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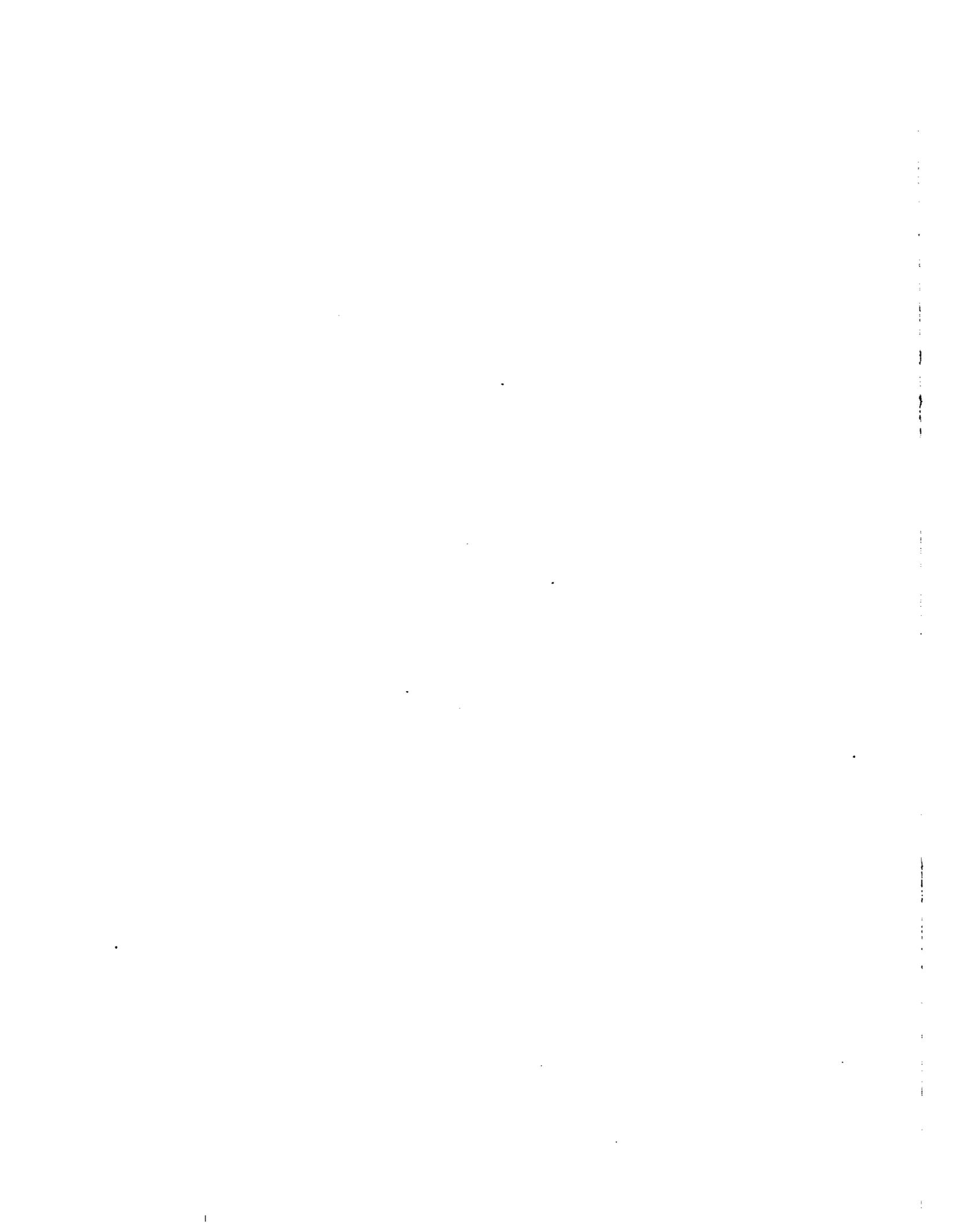
FIRE ENVIRONMENT DETERMINATION IN THE LASALLE NUCLEAR POWER PLANT CONTROL ROOM

J.L. Usher and J.L. Boccio

October 1987

**RELIABILITY & PHYSICAL ANALYSIS GROUP
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UPTON, NEW YORK 11973**

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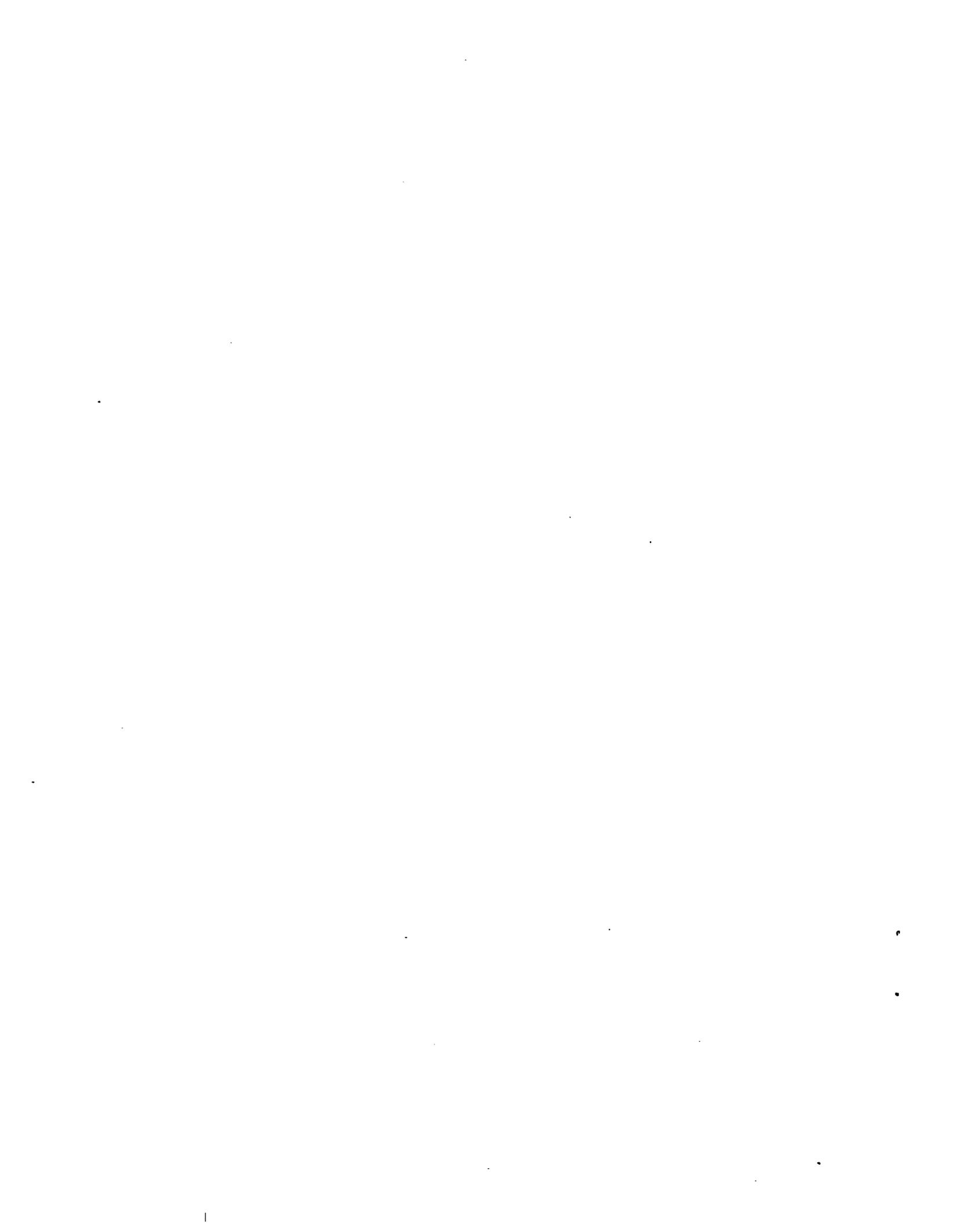
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ABSTRACT

One of the objectives of the Fire Protection Research Program (FPRP) of the U.S. NRC is to improve the modeling of environments caused by fires in typical nuclear power plant enclosures. A three-dimensional fluid dynamics computer code (PHOENICS) has been adapted as a field-model fire code (SAFFIRE) for this purpose. The model has been applied to simulate two distinct fires in the control room of the LaSalle County power plant. The environments determined illustrate hazardous potential for both personnel and equipment.



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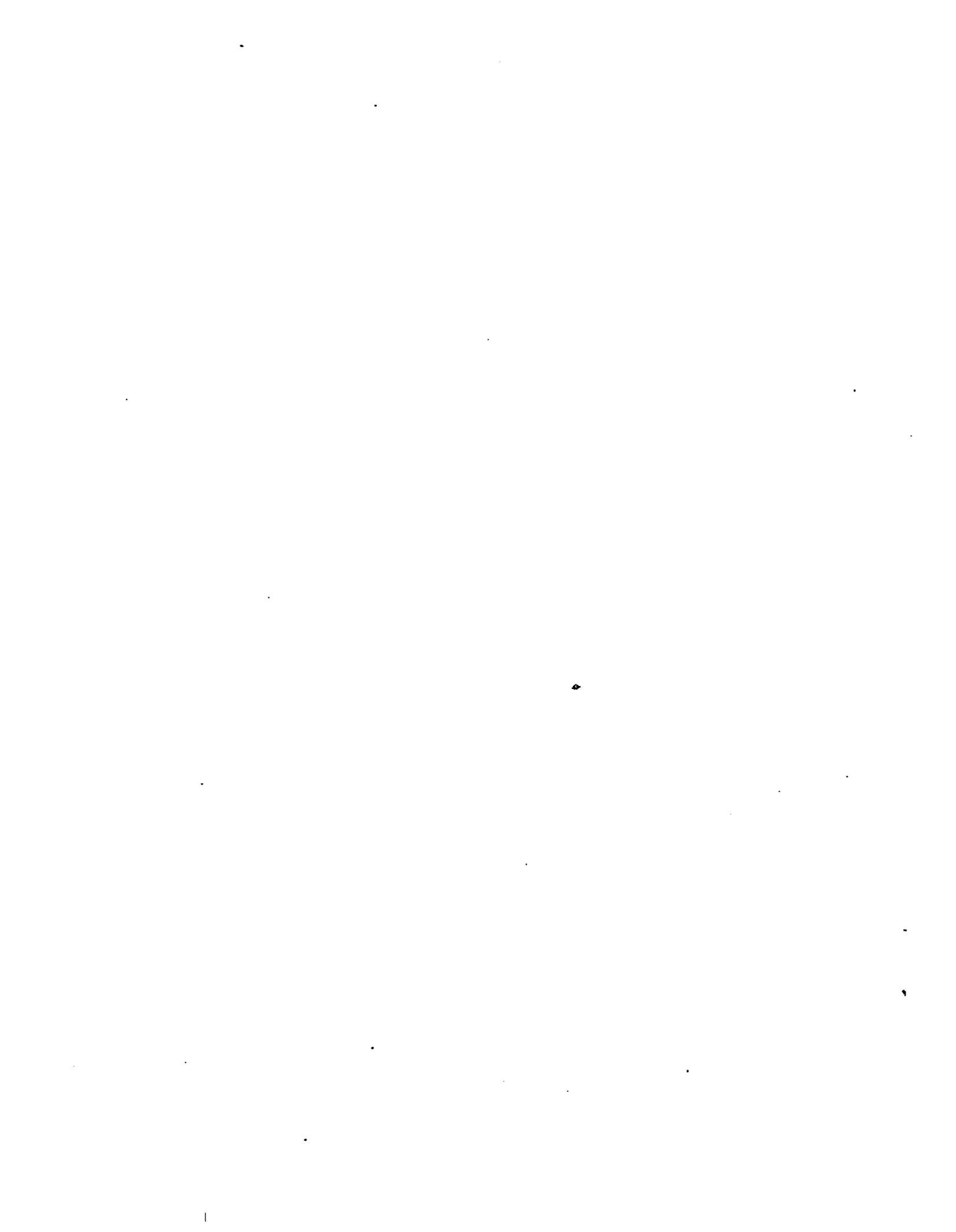
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I. INTRODUCTION

The primary objective of this report is to present the results of several computer simulations of the fire-induced thermal environment within the control room of the LaSalle Nuclear Power Plant. These simulations were performed as part of a sub-task within the Control Room Habitability and Fire Safety Study (CR) which is being performed as part of the overall Fire Protection Research Program (FPRP) for the U.S. NRC. A secondary objective is to describe the development status of the SAFFIRE computer code somewhat in detail. This code, being developed as part of the FPRP, would be the first fire environment model created with NRC fire safety issues in mind and has been validated via comparison with fire tests conducted with nuclear power plant concerns in mind.

Implementation of the NRC's safety goal and severe accident policy will require that a reliable and credible technology, modeling and data base be provided to answer the questions: What is the current and expected level of safety of operational nuclear power plants, and what are cost effective ways to either enhance or maintain acceptable levels of safety. The ability to evaluate the risk contributions of important accident initiators involving equipment malfunctions and human errors including common cause or dependent failures has been improved to a point where useful select applications can be made to assess conditional risks. Risk methodology for estimating risk contributions from external events, such as fires, floods and earthquakes, is being developed. However, seismic risk analysis and seismic hazard analysis, as compared to fire risk analysis and fire hazard analysis, is at a more detailed stage of model development. To assure consistency, accuracy, and credibility in assessing the relative effects of the risk contributions from external events requires that a concerted effort be expended to understand the impacts of fires on the operational envelope of nuclear power plants. The overall purpose of the FPRP was to enhance risk and reliability analysis from a fire-induced-stress viewpoint in order to help inject consistency, accuracy and credibility into the analysis of the impact of fires on the operational safety of nuclear power plants. In addition, since risk-based analyses of inspection and enforcement issues, technical specifications and other licensing issues can augment the safety of operating plants by identifying weaknesses in design and operation, the FPRP was structured to address and resolve concerns regarding implementation of fire-protection guidelines mandated in 10CFR50 Appendix R: "Fire Protection."

A. Fire Protection Research Program

The goal of the FPRP is to develop test data and analytical capabilities to support the evaluation of:

1. the contribution of fires to the overall risk from nuclear power plants,
2. the effects of fires on control room equipment and operations, and
3. the effects of actuation of fire suppression systems on safety equipment.

B. Probabilistic Risk Assessment

NRC research needs in fire risk analysis have been outlined in previous memoranda and reports¹. The recommendations in the area of external event risks, such as fires, included the generation of information regarding equipment performance in accident environments, methods to predict variations in environmental parameters during a fire, and data relating equipment failure probabilities to environmental changes. Specifically, in the area of fire risk, the Office of Nuclear Regulatory Research (RES) was urged to give attention to the aspects of interaction between fire protection features and safety systems, the reliability of fire protection features, and the likelihood of qualified equipment withstanding the effects of fire and fire suppression activities.

1. Fire Hazard Analysis

Theoretically, the fire risk analyst should study the potential contribution to risk of fires anywhere in the nuclear power plant. By screening out unimportant locations, however, he can greatly reduce the amount of work necessary without sacrificing significant confidence in the results. The purpose of the fire hazard analysis is to identify the locations that are important to the fire risk analysis.

For the purposes of initial analysis, fire locations are usually considered to be coincident with the fire zones defined by the utility in its Fire Protection Review. The fire zones consist of one or more compartments and are separated from other fire zones by rated fire barriers. The spread of fire between zones is considered unlikely, although possible. A more detailed analysis of the fire zones may show that only limited areas within the fire zones contain critical safety-related equipment, in which case a number of fire locations may be defined within the particular fire zone.

The "importance" of a fire location is measured by its contribution to the overall frequency of radionuclide release. Since this cannot be determined until at least the first iteration of the fire risk analysis has been completed, more approximate measures are employed. The primary measures are the type and quantity of fire-vulnerable safety equipment at the location of interest. Other factors that may be used in the screening process are the frequencies of fires, the types and amounts of combustible materials, and the suppression systems available. Information on all of these factors can be obtained in fire protection reviews.

To summarize, the step-by-step procedure for fire hazard analysis consists of constructing a simple systems model of the plant, identifying the locations of safety equipment, identifying critical fire-impact locations, identifying locations adjacent to critical locations containing large quantities of combustibles, and determining the distributions for fire frequency for each critical location.

2. Fire Propagation Analysis

The purpose of this analysis is to determine the likelihood and extent of various levels of damage in a compartment given that a fire has occurred.

Several different approaches have been utilized to date: statistical modeling based on past experience, multistage event-tree modeling, and a third requiring the construction of physical models to describe the relevant phenomena. Each of these approaches utilizes data regarding the following elements of a fire model: ignition, detection, suppression and propagation.

Regardless of the modeling approach chosen, the step-by-step procedure for fire propagation analysis retains the same principal features: definition of representative fire-growth scenarios for each location, determination of distribution for growth time for each fire, determination of distribution for suppression time for each scenario, and computation of the distribution for frequency of growth.

C. Control Room Habitability and Fire Safety Study (CR)

In the control room there is a high density of electrical instrumentation and control cables of the redundant trains in necessarily close proximity to each other. Fire protection of the control room is complicated by the fact that malfunctions of critical components may have cascading effects in spreading loss of control into areas remote from the control room. The requirements of operability for components in electrical cabinets in the control room, therefore, becomes more stringent. A systematic study is needed of the control system and how faults may propagate in the event of a fire. A systems approach, utilizing the knowledge and the methodologies of spatial separation, should be used in such a study. The data base produced would be of value in devising ways of ensuring a margin of safety.

The other concern in the control room is that existing requirements to protect the occupants of the control room in accident situations may not be adequate. NRR has responded to this concern with a program plan for a study in control room habitability. One of the desired goals of such a study is that limiting environmental conditions for operation in the control room should be established and should consider human performance as well as equipment operation as the basis for selection of appropriate limits. The program plan itself proposed environmental criteria for human performance. The need is for a determination of whether the generic control room habitability system is adequate for the maintenance of that minimal environment through a credible fire accident. The effectiveness with which the habitability system, which includes the HVAC system, isolates the control room and removes smoke and toxic combustion products from within is to be studied, and possible remedial actions are to be examined. The CR study addresses the issues by determining the fire-generated environment and the purge system effectiveness.

The end products of the CR study will be:

1. a data base on a range of fire scenarios that could cause failure of equipment and lead to conditions resulting in loss of shutdown and safety functions;
2. the system interactions affecting shutdown and safety functions for the identified failures; and
3. an estimate of the smoke removal effectiveness of typical habitability systems.

D. Summary

In conclusion, the overall end products of the FPRP will be:

1. a user-interactive computer program applicable to a wide range of geometries and internal partitioning for the purpose of predicting fire environments in enclosures,
2. a data base of test results depicting fire environment for a range of potential fires in nuclear power plant enclosures,
3. an integrated methodology whereby the environments created by a range of fires in plant enclosures is determined, and in conjunction with equipment damage thresholds is used to estimate the time-to-failure of certain classes of equipment, and
4. a data base for development of fire PRA in nuclear power plant enclosures, including time-to-detection, time-to-suppression, and the probable sequence of equipment failure in potential fire environments.

II. PHOENICS/SAFFIRE COMPUTER MODELS

This chapter describes the mathematical and computational models derived for the purpose of determining the fire environment within an enclosure typical of a nuclear power plant. The PHOENICS^{2,3} code is a proprietary computational fluid dynamics model developed by CHAM, Inc. The model has had broad utilization throughout the fluid dynamics community in various areas such as aerodynamic flow modeling, combustion chamber modeling and fire environment determination⁴. The SAFFIRE computational model, being developed as part of the FPRP, will be a self-contained, non-proprietary code dedicated solely to the determination of the potential fire environments in nuclear power plant enclosures. The SAFFIRE model will utilize a subset of the overall PHOENICS model adapted specifically for this purpose.

The computational field model is based on the solution of the governing partial-differential equations expressing the conservation of mass, momentum and energy. Gas flow is treated as three-dimensional, transient and elliptic. The fluid is assumed to be a perfect gas with constant physical properties identically those of air. Density is calculated as a function of local temperature. Buoyancy effects are accounted for by using local densities in all terms of the conservation equations, i.e., the Boussinesq approximation is not used. Turbulence effects are accounted for by using the two-equation k-ε model of turbulence⁵, with known refinements for buoyant flows⁶⁻⁸.

Independent variables are three coordinates (x,y,z) of a cartesian coordinate system and time (t). Dependent variables include the three velocity components (u,v,w), the pressure (p), the enthalpy (h), the turbulence kinetic energy (k), and its dissipation rate (ε). The conservation equations are expressed in the following time-averaged form:

$$\frac{\partial}{\partial t} (\rho\phi) + \text{div} (\rho\vec{u}\phi + \vec{J}_\phi) = S_\phi, \quad (1)$$

where ϕ stands for a generic property (u,v,w,h,k, etc.) and ρ , \vec{u} , \vec{J}_ϕ , S_ϕ are density, velocity vector, diffusive flux vector, and source term for generic property ϕ per unit volume, respectively. The diffusive flux is given by:

$$\vec{J}_\phi = -\Gamma_{\text{eff},\phi} \text{grad } \phi, \quad (2)$$

where $\Gamma_{\text{eff},\phi}$ is the effective exchange coefficient for the transport of generic property ϕ . The values of Γ_{eff} and S for different χ 's are listed in Table 1.

Table 1

Exchange Coefficients (Γ_ϕ) and Source Terms (S_ϕ) for Different ϕ Variables

ϕ	Γ_ϕ	S_ϕ
1	0	0 (Continuity)
u	ν_{eff}	$-\frac{\partial p}{\partial x} + \frac{\partial}{\partial x} \left(\nu_{eff} \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \left(\nu_{eff} \frac{\partial v}{\partial x} \right)$ $+ \frac{\partial}{\partial z} \left(\nu_{eff} \frac{\partial w}{\partial x} \right)$
v	ν_{eff}	$-\frac{\partial p}{\partial y} + \frac{\partial}{\partial x} \left(\nu_{eff} \frac{\partial u}{\partial y} \right) + \frac{\partial}{\partial y} \left(\nu_{eff} \frac{\partial v}{\partial y} \right)$ $+ \frac{\partial}{\partial z} \left(\nu_{eff} \frac{\partial w}{\partial y} \right)$
w	ν_{eff}	$-\frac{\partial p}{\partial z} - g (\rho - \rho_{ref}) + \frac{\partial}{\partial x} \left(\nu_{eff} \frac{\partial u}{\partial z} \right)$ $+ \frac{\partial}{\partial y} \left(\nu_{eff} \frac{\partial v}{\partial z} \right) + \frac{\partial}{\partial z} \left(\nu_{eff} \frac{\partial w}{\partial z} \right)$
h	$\frac{\nu_{eff}}{\sigma_h}$	\dot{q}'''
k	$\frac{\nu_{eff}}{\sigma_k}$	$G_k - \rho \epsilon + G_b$
ϵ	$\frac{\nu_{eff}}{\sigma_\epsilon}$	$\frac{\epsilon}{k} [(G_k + G_b) C_1 - C_2 \rho \epsilon]$

From the table:

$$\nu_{eff} = \nu_t + \nu_l \quad (3)$$

$$\nu_t = C_\mu \rho k^2 / \epsilon \quad (4)$$

$$\begin{aligned}
G_k = \nu_t \{ & 2 \left[\left(\frac{\partial u}{\partial x} \right)^2 + \left(\frac{\partial v}{\partial y} \right)^2 + \left(\frac{\partial w}{\partial z} \right)^2 \right] \\
& + \left[\left(\frac{\partial u}{\partial z} \right)^2 + \left(\frac{\partial w}{\partial x} \right)^2 \right] + \left[\left(\frac{\partial w}{\partial y} \right)^2 + \left(\frac{\partial v}{\partial z} \right)^2 \right] \\
& + \left[\left(\frac{\partial u}{\partial y} \right)^2 + \left(\frac{\partial v}{\partial x} \right)^2 \right] \} , \quad \text{and}
\end{aligned} \tag{5}$$

$$G_b = \frac{\nu_t}{\rho} g \frac{\partial \rho}{\partial z} . \tag{6}$$

The buoyancy production term, G_b , represents the generation/suppression of turbulence due to buoyancy. In stable stratification (fire enclosures), $\partial \rho / \partial z$ is negative; hence G_b becomes a sink term, and the turbulent mixing is reduced. The turbulence model contains five empirical

$$C_1 = 1.44 ,$$

$$C_2 = 1.92 ,$$

$$C_\mu = 0.09 ,$$

$$\sigma_k = 1.0, \text{ and}$$

$$\sigma_\epsilon = 1.3.$$

Additionally the mathematical model may be applied to determine smoke concentration throughout the enclosure in question by utilizing a smoke mass source term⁶ to replace the heat generation source term from Table 1, i.e., utilize $S_\phi = \dot{m}_f'''$ for $\phi = f$, the smoke concentration, in place of the \dot{q}''' and h terms.

The computational model consists of a finite difference solution of the set of elliptic partial-differential equations expressing the conservation of mass, momentum, energy and other fluid variables in three dimensions. The code (SAFFIRE) generates local predictions of temperature, velocity, species concentrations, and pressure. For finite differencing, the code utilizes a modified version of the SIMPLE algorithm⁹ developed at Imperial College. The SIMPLE procedure is as follows:

1. Guess the pressure field and the distribution of effective turbulent eddy viscosity.
2. Using the guessed values of p and μ_{eff} , solve the momentum equation to obtain approximate velocity components.
3. Calculate the pressure corrections that enforce continuity.

4. Solve the k - ϵ equations using the new values of velocity and pressure.
5. Update the effective turbulent velocity.
6. Repeat from operation 1., until steady state is reached or convergence criteria are satisfied.

The SIMPLE algorithm is fully implicit, and finds a steady-state solution at a designated point-in-time, but without having to march in time about the designated point. An important advantage of SIMPLE is that for a complex problem, where fine grids are essential for accuracy, computer time requirements are greatly reduced over algorithms not based on SIMPLE.

To date results from the computational model described above have been compared to experimental data from two sets of fire tests conducted with NRC needs in mind¹⁰⁻¹¹ for the purpose of preliminary benchmarking of the model. The results of these benchmark comparisons have been detailed previously³ and will not be discussed here.

III. LASALLE CONTROL ROOM SIMULATIONS

As discussed previously, performance and evaluation of the FPRP is being coordinated with work in progress on the Control Room Habitability Program and the Risk Methods Integration and Evaluation Program (RMIEP). RMIEP research is evaluating all risks associated with the LaSalle NPP. As a portion of this coordinated research effort, an additional sub-project was initiated within the FPRP: the Control Room Habitability and Fire Safety Study (CR). This study combines the methodologies of FSC, FED and FFT summarized above. This section presents a description of the geometry of the control room, including internal flow obstacles and the distribution of forced ventilation inlets and outlets. The modeling procedure is summarized and results of several simulation runs with and without fires are presented.

A. Computational Model Parameters

The control room contains control and instrumentation cabinets and cables for LaSalle NPP Units 1 and 2. The enclosure (Fig. 1) is 120 ft x 60 ft x 16.5 ft high with concrete walls generally two feet thick or more at the room boundary. Doors to the control room are fire-rated (3 hr) and are usually closed, although there is a design leakage of 1500 cfm through these doors. Forced ventilation inlets are distributed throughout the room producing a total ventilation rate of 24020 cfm. Cabinets and control consoles are shown in Fig. 1. There are a number of desks and tables located around the control room which are not depicted in Fig. 1, but which are accounted for in the computational configuration. The exhaust configuration in the control room is unique in our experience: two L-shaped exhaust plena (Fig. 2), 40 ft. long x 10 ft. wide, are delineated by fronts of cabinets and consoles and further by steel valances extending to the enclosure ceiling as shown in Fig. 3. One exhaust vent is located in each of these plena, and there are no ventilation sources in either plenum. Air flow from the room proceeds into the exhaust plena through gratings in the bottoms of the cabinets forming the L-shaped boundary. In addition to the high cable loadings in the cabinets and consoles, horizontal cable trays, shown in Fig. 3, are located above the cabinets throughout the plenum areas. The cabinets are open both in the back and on top to the general plenum area. The unique exhaust plenum configuration resulted in the simulation of two basic fire types: one outside the plena in the control room working area and one inside an exhaust plenum behind the cabinets. The locations of these source fires are indicated by "X" on Figs. 1 and 2.

Observation of the geometrical details outlined above together with the locations of the ventilation sources and the locations of internal flow obstacles, guided the set-up of the three-dimensional (x,y,z) computational grid to be analyzed. The enclosure was divided into 4389 cells (x:33, y:19, z:7) of varying length, width and height. The spacing of the cells in the x and y directions is primarily due to the specific locations of flow obstacles in the control room, although consideration is also given to ventilation inlet locations throughout the room. The height (z) of the control cells is determined by the height of the control room benchboards and vertical cabinets (8 ft over 3 cells) as well as the locations of cable trays, ventilation inlets and ducting. At the

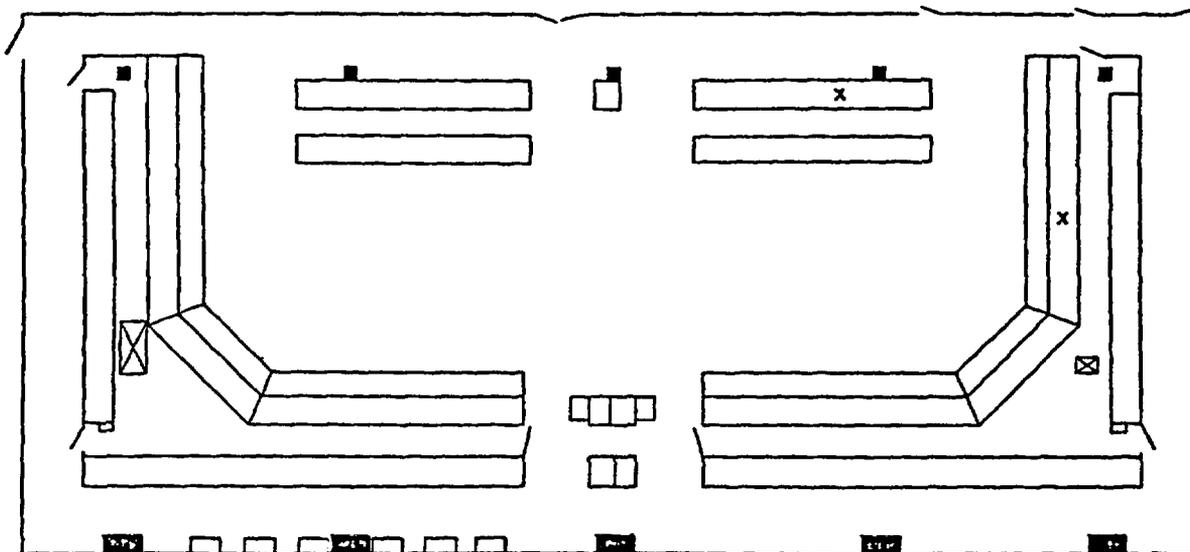


Figure 1. LaSalle control room - plan view

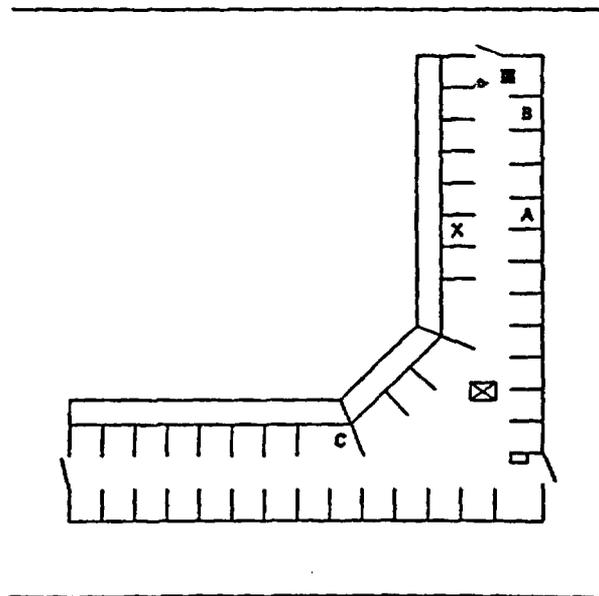


Figure 2. LaSalle control room - exhaust plenum - unit 2

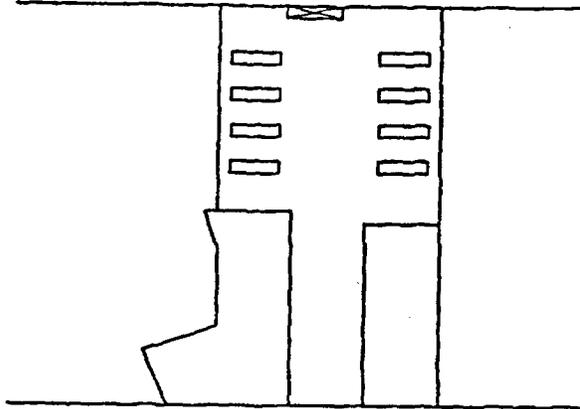


Figure 3. LaSalle control room - exhaust plenum - elevation

present state of evolution the model requires the heat release rate of the source fire as input to the code. The heat release rate used for nearly all of the simulation runs was determined in a series of cabinet fire tests performed previously for the NRC¹². The peak heat release rate used in the simulations is 600 kW; the temporal variation approximates that determined in Ref. 12. The design strengths of each ventilation source are also input to the code. Total flow into the control room is distributed throughout the inlet system as per design specifications. Design leakage through the control room doors is 1500 cfm; the remaining 22520 cfm exhausts through the vents located in each exhaust plenum ceiling. Locations and porosities of all flow obstacles are simulation input parameters.

B. Simulation Results

Each simulation run is preceded by a cold-flow case (without a source fire present) to characterize the steady-state ambient flow environment. Sample flow profiles from the cold-flow simulations are depicted in Figs. 4-6. Fig. 4 illustrates the flow at floor level. By comparison with Fig. 1, it is possible to see the pattern via which air flows into the L-shaped exhaust plenum. It should be noted that maximum velocity in this figure is 0.45 meters/second (m/s). In Fig. 5 the air flow near ceiling level is shown, and the locations of the two exhaust vents are clearly discernable. Maximum flow velocity in Fig. 5 is 1.5 m/s. Fig. 6 is an elevation view of the exhaust plenum showing both the flow of air into the bottom of the exhaust plenum and the subsequent outflow through the exhaust vent located near ceiling level. Maximum flow velocity in this figure is 0.6 m/s.

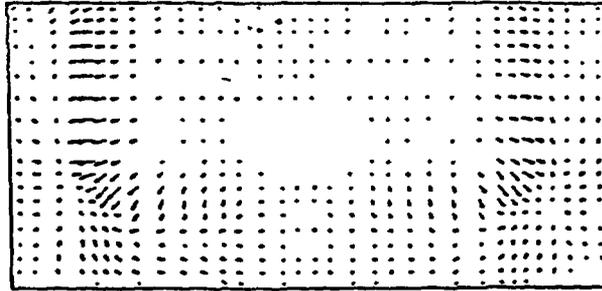


Figure 4. Cold flow velocity distribution - floor level

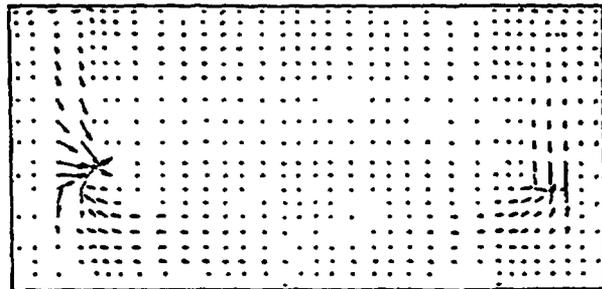


Figure 5. Cold flow velocity distribution - ceiling level

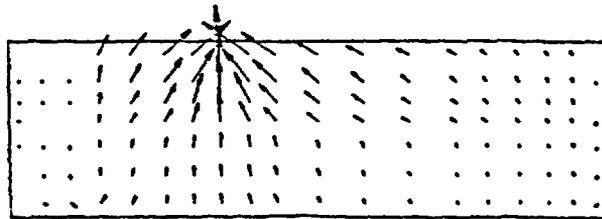


Figure 6. Cold flow velocity distribution - transverse elevation

Two separate simulations involving source fires were performed as stated above: one source fire located in the control room working area and one located in the Unit 2 exhaust plenum as shown in Figs. 1 and 2. As mentioned above, peak fire strength was 600 kW, while fire duration was 18 minutes. The 600 kW heat release rate was distributed in and above the cabinet in question to a flame height calculated from well-known flame-height correlations.

The first case to be examined was that of a fire in the main control room area. The modified flow patterns produced by this fire are depicted in Figs. 7 and 8. Both of these snapshots were taken six minutes after source fire ignition. Fig. 7 shows the flow at floor level indicating the entrainment of air into the fire plume as well as the flow into the L-shaped exhaust plenum. Maximum velocity for this figure is 0.65 m/s. Fig. 8 shows a horizontal elevation of the control room sliced through the source fire. The location of the fire stands out clearly. The flow of air through the bottoms of the cabinets and consoles and out the exhaust vents is also discernable. Maximum flow velocity is 4.2 m/s. The entrainment of air into the fire plume is shown most clearly in this figure.

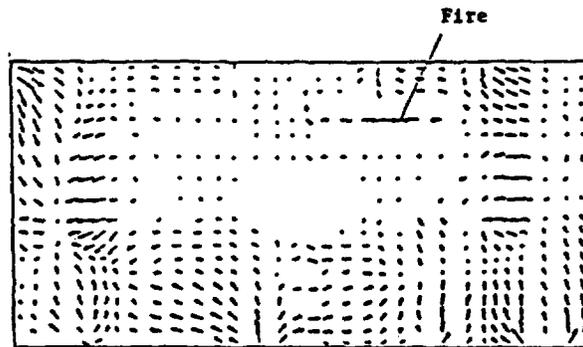


Figure 7. Velocity distribution fire case 1 - floor level



Figure 8. Velocity distribution fire case 1 - longitudinal elevation

Fig. 9 shows the temporal variation of gas temperature at a height roughly equivalent to the tops of the cabinets (-8 ft) both at the fire location and near the center of the control room. The temperature near room center is also representative of the gas temperature at various other locations throughout the control room. Gas temperature rose linearly in six minutes to 150°C in the control room center at the 8 ft height. Gas temperature above the fire plume near the ceiling rose to 240°C in 6 minutes. There was no appreciable gas temperature increase in the exhaust plenum due to this fire. Fig. 10 shows an example of perhaps the most valuable output from the simulations: an isothermal perspective of the control room. The 150°C isotherm is shown at 2, 4 and 6 minutes after fire ignition. The fire plume is clearly visible in the top view. The spread of the isotherm around the exhaust plenum can be seen in the remaining two views. Notice that the 150°C isotherm only descends to the top of the cabinets at the 6 minute mark. Fig. 11 depicts what is probably a more significant result for this case. The 50°C isotherm is shown in Fig. 11. The descent of this isotherm to cabinet (and personnel) height occurs in one to two minutes.

The second case to be investigated produces an entirely different set of results. For this case a source fire of the same strength is located within the exhaust plenum of Unit 2 as indicated on Fig. 2. Recall that the backs and the tops of these consoles/cabinets are open. Fig. 12 depicts the flow at floor level six minutes after the ignition of the fire. Entrainment into the plume can be readily observed. Maximum velocity is 0.75 m/s. Fig. 13 illustrates flow near ceiling level. Maximum velocity is 1.6 m/s. Flow out of the fire plume is observable as is flow into the exhaust vent. Note also the dead-end swirling effect of the flow at the top of the figure at the plenum boundary. This phenomenon accounts for some of the gas temperature data presented subsequently. Fig. 14 shows an elevation view of the flow pattern located adjacent to the fire. Maximum velocity is 6.0 m/s. This figure also illustrates both flow into the exhaust vent and the swirling at the end of the plenum.

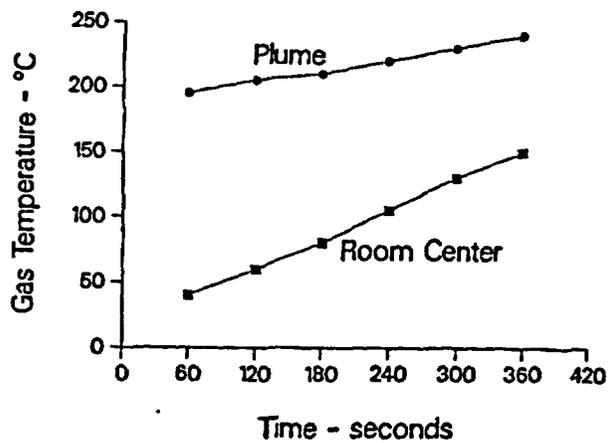


Figure 9. Gas temperature at cabinet level - fire case 1

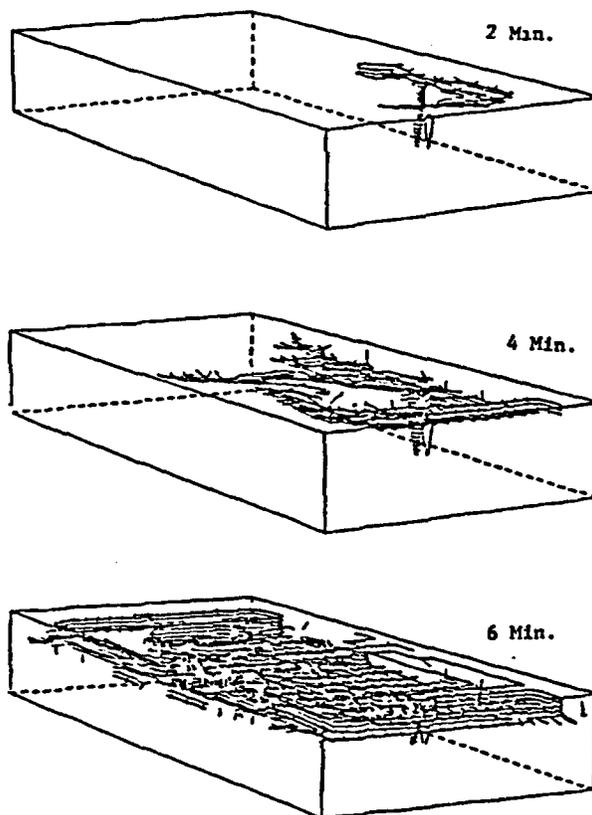


Figure 10. 150°C isotherm - fire case 1

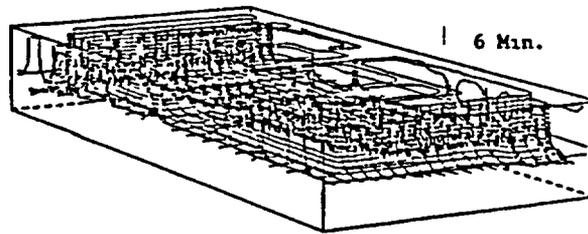


Figure 11. 50°C isotherm - fire case 1

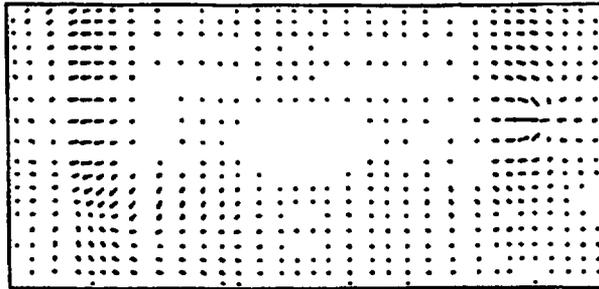


Figure 12. Velocity distribution - fire case 2 floor level

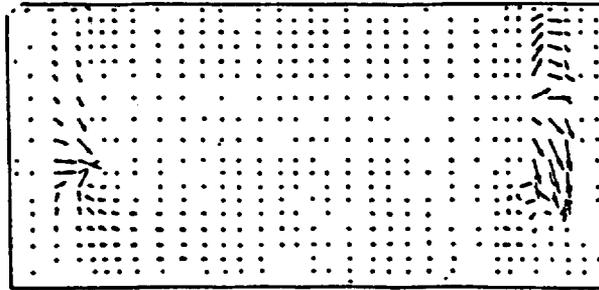


Figure 13. Velocity distribution - fire case 2 ceiling level

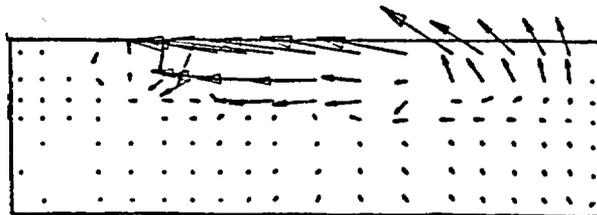


Figure 14. Velocity distribution - fire case 2 transverse elevation

In the case of a fire inside the exhaust plenum, temperature rise near the cabinet tops was more pronounced than in the previous case. Gas temperature rose to 200°C near cabinet level in about two minutes, as shown in Fig. 15. The three positions at which temperature is determined are indicated on Fig. 2.

Note that the gas temperature at position B at the plenum end is the most sensitive to the source fire. Mention must be made here that the gas temperature is a measure of the convective heat flux only; no radiation effects are yet included in the model. Fig. 16 shows the temporal evolution of the 150°C isotherm. The fire plume is clearly visible as is the dead-end effect generated by the plenum boundary and swirling flow pattern seen previously. Fig. 17 illustrates the evolution of the 200°C isotherm. Gas temperature at cabinet level at point B reaches 200°C about three minutes after ignition.

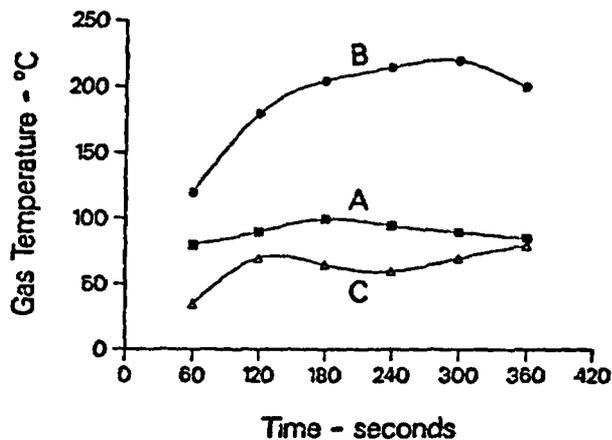


Figure 15. Gas temperature at cabinet level - fire case 2

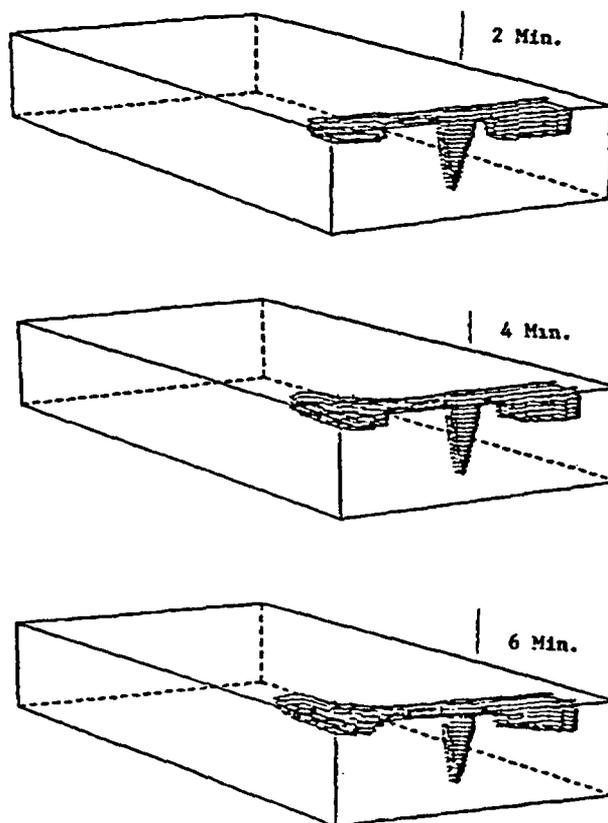


Figure 16. 150°C isotherm - fire case 2

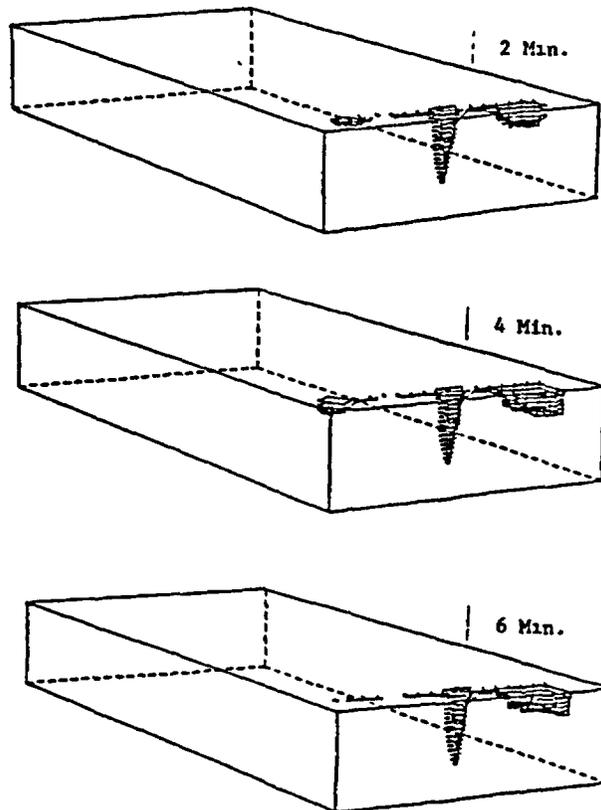


Figure 17. 200°C isotherm - fire case 2

A third case with a smaller source fire was also simulated. The location of the fire was in the exhaust plenum as above. Total heat release rate for this fire reached a peak value of 90 kW after 8 minutes, maintained this level for 22 min, and eventually burned out after 40 min. This fire was a comparison with an actual cabinet fire observed in the experimental portion of the FPRP conducted at SNL.¹³ This fire was so small that no effect was seen outside in the control room working area. Inside the exhaust plenum, a peak gas temperature of 70°C was reached at location B (ceiling level) 15 min after ignition. Temperatures near cabinet height were less than 60°C at all plenum locations. Flow phenomena were similar to those observed in the cold-flow case described above.

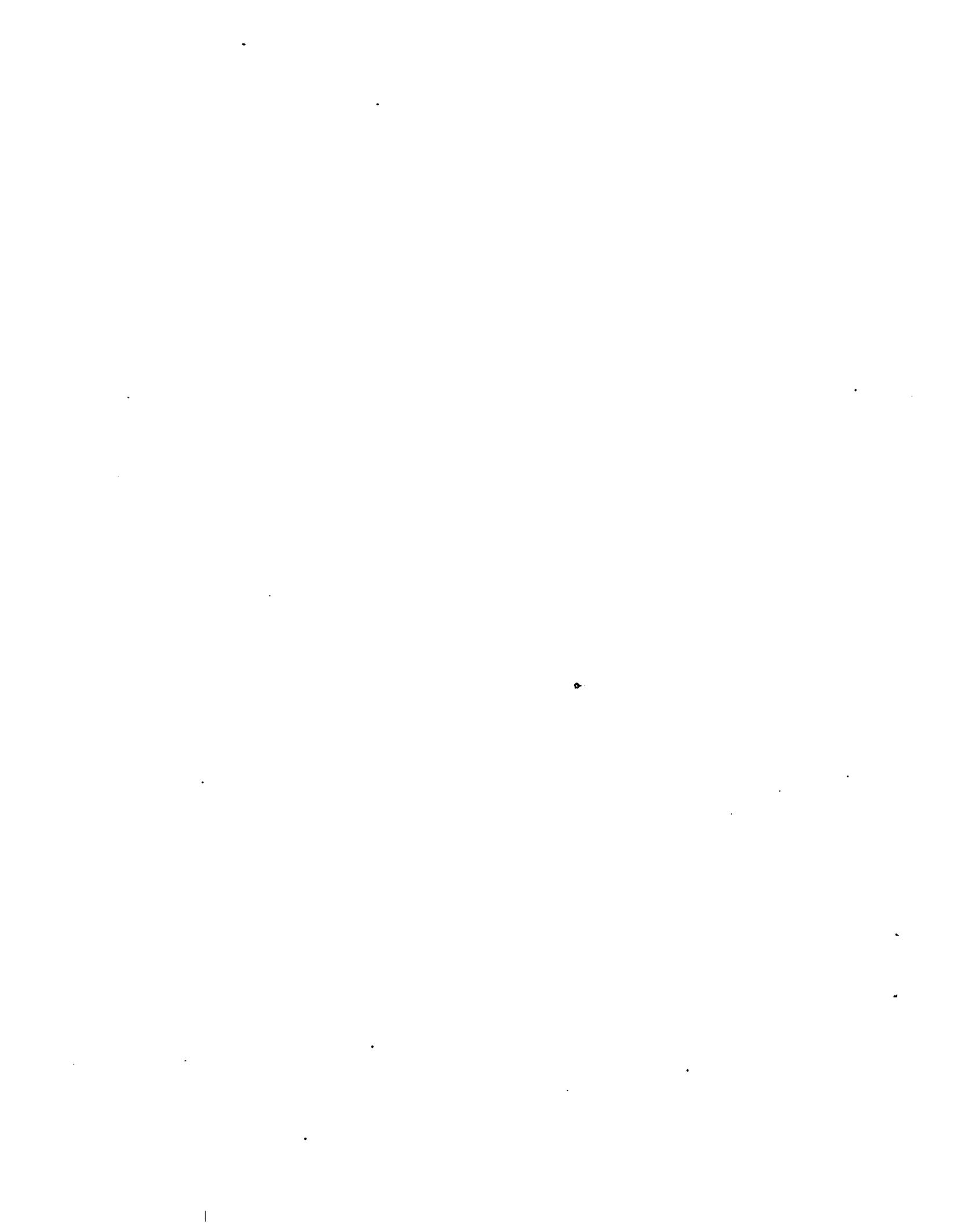
Detailed graphical analysis of each of the simulation cases described above is contained in a series of progress reports¹⁴⁻¹⁷ prepared by CHAM of North America, Inc., who performed the simulation calculations. These reports are available from the authors at BNL.



IV. CONCLUSIONS, FUTURE DIRECTIONS

Conclusions were reached regarding the two separate fire simulation examples, inside and outside the exhaust plenum. The fire in the control room working area did not produce temperatures higher than 150°C in the area of the control cabinets/consales over the time frame considered. These temperatures are probably not sufficient to cause equipment damage in the time scales noted. There is, however, concern in the area of habitability due to the fact that the temperature in the control room working area at cabinet level rose above 50°C in 1.5 minutes. Smoke may well descend in a manner analogous to the 50°C isotherm driven by the effects of room filling and the location of the exhaust gratings at the bottoms of the cabinets. The control room may become uninhabitable in this time frame. In the case of a fire in one of the exhaust plena, different conclusions are reached. Temperatures rose above 200°C at the cabinet level in 2 minutes, which may indicate when equipment or cable damage would begin to occur. Equipment in the dead-end area of the plenum may be most sensitive to this potential damage from high gas temperatures. Conversely, the environmental effects outside the plenum in the working area are negligible for this fire scenario; only the plenum area environment becomes inhospitable. It is also important to recall that there is at present no radiative heat transfer model in SAFFIRE; thus, thermal radiation damage effects on equipment/cables can not be determined at present. There is also evidence that fires larger than 600 kW can occur in cabinets/consales,¹³ which would correspondingly increase the damage potential of the fire. It was assumed in the course of these simulations that no secondary fires occurred; this may not be the case in the plenum area in view of the fact that cable trays pass through the upper portion of the fire plume (Fig. 3). Any of these effects would exacerbate equipment/cable damage potential.

A final series of definite conclusions regarding the specific effects of these potential fire-induced environments on equipment can not be reached at this time due to the need for specific values and parameters of damage criteria. These criteria are being determined as part of the FPRP. Additional specific conclusions concerning smoke and harmful combustion species also await the determination of source term and propagation properties being measured as part of experimental portions of the FPRP. The future direction of the FPRP as well as the integration of the products of the FPRP with PRA methodology are indefinite at this time due to severe cutbacks in NRC research funding as initiated by the Gramm-Rudman legislation. Nevertheless, we continue to recommend the extension of the modeling efforts of the FPRP as well as the efforts to integrate SAFFIRE into PRA methodology and the more general areas of concern to both Nuclear Reactor Regulation and Inspection and Enforcement.



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One of the objectives of the Fire Protection Research Program (FPRP) of the U.S. NRC is to improve the modeling of environments caused by fires in typical nuclear power plant enclosures. A three-dimensional fluid dynamics computer code (PHOENICS) has been adapted as a field-model fire code (SAFFIRE) for this purpose. The model has been applied to simulate two distinct fires in the control room of the LaSalle County power plant. The environments determined illustrate hazardous potential for both personnel and equipment.

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