, and z directions; t is time;  $\rho$  is water density; T is temperature; R is the radius of curvature of the centerline of the river and is a function of y; P is pressure;  $\alpha_H$  and  $\alpha_V$  are eddy thermal diffusivity coefficients in x and z directions;  $\epsilon_H$  and  $\epsilon_V$  are eddy viscosity coefficients in x and z directions; and g is acceleration of gravity.

The use of the curvilinear coordinate system permitted a good simulation of the river topography in the vicinity of the Waterford site and rendered an efficient way to include the centrifugal force resulting from the river bend in the governing equations.

The values of  $\epsilon$  and  $\alpha$  in Equations 2-4 are usually obtained empirically. However, for this study, the horizontal eddy viscosity coefficient,  $\epsilon_H$ , was computed by means of Prandtl's mixing length theory. Based on the mixing length equation developed by Yalin [4],  $\epsilon_H$  can be expressed as

$$\epsilon_H = 0.16(D-d)^2 \frac{d}{D} \frac{\partial q}{\partial z} \quad (6)$$

where:

d is the depth below the surface; D is the maximum water depth at the location where d is measured; and q is equal to  $\sqrt{u^2+v^2}$ .

The horizontal thermal diffusivity,  $\alpha_H$ , is related to  $\epsilon_H$  by the turbulent Prandtl number,  $P_t$ , as

$$\alpha_H = \frac{1}{P_t} \epsilon_H \quad (7)$$

For this study, a Prandtl number of 0.75 was assumed.

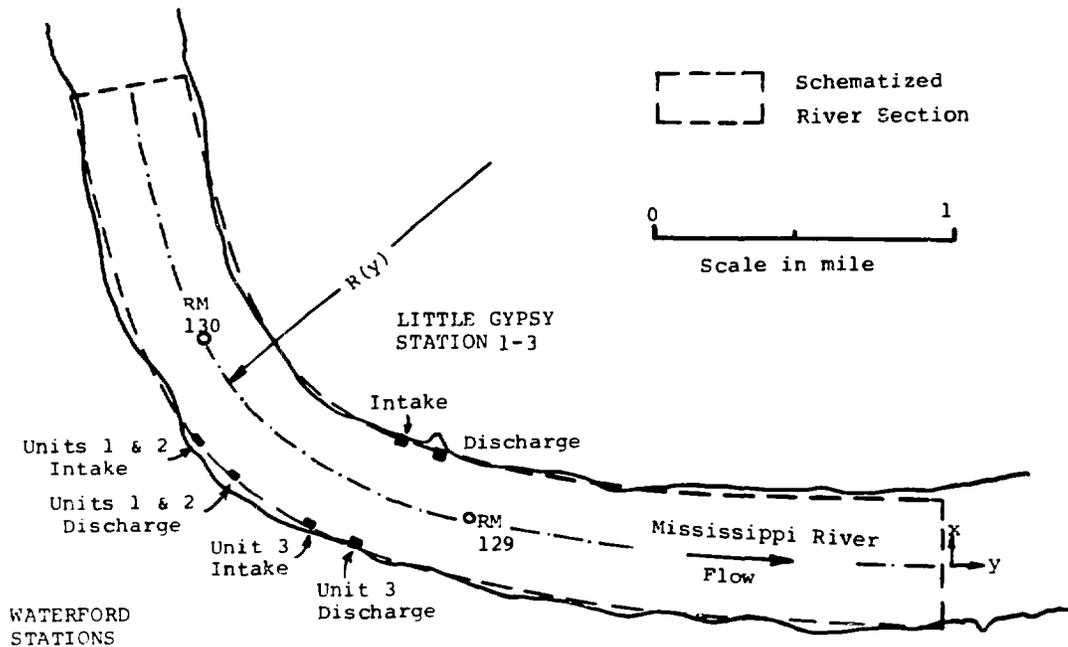


Fig. 3. Coordinate System and Schematized River Section

The vertical viscosity and diffusivity were related to the local horizontal coefficients. Because of the vertical density stratification, the vertical momentum and heat transfer are strongly suppressed [5,6]. This effect was incorporated by Waldrop [2,3] into the model by adopting the empirical damping functions of Munk and Anderson [5] for  $\epsilon_V$  and  $\alpha_V$ :

$$\epsilon_V = \epsilon_H (1 + 10R_i)^{-1/2} \quad (8)$$

and

$$\alpha_V = \alpha_H (1 + \frac{10}{3}R_i)^{-3/2} \quad (9)$$

where:

$$R_i = - \left(\frac{g}{\rho}\right) \left(\frac{\partial \rho}{\partial z}\right) \left(\frac{\partial q}{\partial z}\right)^{-2} \quad (10)$$

Equation 10 is the Richardson Number defined locally from the horizontal flow and vertical density gradient. In this way, the vertical viscosity and diffusivity are attenuated when stratification is present.

Other effects such as wind shear and surface heat transfer were not included in this study.

### 3. NUMERICAL SOLUTION OF THE BASIC EQUATIONS

The basic equations presented in the previous section were solved numerically by using an explicit finite-difference scheme. The details of the numerical technique can be found in Reference 3 and, therefore, will not be repeated here. The computer program for the Waldrop plume model was originally developed to study the hydrothermodynamics in the streams or rivers where there was only one intake and one discharge. In this study, the program

was modified and expanded to a more generalized fashion such that it was able to accommodate the multiple intake and discharge boundary conditions at the Waterford site.

The schematized river section used in this study extends about 1 mile (1.6 km) upstream from the Waterford 1 and 2 intake location and about 1.5 miles (2.4 km) downstream from the Waterford 3 discharge location (Figure 3). This section was chosen to cover the entire river bend at the Waterford site. A three-dimensional grid network with even spacing of the grid points was placed over the study region. The use of a uniformly-spaced grid pattern was possible because of the stretching transformation of the true spatial coordinates [2,3]. This transformation technique enabled a larger lateral extent to be covered by the grid system, while at the same time retaining finer resolution near the discharge point. A grid spacing of 0.1 was used for each coordinate in the transformed system. The number of grid points used in the x, y, and z directions were 15 by 63 by 12. To ensure computational stability, an incremental time step of one second was used in all numerical calculations.

The computer program, as modified for this study, was run on a CDC 7600 digital computer. The CPU time required to execute 1000 time steps was about 600 seconds. Based on the convergence criteria established in the model, the computed results generally indicated that the solutions became sufficiently close to a steady state after 20,000 time steps.

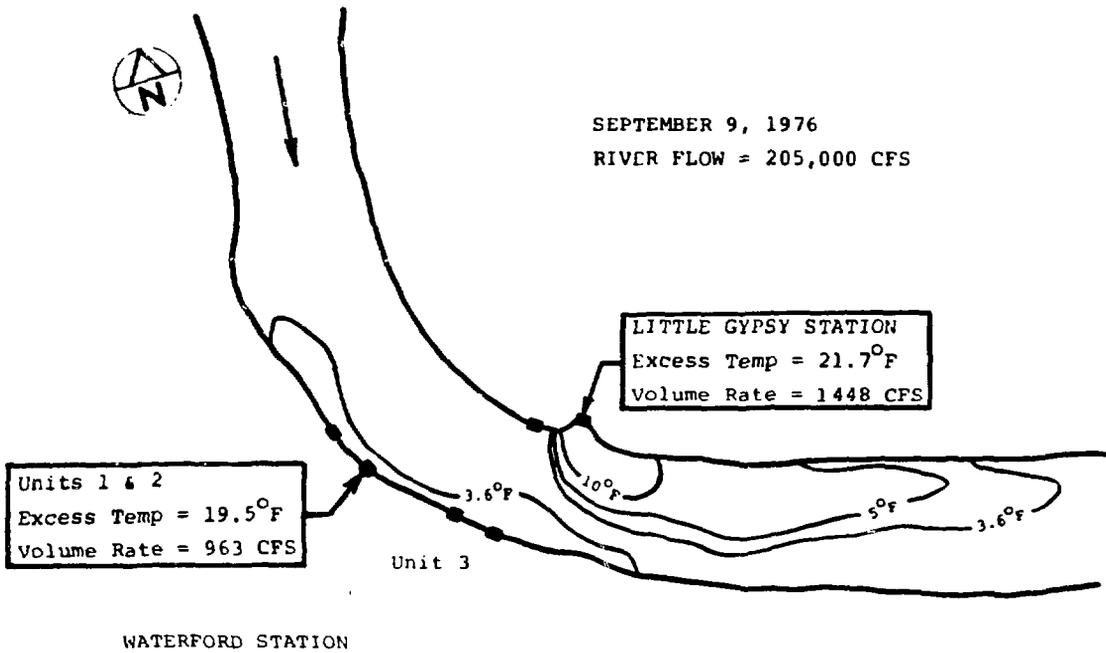
#### 4. MODEL VERIFICATION

Prior to applying the Waldrop plume model to study thermal plume characteristics in the Mississippi River near the Waterford site, the model was utilized to simulate a river flow condition for which field data had been obtained. On September 9 and 10, 1976, the LP&L conducted temperature surveys in the Mississippi River with both Waterford 1 and 2 and Little Gypsy stations operating. The river flows during the surveys were about 200,000 cfs (5660 m<sup>3</sup>/s). The measured isotherms shown in Figures 4 and 5 indicate that although the station discharge and river flow conditions were similar on both days, the extent of the thermal distribution in the river was much less on September 10. This difference was possibly caused by the wind shear effect. There was a 12.3 mph (5.5 m/s) westerly wind on September 9, which would have a large down-river component. On September 10, there was a 6.3 mph (2.8 m/s) southerly wind, which would have a component in the up-river direction. This change in wind speed and direction could have affected the plume dispersion, particular in regions of relatively low river flow (e.g., offshore of the Little Gypsy discharge canal).

As previously mentioned, the effects of wind shear were not considered in this study. Nevertheless, the results of the computed surface temperature isotherms shown in Figures 4 and 5 compare reasonably well with the measured isotherms. Deviations of observed isotherms from calculated isotherms agree qualitatively with the expected effects of wind shear. These data comparisons along with some previous comparisons performed by Waldrop [2,3] provided adequate verification of the model.

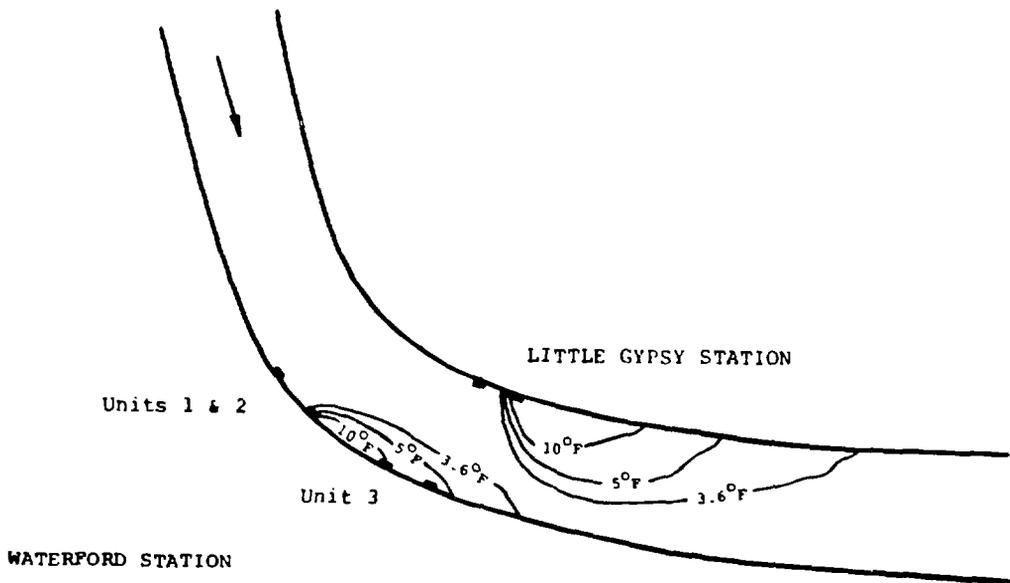
#### 5. DISCUSSION OF PREDICTED RESULTS

Numerical results of thermal plume temperatures resulting from the individual and combined operation of Little Gypsy, Waterford 1 and 2, and Waterford 3 stations were obtained for the typical low flow conditions of 200,000 cfs (5660 m<sup>3</sup>/s). This flow rate was considered to be the extreme low flow that



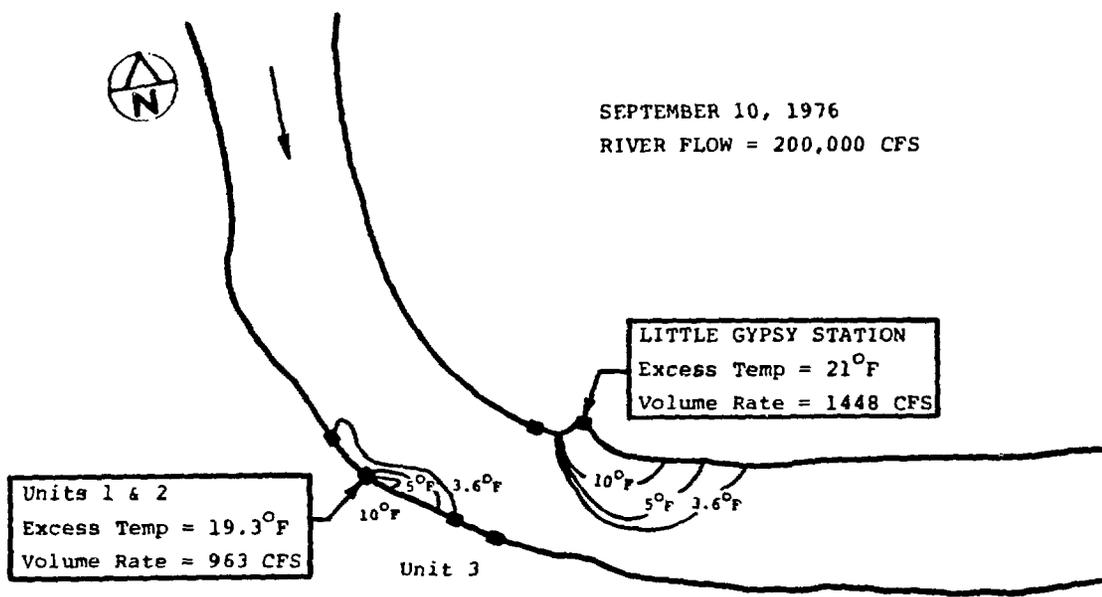
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Measured Isotherms



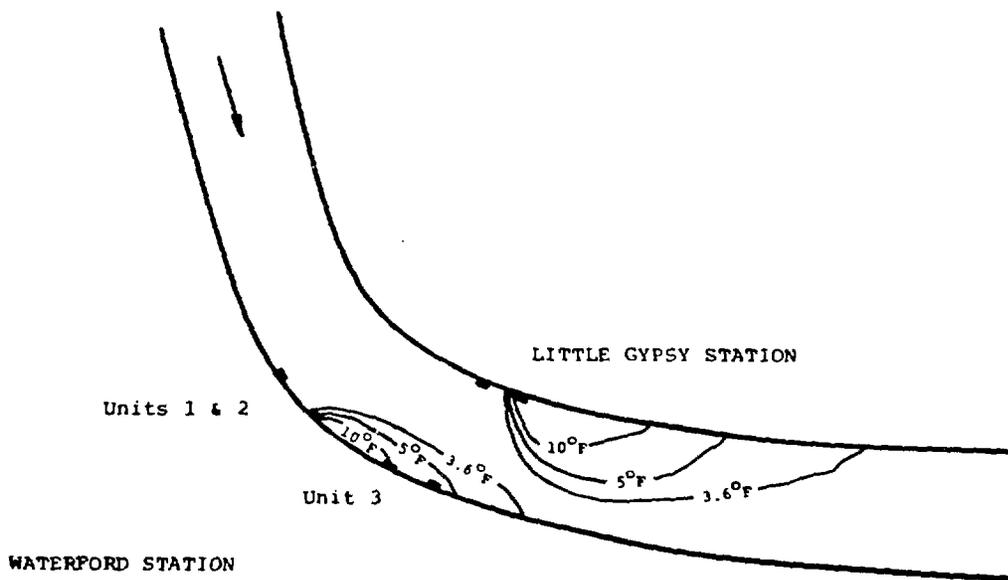
Calculated Isotherms

Fig. 4. Comparison of Measured and Calculated Isotherms, September 9, 1976



Data Source : LP & L

Measured Isotherms



Calculated Isotherms

Fig. 5. Comparison of Measured and Calculated Isotherms, September 10, 1976

would be experienced during the operational lifetime of the Waterford 3 station. For all computations, the three stations were assumed to be operating at maximum power level. The station discharge conditions and the predicted thermal characteristics of 3.6°, 5°, and 10°F (2.0°, 2.8°, and 5.6°C) excess temperature isotherms are presented in Tables 1 and 2. The corresponding surface plumes are depicted in Figures 6 through 10.

Table 1. Station Discharge Conditions for This Study

Operating Station	Discharge Volume Rate (cfs)	Excess Temp. (°F)	Discharge Velocity (fps)
Little Gypsy	1448	21.7	2.4
Waterford 1 & 2	963	19.5	0.1
Waterford 3	2235	16.1	6.1

Table 2. Predicted Thermal Plume Characteristics

Operating Station	Parameter <sup>a</sup>				
	X <sub>m</sub> (ft)	Y <sub>m</sub> (ft)	Z <sub>m</sub> (ft)	E <sub>c</sub> /A <sub>r</sub> (%)	Vol. (ac-ft)
3.6°F					
Little Gypsy	1,300	6,600	10.5	3.2	1,250
Waterford 1 & 2	600	4,000	5.6	1.5	560
Waterford 3	1,200	9,600	12.7	4.4	1,650
Combined	1,800	10,800	15.0	11.0	4,680
5°F					
Little Gypsy	1,100	3,400	6.8	2.2	600
Waterford 1 & 2	400	2,800	3.9	0.8	180
Waterford 3	800	6,600	8.5	3.4	890
Combined	1,800	7,600	10.5	7.3	2,250
10°F					
Little Gypsy	600	2,200	3.8	0.7	50
Waterford 1 & 2	200	1,500	2.3	0.3	20
Waterford 3	600	3,500	5.1	1.2	85
Combined	1,200	3,900	6.0	2.4	195

<sup>a</sup>X<sub>m</sub> = maximum lateral spread; Y<sub>m</sub> = maximum longitudinal spread; Z<sub>m</sub> = maximum vertical spread; A<sub>c</sub> = maximum cross-sectional area for a given excess temperature; A<sub>r</sub> = area of the river cross section as denoted in Figure 9; Vol. = volume occupied by excess temperatures higher than that indicated.

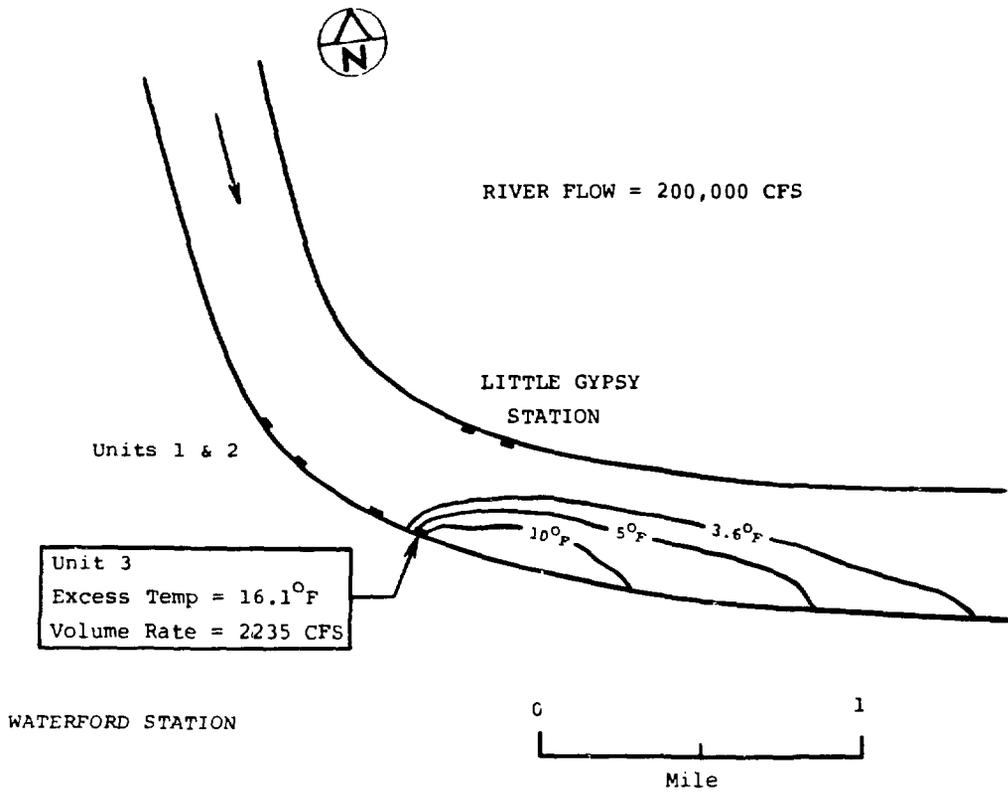


Fig. 6. Predicted Surface Isotherms for the Little Gypsy Station

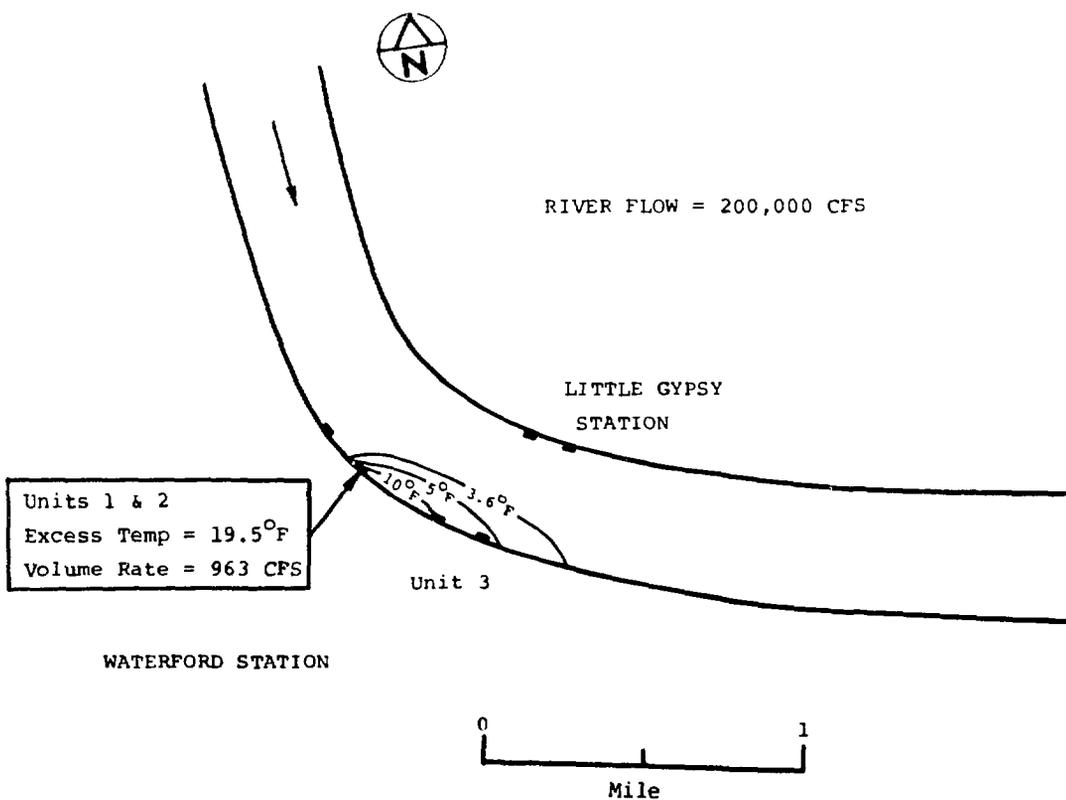


Fig. 7. Predicted Surface Isotherms for the Waterford 1 and 2 Station

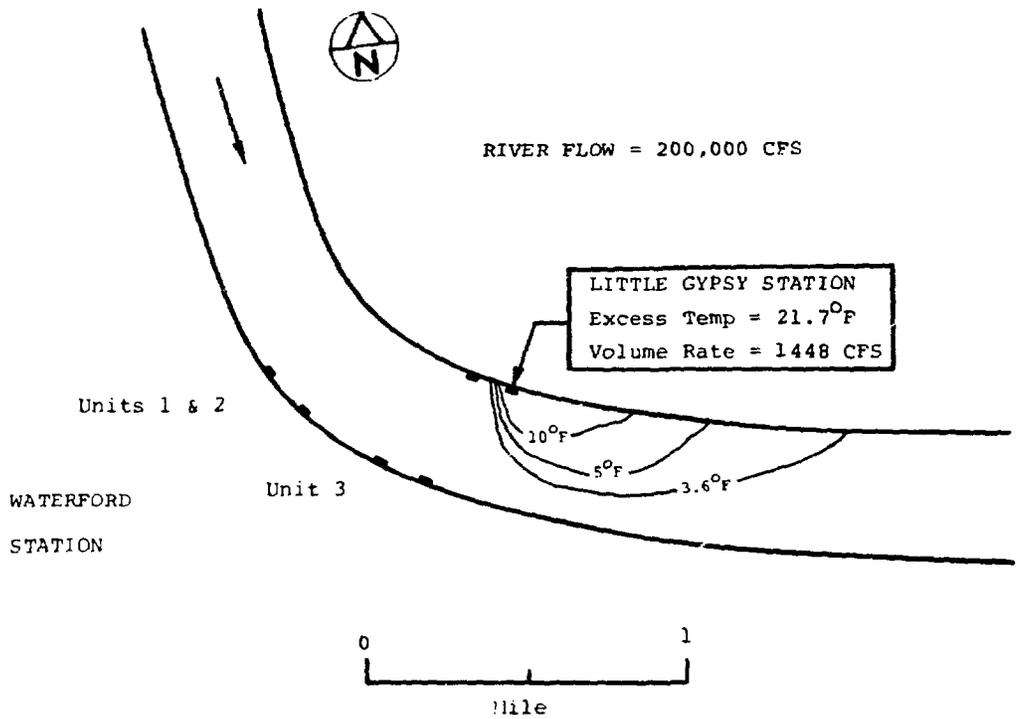


Fig. 8. Predicted Surface Isotherms for the Waterford 3 Station

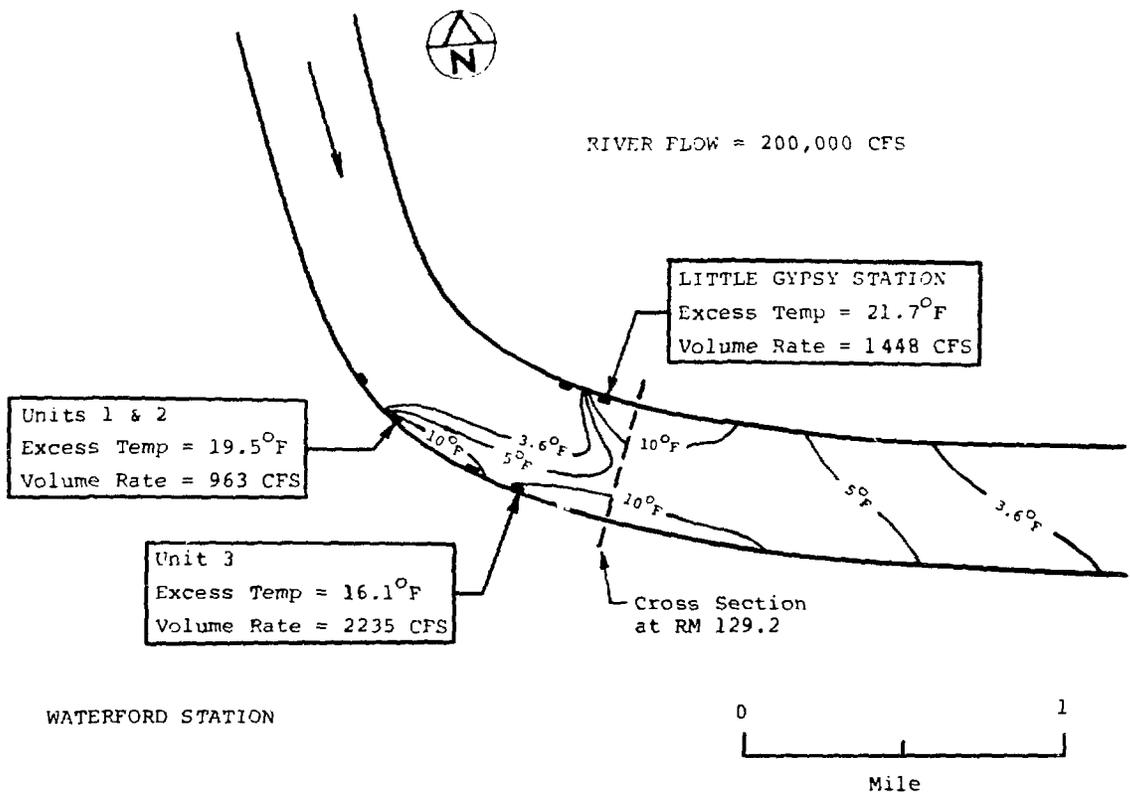


Fig. 9. Predicted Surface Isotherms for the Three Stations Combined

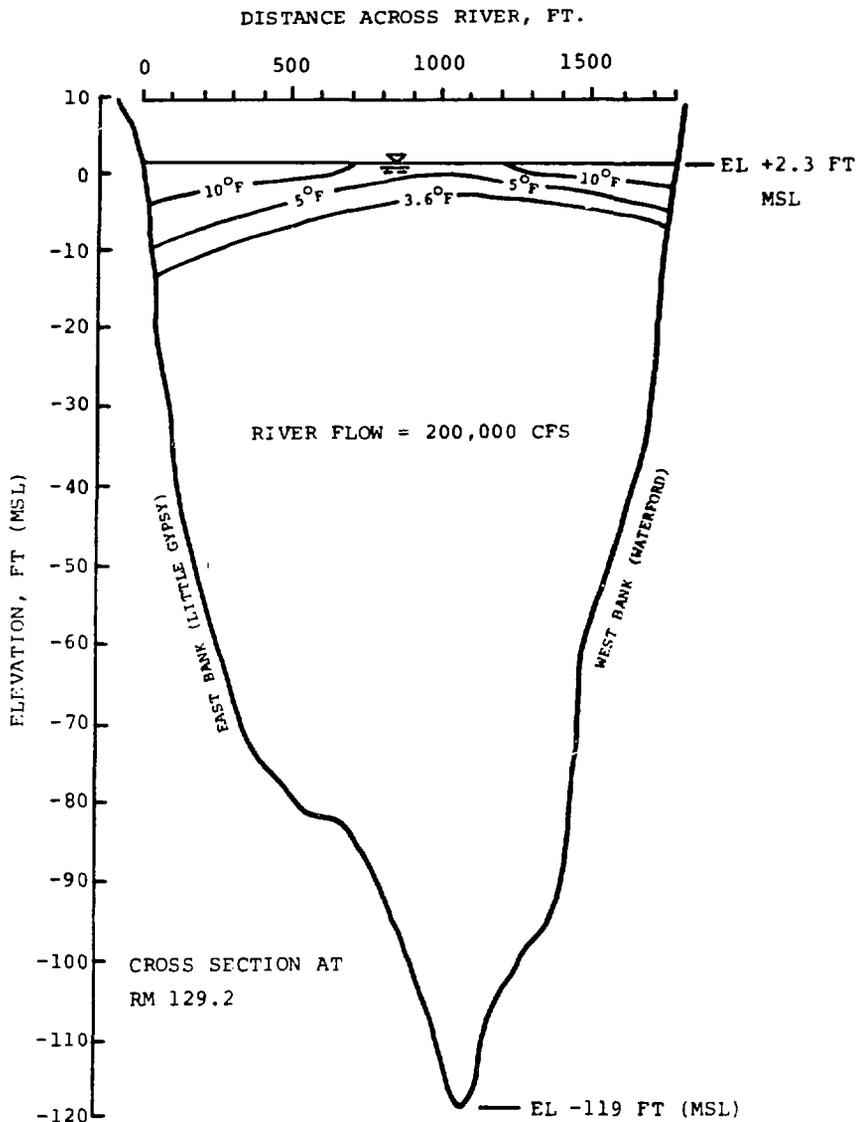


Fig. 10. Cross-Sectional View of Combined Isotherms

For the case with stations operating individually, the results presented in Table 2 and Figures 6 through 8 indicate that the predicted lateral spread of the plume from Little Gypsy station is greater than that from Waterford 3 station, despite the fact that Waterford 3 has a higher discharge velocity. Conversely, the longitudinal and vertical spreads of the plume produced by Waterford 3 are greater than those of Little Gypsy. These plume characteristics are present primarily as a result of the complex flow pattern around the river bend. A major portion of the river flow starts near the Little Gypsy side upstream of the river bend and then bears to the Waterford shore downstream of the river bend. This change of flow direction creates a high river flow region near the Waterford site and a low river flow region offshore of the Little Gypsy station. Consequently, the Little Gypsy surface jet discharge would displace the natural flow and extend itself laterally into the center region of the river whereas the high flow near the west bank of the river would serve to dilute and convect the heated water from Waterford 3 into

the downstream portion of the river bend. The Waterford 1 and 2 thermal discharge would affect a smaller portion of the river than the Little Gypsy and Waterford 3 discharges. This is due partly to the low heat-release rate from the Waterford 1 and 2 station and partly to the high river flow rate on the Waterford side of the river.

The characteristics of the combined thermal field as presented in Table 2 and Figure 9 indicate that for typical low river flow conditions, the surface jet discharge from Waterford 3 would interact with the plumes produced by the Little Gypsy and Waterford 1 and 2 stations. Furthermore, the numerical results of the plume temperatures indicate that for the 5°F (2.8°C) isotherm, the combined surface area and volume of all three stations would be about 15 and 35 percent greater than the sums of the individual surface areas and volumes generated by each station. These results are to be expected simply because when individual plumes interfere, they form a single plume with reduced periphery and therefore a diminished ability to entrain ambient water. The combined plume will have to transport a greater distance longitudinally, covering a greater area to entrain sufficient water to reduce plume temperature to 5°F (2.8°C) above ambient.

The combined temperature field as depicted in Figure 9 also shows that heat recirculation between the Waterford 1 and 2 discharge and the Waterford 3 intake is expected to occur. By integrating the water temperature over the entire water column at the Waterford 3 intake, it was calculated that the water with temperature as high as 2°F (1.1°C) above ambient might be swept into the Waterford 3 intake. As the river flow increases, the recirculating tendency of the effluent would tend to be reduced and the plume from the Waterford 1 and 2 station would be expected to hug the downstream shore before it could reach the Waterford 3 intake.

The approximate location of the river cross section, where the combined temperature isotherms occupy the largest cross-sectional area, is denoted in Figure 9. The excess temperature distributions at the cross section are shown in Figure 10. The cross-sectional areas enclosed within 3.6°, 5°, and 10°F (2.0°, 2.8°, and 5.6°C) excess temperature isotherms were computed and the results are shown in Table 2. These results were further examined to ensure that the combined thermal plume distributions produced by the simultaneous operation of all three power stations at the Waterford site would be in compliance with Louisiana water quality criteria [1]. The predicted results indicated that for low river flow conditions, a mixing zone defined by the 5°F (2.8°C) excess temperature isotherm would only occupy a maximum of 7.3 percent of the river cross-sectional area, which is well below the allowable limit of 25 percent. As the river flow increases, the plume distributions on either side of the river would tend to remain separated from each other and the mixing zone area would be reduced.

## 6. SUMMARY AND CONCLUSIONS

This paper presents the results of an analysis of the mixing and interaction of thermal plumes in the Mississippi River resulting from individual and combined circulating water discharges from the Waterford 3, Waterford 1 and 2, and Little Gypsy power stations. The analysis was performed by using the Waldrop plume model, which numerically solves the three-dimensional equations of continuity, momentum, and energy for velocity and temperature and includes the effects of the river curvature. The computer program of the model was generalized to treat the multiple intake and discharge boundary conditions at the Waterford site and was verified for this study.

Numerical results of thermal plume temperatures obtained for typical low river flow and maximum station operating conditions predicted that the three thermal plumes would interact with one another and that heat recirculation between the Waterford 1 and 2 discharge and the Waterford 3 intake would occur. However, the overall results indicated that the combined temperature distributions would comply with the thermal standards established by the state of Louisiana.

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#### ACKNOWLEDGMENTS

The author wishes to thank Dr. W.R. Waldrop and Mrs. Dalpha Stubblefield of the Tennessee Valley Authority for providing the computer program used in this study and for valuable discussions related to the program. Special thanks are due to the author's colleague, Mrs. Dee Wyman, for her excellent editorial work. This study was conducted under the auspices of the Nuclear Regulatory Commission.