NUREG/CR-4479
BNL-NUREG-51948

THE USE OF A FIELD MODEL TO ASSESS FIRE BEHAVIOR IN COMPLEX NUCLEAR POWER PLANT ENCLOSURES: PRESENT CAPABILITIES AND FUTURE PROSPECTS

John L. Boccio and John L. Usher

December 1985

RELIABILITY & PHYSICAL ANALYSIS GROUP
DEPARTMENT OF NUCLEAR ENERGY, BROOKHAVEN NATIONAL LABORATORY
UPTON, NEW YORK 11973

Prepared for
United States Nuclear Regulatory Commission
Washington, D.C. 20555

8603310046 851231
PDR NUREG
CR-4470 R PDR

NUREG/CR-4479
BNL-NUREG-51948
AN, R-7

THE USE OF A FIELD MODEL TO ASSESS FIRE BEHAVIOR IN COMPLEX NUCLEAR POWER PLANT ENCLOSURES: PRESENT CAPABILITIES AND FUTURE PROSPECTS

J.L. Boccio and J.L. Usher

Manuscript Completed — November 1985
Date Published — December 1985

RELIABILITY AND PHYSICAL ANALYSIS GROUP
DEPARTMENT OF NUCLEAR ENERGY
BROOKHAVEN NATIONAL LABORATORY
UPTON, N.Y. 11973

Prepared for
DIVISION OF ENGINEERING TECHNOLOGY, RES
OFFICE OF NUCLEAR REGULATORY RESEARCH
U.S. NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555

UNDER CONTRACT DE-AC02-76CH00016
FIN A-3252

ABSTRACT

This report provides a summary of the work conducted during FY-1984 by Brookhaven National Laboratory (BNL), under FIN A-3252 "Fire Protection Research Program." It was undertaken under the cognizance of the Electrical Engineering Branch in the Division of Engineering Technology within the Office of Nuclear Regulatory Research. The report describes a mathematical model for predicting the thermal environment within complex nuclear power plant enclosures. It demonstrates the capability of the existing numerical code by direct comparisons with electrical cable fire/large enclosure tests performed by Sandia National Laboratories (SNL) for the NRC and by the Factory Mutual Research Corporation (FMRC) for the Electric Power Research Institute (EPRI). It further demonstrates the potential usefulness of the existing code in addressing fire-protection issues. This is done through a parametric study of the thermal environment resulting from a series of fires within cabinets in a nuclear power plant control room (similar to LaSalle). Also, it presents an example of how the code can be utilized by addressing an Appendix R exemption request which deals with the vulnerability of containment fans to a fire emanating from a reactor coolant pump bay. Recommendations are also given as to how the model/code can be further enhanced and where current effort is proceeding.

ACKNOWLEDGEMENT

This work was performed for the Electrical Engineering Instrumentation and Control Branch (EEICB) of the U.S. Nuclear Regulatory Commission. Dr. Amar Datta of EEICB was the technical monitor of the project and the authors wish to acknowledge him for providing useful guidance and comments throughout the course of this program. Special thanks go to our subcontractor, CHAM of North America, and especially this organization's technical director, Dr. Ashok Singhal. The use of this organization's proprietary code, PHOENICS, was the basis for the numerical predictions present herein.

Finally, the authors wish to acknowledge our secretary, Ms. Jeanne Danko, without whose dedicated efforts and attention to detail this report would not have been completed in a timely fashion.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (Cont'd)

EXECUTIVE SUMMARY

A. BACKGROUND

For the past several years research in fire protection measures and fire safety conducted by the U.S. Nuclear Regulatory Commission (NRC) has focused on providing technical bases upon which specific deterministic requirements for fire protection could be established. The requirements, buffered by these research activities, are contained in Appendix R to 10CFR50 and in Section 9.5.1 of the Standard Review Plan (SRP). These criteria/guidelines indicate the minimum necessary fire protection measures and features such as separation by fire barrier or distance, automatic fire detection and suppression, and system redundancy to limit fire damage while not impairing those engineered safety features designed to safely shut down the plant.

Efforts by utilities in either complying with or seeking exemption from these requirements have largely relied on the use of analytical fire models to provide justification to their proposed fire-safety design changes or to indicate that existing features conservatively comply with the overall fire safety mandates. In the course of evaluating these analyses, the NRC must judge whether they incorporate state-of-the-art models and recent test results. Particular attention must be given to ensure that the application of the models is consistent with the assumptions and limitations of the particular unit-problem fire models employed in the fire hazards analysis.

The scope of these reviews entail answers to the following questions:

- Are the fire scenarios analyzed reflective of what may realistically occur? In other words, does the physical model employed represent an adequate and conservative replication of the major fire-related phenomena.

- Concomitantly, does the mathematical model adequately portray these major physical processes and geometrical constraints?

- Does the actual scenario bound the overall problem?

- Are the conclusions drawn from the calculated results uniformly valid with the assumptions made to provide a tractable analysis?

Responding to these questions as well as other "fire damage" issues which have been raised indicates a need for NRC to develop a computational capability to determine the margins of safety inherent in various fire protection features and layouts in nuclear power plants (NPPs).

Also, reflecting upon the increasing emphasis and use of probabilistic techniques in the assessment of NPP risk in general, and the risk due to internal fires in particular, further indicates a need to develop a fire-scenario modeling capability. Only recently has the probabilistic analysis of internal

fires become an accepted, albeit immature, part of full-scale Probabilistic Risk Assessment (PRA) studies. The more difficult aspects of the probabilistic analysis occur in estimating the likelihood that equipment will be disabled by a fire. This problem is compounded by the existing uncertainties in deterministic/probabilistic modeling of detection and suppression systems, the stochastic nature of fire growth over time, and the size and geometric complexity of the fire zone wherein hot gases can cause equipment failure or induce secondary fires.

A number of important models have been developed over the years to assist the analyst in calculating the likely progression of a fire, but in even the simplest cases the quantitative uncertainties remain large. Available fire-growth and fire-enclosure models are highly approximate in character and are not capable of accurately modeling the fire-induced environment in a compartment of crowded objects situated in a unique configuration. Also, the analysis of failure modes for components exposed to the whole spectrum of combustion products (heat, smoke, toxic aerosols) needs more methodological development enhanced by test data. Methods must also be developed for treating the intercompartmental spread of fire and combustion products.

The need for conducting fire testing in complex, large test enclosures that contain flow obstacles, prototypic fire-sensitive equipment, and house forced ventilation systems requires that a computational capability be developed to economically scope a fire-test program.

For the NRC to determine how fire safe nuclear power plants are, how much fire-safety improvement, if any, is required, and how the desired level of fire safety can be ensured during the lifetime of the plant more sophisticated and phenomenologically complete mathematical tools must be developed to assist them in their regulatory, decision-making process.

B. SUMMARY OF EFFORTS

As a continuation of a research project initiated in FY 1982, prior efforts entailed surveys of both national and international research programs which could be a factor in formulating nuclear power plant fire protection programs and guidelines. Keeping abreast of these fire-protection research programs undertaken by the fire-science community and apprising NRC of the results, conclusions, and possible implementation into NRC's decision-making process (as it relates to fire-safety issues) provided the necessary background and experience to complete a survey of enclosure fire models that specifically employ three-dimensional, transient field model techniques. Also, understanding NRC needs in nuclear power plant fire safety and the issues raised allowed BNL to develop criteria for selecting one of these modeling approaches which has the potential for analyzing the fire-induced environment in enclosures typical of NPP critical areas.

Based on the criteria established, a computational model was selected. Efforts in FY 1984, summarized in this report, were scoped to demonstrate further the capability of the selected analytical model/numerical code. This largely entailed comparisons with cable fire/enclosure tests conducted for the Electric Power Research Institute (EPRI) and for the NRC. The former test program was performed by the Factory Mutual Research Corporation (FMRC) in their intermediate scale facility; the latter was performed for Sandia National Laboratories in their investigation of spatial separation as a fire protection method. Comparisons with both test programs are promising to the extent that the model-demonstration phase is essentially complete and model enhancement can proceed.

This report also describes the effort started in FY 1984 in which a parametric study of potential fire environments within nuclear power plant control room configurations was conducted. This work was undertaken to provide additional fire-modeling capability to those fire-risk tasks associated with NRC's Risk Methodology, Integration, and Evaluation (RMIE) Program. As such, preliminary efforts have been directed toward numerical investigation of potential fire scenarios in the LaSalle NPP control room. Prefatory analysis of the fire environment within the LaSalle Control Room, caused by a fire within a control cabinet is documented in this report also. The results are indeed promising, and the ensuing thermal environment is physically plausible.

In addition to numerical comparisons of enclosure fire tests involving electrical cables and parametric studies of cabinet fires within realistic complex control-room configurations, this report presents numerical comparisons of the effects of a reactor coolant pump lube oil fire within a particular plant containment building. This latter demonstration emphasizes the value of the mathematical model as a tool which can be used by NRC in their review of licensee Appendix R exemption requests.

C. RECOMMENDATIONS

Based upon favorable comparisons with experiments and the plausible results from parametric studies and case-specific Appendix R exemption requests, this report details future directions in model improvement which can further enhance its usefulness in addressing fire protection and fire risk issues. In this regard, it is recommended that effort should continue in the following three areas:

1. Further adapt the three-dimensional field model in order to incorporate within the numerical code additional energy generation and heat exchange mechanisms. Energy generation mechanisms to be included in the multi-component aspects of the mathematical model should contain those features which account for the afterburning of pyrolysis products. To keep the analytical modeling tractable, emphasis should be placed on employing a simple, existing chemical-reaction scheme or a one-step quasi-global gaseous reaction mechanism, coupled with a

combustion-inefficiency parameter. This presupposes that input to the code will include mass fractions of the major reactant products.

Heat exchange mechanisms, notably losses due to conduction and radiation, should also be modeled. However, these loss mechanisms (or thermal energy transfer mechanisms) are to be treated in an ancillary manner and coupled to the conservation equations through a unit-problem approach. For example, instead of using relations directly linked to the general governing equations, constitutive unit models will be employed which are somewhat decoupled from the convective and diffusive exchange processes. Thus, radiative heat transfer could be treated by linking zone models to the field model, employing view factors and global energy transfer considerations. This will allow global radiation transfer from the hot gas layer and the flame zone to selected targets to be determined simply.

This model enhancement can be used in the design of a fire-test experimental program and could assist SNL's fire-research efforts by identifying the parameters, instrumentation locations, relevant fire locations, etc., for their test program.

2. Apply the upgraded model, at an appropriate level of development, to complete the parametric study (started in FY 1984) to investigate potential fire environments in the LaSalle Plant control room. The parametric study and model development should be initially tied directly to existing NRC concerns for this type of fire area, e.g., control room habitability during the early stages in the developing fire. Means for appraising final room-damage states and plant operability from the control room after the fire has been extinguished will also be key modeling features that should be examined. Fire suppression activities (manual/automatic) can be modeled during this effort. Detection/suppression models can be augmented into the existing code/mathematical model.

3. In addition to parametric studies of control room environment, given a selected series of realistic initiating fires, the upgraded model should be used to predict potential fire environments in other nuclear power plant enclosures. As potential support to the fire-risk tasks of the RMIE Program (FIN A-1391) initial guidance for choosing other enclosure/geometries will come from the critical fire area screening analyses to be conducted for the LaSalle plant.

This report indicates that continued future efforts should be conducted with the existing code and its adaptations through parametric studies of critical fire areas and identified by screening analyses performed through "external-event" risk studies. By the example applications described in this report, however, the results show that at its present stage of development, the model/code can be a useful adjunct to NRC's decision-making process in addressing fire-safety issues.

I. INTRODUCTION

A. BACKGROUND: FIRE PROTECTION SAFETY ISSUES AND PROGRAM OVERVIEW

Appendix R to 10 CFR Part 50 and the Branch Technical Position CMEB 9.5-1 establish the fire damage limits to systems associated with achieving and maintaining safe hot shutdown condition of the nuclear reactor as follows:

> "One train of equipment necessary to achieve hot shutdown from either the control room or emergency control station(s) must be maintained free of fire damage by a single fire, including an exposure fire."

This is interpreted as a clear requirement to maintain at least one of the redundant trains of safe hot shutdown equipment in continued operable condition, even after exposure to a fire or a fire environment. Section IIIG of Appendix R and Section C5.b of the BTP spell out three options available to the licensee to meet this requirement, one of which is the "20-ft separation" option. The licensee may meet the requirement of maintaining a hot shutdown capability by separating the redundant trains by a horizontal distance of more than 20 ft, with no intervening combustibles or fire hazards, provided that fire detectors and an automatic fire suppression system are also installed in the fire area.

The Office of Nuclear Reactor Regulation requested a series of tests to ascertain the adequacy of the 20-ft separation option. Full-scale replications of a nuclear power plant enclosure were set up, with cable tray systems representing the two redundant trains located a horizontal distance of 20 ft apart. In some of the tests[1] in which one of the redundant trains (a vertical cable tray) was set on fire, the second train suffered electrical failures occurring at varying times from the inception of fire. IEEE Std. 383-qualified cables fared better than their unqualified counterparts, and expectedly, fire retardant coatings and ceramic fiber blankets on cable trays improved the chances of survival of both types. No suppression of the fire was attempted in order to ascertain the level of protection afforded by spatial separation alone without benefit of the automatic suppression system.

The tests provided valuable insight into the fire growth process in a cable tray and the nature of the consequential damage to a second cable system separated by an intervening space. They did not, however, provide the basis for extrapolation of the data to the numerous combinations of enclosure geometry and equipment layouts that are encountered in nuclear power plants. It has also since been realized that safe shutdown equipment other than cables may be vulnerable to fire. Obviously, some measure of protection is obtained by spatial separation of the redundant trains. This protection, however, is effective for a limited maximum severity of the exposure and for a limited duration. The severity of the fire exposure in turn is dependent not only on its own characteristics, such as the heat evolution rate, but also on factors such as fire enclosure geometry, equipment layout, door and vent locations, fire locations, and ventilation rate. Therefore, the NRC has not been able to clearly confirm the adequacy of the 20-ft separation option. However, based on experience to date, the question may best be addressed by studying the various factors affecting the continued operability of equipment exposed to fire. These factors are:

1) the characteristics of the fire (energy and mass release rates),

2) the environment produced by the fire (temperature, heat flux, species concentrations), and

3) the response of the equipment itself to the environment (fire damage thresholds).

The overall fire protection research program being conducted by NRC, which is discussed in more detail below is, therefore, to investigate these factors separately and to combine the acquired knowledge at a later stage to address the totality of the problem.

Additional specific needs are also addressed within the overall framework of the fire protection research program. Among these are: 1) enhancing fire test programs, and 2) addressing PRA fire-related issues. The above issues constitute a more thorough view of the overall objectives of the fire protection research program.

Full-scale fire test programs represent necessary yet expensive means for determining enclosure fire environments. Case-specific fire tests represent prohibitive costs to both the NRC and licensees. Careful fire environment characterization and consequent modeling capability produced by this program can aid in the careful selection of full-scale test cases and reduce the number of tests required, thereby lowering costs.

Probabilistic studies (PRA) of nuclear power plants require data regarding the occurrence frequencies and consequences of events which take place within plant environs. Also, more detailed fire models can be used to benchmark models used in fire-risk analysis thereby providing some measures of modeling and data uncertainties inherent in these simpler models. An example of an event of interest would be a fire within a safety-related NPP area. Data regarding the consequential outcome of a fire in a specific plant area would likely not be readily available. The effects of fire on safety-related equipment within the NPP characterized by the fire protection research program would provide data to the PRA analysis.

B. STUDY OBJECTIVES

NRC's Fire Protection Research Program (FPRP) is a multiphase, multiyear research program requiring close coordination between the fire-modeling effort being conducted at BNL and the continuing experimental program being undertaken at Sandia National Laboratories. 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. These three goals will be met by (a) defining fire sources with respect to their energy and mass release rates, (b) determining the environment resulting from the fire, and (c) determining the response of certain safe shutdown equipment and components to the environmental conditions.

As a subset to this overall objective, this report summarizes the work conducted by Brookhaven National Laboratory (BNL) to utilize, enhance, and develop a computational capability for determining the environments within plant enclosures caused by fires and to initiate a probabilistic fire model/fire data base to support fire-risk activities and projects within the NRC.

In this regard, this report essentially provides, in Section II, a detailed description of the various elements and basics of the FPRP that have been conducted at BNL. This section also illustrates the coordination efforts between the two laboratories. In Section III, the results of these fire-modeling efforts are presented. Where this program is currently directed and what further fire protection issues remain for analysis are discussed in Section IV. More specifically, this report provides the following:

1. A survey of actual fire loads and configurations within nuclear power plants (NPPs) and a classification scheme into several generic enclosure configurations. The purpose of this effort and the results, detailed more fully in Section II-A, is to assist in the development of a cost-effective enclosure fire-test program.

2. A process for selecting an existing fluid dynamic model/code which can be utilized to investigate the thermal environment within complex NPP enclosures resulting from prespecified initiating fires. The results of this selection process are described in Sections II-C, III-B-1, and III-B-2.

3. A demonstration that, by experimental comparison, the selected model/code has the potential for addressing the fire-protection issues previously described. Results of the efforts devoted to this demonstration phase are provided in Sections II-C and III-B-2.

4. A description of BNL's involvement in the development of an enclosure fire test program structured to conform to the generic enclosure survey delineated above. Further details summarizing this effort are given in Sections II-C and III-B-3.

5. A parametric study of the thermal environment within a plant-specific control room resulting from a series of control cabinet fires. The results of this phase of the study are detailed in Section III-C.

6. An example of the use of the code in an existing nuclear plant. In Section III-D, results are shown in which the selected code was used to analyze the spatial and temporal variations in a plant-specific containment building resulting from a fire in one of its reactor coolant pump bays.

7. A discussion in Section IV concerning where effort in this program is currently proceeding.

II. FIRE PROTECTION PROJECT DESCRIPTION

Within the four sub-program areas, outlined in the NRC Program Plan, there is a division of effort between BNL and SNL which is essentially along the lines of modeling and experiment. The remainder of this report addresses the BNL contributions to the overall FPRP which are essentially the modeling and code development efforts. A summary of the BNL contributions within each subprogram is outlined below.

A. FIRE SOURCE CHARACTERIZATION (FSC)

Survey of Actual Fire Loads and Configurations in NPPs. A survey of a number of nuclear power plants has been performed and a tabulation made fire-area wise of in situ and transient fire loads. The geometry of the fire area, classification as to room type (vault, corridor, or bay), ventilation conditions, and equipment type and location were also noted. The survey was restricted to fire areas where threats to safety-related equipment may originate. Plant fire hazard analyses, licensee submissions for exemption from Appendix R requirements, PSARs, and FSARs were the sole sources of this survey.

Survey of Existing Research Results. The mass and energy release rate characteristics of probable source fuels such as flammable liquids in pools and cable bundles were assembled from the literature. This project has already been detailed in previous letter reports to the NRC and is not discussed further here.

Experiments to Augment Existing Data. Experiments have been planned to fill gaps in the information. The fuel configurations in such experiments will be well defined and the fire unrestricted by ventilation. The experiments will cover a range of sizes (Btu content) for each fuel and configuration. A large part of this effort is described below under the subject of test matrix development.

Recommendations for Source Fires. Source fires are to be defined from the envelopes of mass and energy rate curves and possibly species concentrations also obtained from the above experiments and surveys. This project has already been detailed in previous letter reports to the NRC from BNL and SNL and is not discussed further here.

B. FIRE ENVIRONMENT DETERMINATION (FED)

Fire Environment Model and Computer Code Selection. This task involved a survey of existing fire models and selection of one for development in order to address the problem of determination of fire environments in nuclear power plant enclosures with typical layouts of safety-related equipment. The model is to be translated into a user-oriented computer code, capable of describing the environmental parameters (temperature, velocity, fire-induced species concentrations) in three dimensions as functions of time elapsed from fire inception.

Computer Code Selection/Development. The computer code, which is the numerical counterpart of the fire environment model, was selected based upon the following requirements:

1) The analysis/numerical code in its basic form has already been utilized in enclosure/fire plume studies.

2) The code has the capability to predict the spatial and temporal variation of those fire-induced physical parameters deemed necessary to appraise the vulnerability of safe shutdown equipment, e.g., temperature, smoke, toxic gases and unburned pyrolysis products.

3) The code has the capability to assess the effects of enclosure geometry complexity such as obstacles and openings to the movement of the thermal energy flux, mass flux, and momentum flux fields.

4) The effects of forced ventilation and its attendant impact on the distribution of the thermal energy generated by the fire within the enclosure can be addressed by the code.

5) The code is able to treat several types of enclosure fires resulting from the burning of liquid and solid combustibles.

6) The code has the flexibility to analyze fires resulting from the burning of complex solid fuel configurations.

7) Exposure fires at various locations within the enclosure (e.g., centrally located, against a wall or corner) are also within the realm of the code's capability. The code is capable of mapping the three-dimensional, fire induced thermal energy field.

8) The code is structured in a modular fashion so that other fire related aspects such as detection, suppression, and barrier effectiveness can be readily analyzed once the requisite additional analysis is supplied.

9) Fluid flow is treated as three dimensional and elliptic, i.e., flow in one part of the building can be affected by changes in conditions in other parts as well as outside the building.

10) Transient analysis is to be performed for the entire duration of the exposure fire burn (i.e., typically 30 minutes).

11) The flow rate, temperature, and composition of the plume gases, prescribed as boundary conditions, can change with time.

12) The afterburn of plume gases may be accounted for by using an equilibrium chemistry model. The practice of simple chemically reacting systems will be adopted. In this manner, scrupulous details of local, multiple step reactions will be avoided, and the calculated gas temperatures will be expected to err slightly on the conservative side.

13) Buoyancy effects are accounted for by having an appropriate gravity force term in the momentum conservation equation.

14) Fluid is allowed to enter or exit through the openings (vents, etc.) in the building, the magnitude and direction of the flow depending on the local difference between the ambient and inside pressure, which can and does change with time.

15) Internal solid objects such as interbay walls, columns, horizontal working platforms, etc., are simulated by specifying infinitely large flow resistances in the appropriate momentum equations. As a result, the normal velocity components at solid surfaces will be zero.

After demonstrating that the code has the capability of complying with the above requirements/criteria, the FPRP is structured for further code development. In conjunction, it will subsequently be used to compare with the "benchmark" tests (see following) so that reasonable confidence is gained in its predictions in new applications. The postulated fire conditions for the computer simulation will be the source fires developed in the FSC Project. Prior to direct comparison with results from the test program the code will be developed independently of the FSC Project in the interim period, using characteristics of known test fires as input. Two sets[1-2] of previously conducted cable fire tests have been utilized in a series of preliminary benchmarking calculations. The results of these preliminary comparisons are described below.

Benchmark Testing. The generic enclosure survey has produced information on typical enclosure geometries and equipment layouts so as to define a number of generic enclosure geometries and generic equipment configurations. These enclosures, and to some extent the equipment, are to be replicated in a series of fire tests where the energy and the mass inputs will be controlled to reproduce the postulated fire sources. The instrumentation is designed to monitor the various thermodynamic variables throughout the enclosures. The tests have been planned to cover a range of geometrical variables (length, width, and height ratios) and a range of fire severities (Btu outputs), so that the totality of the test results by itself permits a degree of confidence in extrapolation to other realistic situations.

Code Validation and User Package Preparation. The fire environment computer code will be continuously refined by comparison with the benchmark tests until reasonable confidence is gained concerning the accuracy of its predictions. A complete package will then be developed for the NRC comprising the necessary software, including a full listing of the program statements, flow charts, and user instructions.

Combustion Product Migration. With the addition of existing submodels, the computer code will be extended further to compute room-to-room migration of toxic combustion products, which may affect the operability of equipment not within the enclosure containing the source fire. This capability will be useful in evaluating designs/layouts for which fire dampers and 1- or 3-hour fire barriers have been employed for fire protection but for which migration paths may exist between fire areas.

C. CONTROL ROOM HABITABILITIY AND FIRE SAFETY STUDY (CR)

Control Room Fire Vulnerability. Control rooms are characterized by assemblies of complex instrumentation and control cables in a high density layout. Adequate separation of the redundant trains of the safety-related equipment is usually impractical in this situation. Fire protection in a control room situation must, therefore, rely on immediate detection and automatic suppression of the fire, as well as on the installation of protective enclosures, thermal insulation, and barriers where practicable. The vulnerability of the equipment to the fire, its products, and the suppressants becomes especially important. The techniques of analysis by computer simulation developed in the FED Project will be applied to control rooms to predict the environment in the event of various postulated fires, whose characteristics have been developed by FSC. The environments, coupled with the fire failure thresholds (FFT) of the various safety-related equipment, would enable determination of safety margins. Consideration will be given to the electrical systems aspects of control.room designs including employment of circuit breaking devices and the capability to control and monitor shutdown activities from a remote control panel.

While some of the above projects represent future aims of the FPRP, a large majority of the code development and the experimental planning projects have been performed in this past fiscal year. Detailed descriptions of these projects and summaries of their results follow.

III. BNL PROJECT SUMMARIES

A. FIRE SOURCE CHARACTERIZATION PROGRAM

Survey of Actual Fire Loads and Configurations in Nuclear Power Plants. A survey of enclosures (fire areas) in thirteen nuclear power plants was performed. The plants surveyed were either PWRs or BWRs. The overall purpose of the survey was to identify the generic enclosure parameters present in NPPs along with equipment types present in each enclosure. Combustible loadings were also specified as part of the task. A total of 134 enclosures were tabulated and are presented in Table 1. A key is also provided as an aid in understanding the enclosure specifications.

Enclosures are classified according to three generic types: (1) vault (ℓ:w:h ≈ 2:2:1), (2) corridor (ℓ:w:h ≈ 4:1:1) and (3) bay (ℓ:w:h ≈ 1:1:3). In the fire area survey 89 vaults and 34 corridors were found. The typical vault enclosure had a $\bar{\ell}:\bar{w}:\bar{h}$ ratio of 3.5:2.2:1.0 with an average height of 20 ft. The corridors had a $\bar{\ell}:\bar{w}:\bar{h}$ ratio of 9.2:1.3:1.0 with an average height of 15 ft. Also encountered in the geometry survey were 19 rooms with odd configurations, i.e., L-shaped, C-shaped, T-shaped, etc.

Fuel loads in the range of 1-19 lb (combustible)/ft^2 and 1-50 kBtu/ft^2 were found. The cable insulation loads were predominately in the ranges 14-18 lb/ft^2 and 35-50 kBtu/ft^2. Oil, grease, cellulose and charcoal were the other significant combustibles located within the fire areas.

Ventilation was also surveyed as a part of the project. Natural ventilation was found throughout in the form of doors, hatches and access openings at the fire area boundaries. Stairwells, elevators and pipe chases are also indicated in Table 1. Forced ventilation strengths and locations are also delineated where available. Typical ventilation rates in vault-type enclosures range from 1-12 room changes/hr. Switchgear rooms are typically at the high end of this range with from 10 to 12 room changes/hr.

Equipment types present in each fire area have been surveyed. Equipment type has been categorized generically as (1) cables, (2) panels and cabinets, and (3) motors, generators and pumps. Designations of safety related equipment have also been recorded in order to determine the relative positions of redundant safety systems within a given fire area. Due to space limitations these data are not depicted in Table 1.

The sources of this survey were fire hazard analyses, licensee submissions for exemption from Appendix R requirements, and to a lesser extent, PSAR's and FSAR's.

TABLE 1 KEY

ENCLOSURE CLASS	V	Vault (L:W:H≈2:2:1)
	C	Corridor (L:W:H≈4:1:1)
	B	Bay (L:W:H≈1:1:3)
EQUIPMENT	P	Panels, Cabinets
	G	Generators, Pumps
	C	Cables
FUEL LOAD	lb	(combustible)/sq. ft.
	g	gallons
	kB	thousand BTU
	kBsf	thousand BTU/sq. ft.
	lb	pounds of grease
	C'	cellulose (lb/sq. ft.)
	char	charcoal
	NF	treated with flamemastic and not considered flammable
DOORS	x/yN	x-single/y-double North Wall
	zE	z-single East Wall
	eW	Elevator West Wall
ACCESS	N/y'	north wall/y ft wide
	pc	pipe chase
STAIRWELLS	d	down
	u	up
HATCHES	n/y'xz'	n hatches/y ft. x z ft.
	F	floor
	pc	pipe chase
	c	ceiling
VENTILATION RATE		thousand cubic feet/minute
	AC	air conditioning
	EX.	exhaust
	SP.	supply
GEOMETRY	x	L length/height
	y	W width/height
	z	H height in feet
	C	C-shaped room
	L	L-shaped room
	I	I-shaped room
	X	intersecting hallways
	T	T-shaped room
	Δ	triangular room

TABLE 1 KEY (Cont'd)

PLANT	L	Limerick
	Z	Zion
	PI	Prairie Island
	Pt.B	Point Beach
	IP	Indian Point 2
	P	Palisades
	PB	Peach Bottom
	G	GESSAR
	M1	Millstone 1
	M2	Millstone 2
	St.L.1	St. Lucie 1
	TP	Turkey Point
	B	Brunswick
TYPE	P	PWR
	B	BWR
ROOM LOCATION	C	Control Building
	R	Reactor Building
	A	Auxiliary Building
	T	Turbine Building
	G,DG	Diesel Generator Building
	RW	Rad Waste Building
	F	Fan House
	I	Intake Building
	SW	Service Water Intake Structure

ROOM NUMBER	1	2	3	4	5	6*	7*	8	9	10	11	12	13
ENCLOSURE CLASS	V	V	V	V	V	V	V	V	V	V	V	V	V
EQUIPMENT	P	P	P	P	P	P	P	P	P	P	P	C,P	P
FUEL LOAD CABLE OIL TRANS/MISC.	1,8	1,0	3,1	1,7	3,4	2,6	2,0	2,7	1,2	6,0	13,5	17,8	2,6
DOORS	0/1 N 2/1 E 3/1 W	2 N	1 E 2 W	1 N 1 N eW	2 N 2 W 0/1 E	0/1 E	0/1 N 0/1 S 0/2 W	2 N 2 E 1 S	1 N 1 S 1 NW		1 W 1 S	1 N 1 S	1 N 1 S
ACCESS								W/?		S/8'			E/1'
STAIRWELLS												1	1
HATCHES	FAN VENTS			3									
VENTILATION RATE							2,0	1,7	4,0	3,3	3,8	15.	10,8
VENTILATION ORIENTATION													
GEOMETRY	5,7 2,6 22	6,5 3,3 18	9,2 4,4 14	5,4 4,8 28	2,8 1,9 24	3,5 2,8 12	4,3 2 24	5,6 3,8 [illegible]	2 1,4 19	3,1 1,2 16,5	3,9 1,6 17	4,6 3,0 16,5	5,2 3,4 14,5
PLANT TYPE	L B	L B	L B	L B	Z P	Z P	Z P	PI P	PI P	PIB P	PIB P	PIB P	PIB P
ROOM LOCATION	C	C	L	R	A	A	A	A	T	A	C	C	C

ROOM NUMBER	14	15	16	17	18	19	20	21*	22	23	24	25	26
ENCLOSURE CLASS	V	V	V	V	V	V	V	V	V	V	V	C	C
EQUIPMENT	P,G	P,G	G,P	G	G	G	G	G	G	G	G	P,C	P
FUEL LOAD CABLE OIL TRANS/MISC.	3,0 2 g	1,0	1,0 34 g	6,9 8 g	1425 g	2,3	1,0	9,0	16,9	7,8	2,7	16,6	1,9
DOORS	1	1 NE	1 E 1 W		1 E 1 S	3 N 1 S eW	4 N 3 S 3/eW	2 E	1 E 3 W	1 N 1 S		2 E	1 N 1 S 1 E eW
ACCESS		W		N/8' S/8'			PC				F		
STAIRWELLS							5				3		
HATCHES							?						MANY
VENTILATION RATE	8,0	3,0	3,6	11,0	5 FANS 16,0						4,8		
VENTILATION ORIENTATION													
GEOMETRY	4,6 2,7 17	9 45 19	3,8 2,6 19	4 1,6 16,5	2,9 1,8 22	5,4 4,8 28	15,3 7,3 12	1,8 1,4 12	4,1 3,1 14	5,4 4,5 11	5,6 4 19	3,6 1,1 14	3,9 0,7 34 C
PLANT TYPE	PIB P	PI P	PI P	PIB P	PI B	L B	Z P	Z P	L B	Z P	PI P	L B	L B
ROOM LOCATION	C	A	A	A	G	R	A	A	C	A	A	C	R

Table 1. Generic Enclosures Survey

ROOM NUMBER	27*	28	29	30	31	32	33	34	35*	36	37	38*	39*	40	41	42	43	44	45	46	47	48	49
ENCLOSURE CLASS	C	C	C	C	C	V	C	V	C	C	C	C	C	C	C	C	C	V	V	V	V	V	C
EQUIPMENT	P	P	P	P,G,C	P,G	P,G	G	G,P	P	C,P	C,P	C	C	C	C	C	C	C	C	P,C	P,C	P,G,C	P,C
FUEL LOAD CABLE OIL TRANS/MISC.	8-20	<<1.0	6.0	.2kBsf	.2kBsf	4.5	6.6 1 g	.9kBsf	1.5 0.4	10.1	9.1	1.2 1.8	0.7 0.1	5.9	76kB	76kB	76kB	NA	118kBsf	32kBsf	52kBsf	11.3kBsf 14.9kBsf	[illegible].0kBsf 1.8kBsf
DOORS	2 N 1 S	1 N 4 E		4	2	1 N 1 E 1 S		0/1 E 1/0 N	1 E 1 S	1 N 0/2 S	1/0 W 0/1 E 1/1 S	3 E 1 W	6 E 3 W	2 E 7 W 1 S				1 E 1 W	1 E 1 W	2 N 1 S	1 N 1 S	0/1 E	1 S 1 NW 1/w E
ACCESS			S/8'			N/8' S/8' W/60'	2/8'	S-2/10'				' 4'	N/4' S/4'		2/10'	2/8'	E/PC		S/9.5'x 10'	N/ Partial		NE/3'	N/3'
STAIRWELLS		2				2	2	1d				2d 1u	2d							2		1	4
HATCHES						9									2/2'x2'								
VENTILATION RATE		8.5	0.7	FAN	3 FANS 20.	8.5	7.0	54.		2.0	2.0					21.0	54.0	SMOKE EXHAUST					
VENTILATION ORIENTATION																		1E		1N 1S		1E 1N-5'	
GEOMETRY	4.5 0.9 10	11.5 2.4 19 L	5.7 1 16.5	6.7 1 16.5	6.7 1.7 15	7.1 1.8 15	[illegible] 4.1 18.5	6.3 1.3 16.5 L	4.8 4.6 14	8.3 1.7 18	8.8 0.6 15	6.5 1.7 17.5	17.9 0.9 14	9.4 0.3 14	16.2 3.8 11	6.8 1 10	18 1 8 L	6.9 5.7 9.5	5.7 1.1 9.5	19.4 1.9 16 L	2.1 2.1 16	6.3 5.0 16	10.1 1.0 26 C
PLANT TYPE	P P	P1 P	PYB P	1P P	1P P	PYB P	PYB P	1P P	PB B	G B	G B	PE B	PB B	Z P	1P P	1P P	1P P	MI D	MI B	MI B	MI B	MI D	MI B
ROOM LOCATION	P	A	A	C	C	A	A	A	BW	A	A	T	T	A	A	C	F	T	T	T	T	T	R

Table 1. Generic Enclosures Survey

ROOM NUMBER	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67
ENCLOSURE CLASS	V	V	V	V	V	V	C	V	V	V	C	C	V	V	V	V	r	V
EQUIPMENT	G,C	C,P,G	C,G,P	C,G,P	G,C,P	P,C	P,C	L	G,C	P,C	P,C	P,C	P,C	C,P	P,C	P,C	G,C	---
FUEL LOAD CABLE OIL TRANS/MISC.	4,5kBsf 0,5kBsf	2,5kBsf 0,8kBsf	2,2kBsf	26,8kBsf	7,7kBsf 1,9kBsf	40,2kBsf	33,9kBsf 0,7kBsf	NA	47,6kBsf 64 g 3,5kBsf	10,3kBsf	34,2kBsf	9,7kBsf	NF 1,3kBsf	NF 20 g	NF	NF 5,0kBsf	NF 1,9kBsf	---
DOORS		eE	eE			1 N 2 W 0/1 E	2/ E N 0/1 E 1W 1/2 S	1 E 1 W	1 N 1 E 0/1 S	2 E 1 W 1 S	0/1 N 1 W	0/1 N 1W	1N 1W E/12x12 ROLL-UP	1N 1W 1E	1N 1S 1W	1W 1E 1S	1N 1/1E 1W	1N
ACCESS	N,S/3'	2N/3'		E/6'	S/4' S/6'								N/18x20	W/4x7 S/18x20	E/8x7 W/12x12		E/1x3 W/16x10	
STAIRWELLS		2	1		2		1	1						1		1		
HATCHES		1/20x20	1/20x20	2 PC	1/20x20		1/14x10						F/10x10					
VENTILATION RATE						61,9		9,3 OUTSD 2,0 AC RECIRC.	3 FANS 30,0	INDEP. RECIRC.	INDER. RECIRC.	INDEP. RECIRC.	AC 45,2	AC 25,4	AC/FAN 17,0	AC 19,0	AC 4,0	
VENTILATION ORIENTATION					W/54"	CEILING EXHAUST		EX-FLOOR	IN-WALL EX-CEIL.				W/5' FAN	W/10x10 E/.5x2.	C/5x3 S/.5x.67 W/2x4		1N 3W	
GEOMETRY	1,3 0,9 26	9,1 4,5 15	6,0 2,5 24	3,3 3,3 22	6,8 4,5 27	6,1 2,2 10	6,4 1,0 20 1	13,8 5,9 10	4,1 3,3 20	4,1 3,3 20	10,9 1,8 12	11,9 1,8 12	5,5 3,2 17	4,1 3,2 17	4,0 1,4 17	3,5 3,0 18	6,1 1,1 18	3,0 2,4 18
PLANT TYPE	M1 B	M1 B	M1 B	M1 B	M1 B	M2 P	M2 P	M2 P	M2 P	M2 P	M2 P	M2 P	St,LI P	St,LI P	St,LI P	St,LI P	St,LI P	St,LI P
ROOM LOCATION	R	R	R	R	R	A	A	A	I	T	T	T	A	A	A	A	A	A

Table 1. Generic Enclosures Survey

ROOM NUMBER	68	69	70	71	72	73	74	75	76
ENCLOSURE CLASS	V	V	V	V	V	V	V	V	V
EQUIPMENT	C	C	G,C	P,C	G,C	G,C	G,C	G	C,P
FUEL LOAD CABLE OIL TRANSF/MISC.	NF	NF	NF >0.	NF 4,4kBs†	NF 7,0kBs†	NF 4,0kBs†	NF 4,4kBs†	12,0kBs†	NF 0,1kBs†
DOORS	1E 1W	1E 1W	1S 1W	1N					3W 2S 2E
ACCESS			C/8x10	S/19' W/28(1/2 WALL)	S/3' S/27(1/2 WALL)	S/10'	S/4'	E/4' E/13(1/2 WALL)	
STAIRWELLS									
HATCHES									
VENTILATION RATE	AC 1,1	TC 0,8	FAN 3,0	AC 0,7	AC 2,0	AC 2,1	FAN 0,4	EX. FAN 6,0	AC 2,5
VENTILATION ORIENTATION			S,E,W	C/1x3					W/3 DUCTS
GEOMETRY	2,1 1,1 18	1,7 1,1 19,5	3,1 1,3 19,5	1,8 1,7 22	1,9 1,4 20	2,9 2,4 17	2,1 2,0 20	1,1 0,7 17,5	5,9 3,0 11,5
PLANT TYPE	St,LT P	St,LT P	St,LT P	St,LT P	St,LT P	St,LT P	St,LT P	St,LT P	TP P
ROOM LOCATION	A	A	A	A	A	A	A	A	C

ROOM NUMBER	77	78	79	80	81	82	83	84	85
ENCLOSURE CLASS	C	C	C	C	C,B	V	V	V	V
EQUIPMENT	C,G	C,G	C,G	C	G,C	C,G	C,G	C	G,C
FUEL LOAD CABLE OIL TRANSF/MISC.	NF --	[illegible]	NF	NF 3,kBs†	NF 5,6kBs†	NF >0 5,4kBs†	NF >0 6,1kBs†	NF 7,4kBs†	NF >0 2,2kBs†
DOORS		1E 2S	1W					1E	1N 1/1W 0/1E
ACCESS	S/5x6 E/5x6	S/4x6 W/5x6		3N/4x6 N-S HALL OPEN		S/5x6 E/16x22	E/7x6 S/12x6 W/16x22		
STAIRWELLS				3	1	1	1	1	
HATCHES									
VENTILATION RATE	N/A	N/A	N/A	FAN 1,0	FAN 1,0	FAN 0,2	FAN 0,2	FAN 1,0	N/A
VENTILATION ORIENTATION								N/EX1x1,5 E/SP,1x2	
GEOMETRY	7,5 0,5 11,5 L	7,5 0,9 11,5 C	2,9 0,5 13,5 L	47,2 2,4 6, X	1,0 0,3 36,5	1,1 0,6 21	1,1 0,6 21	2,4 1,6 14,5	5,6 1,9 16
PLANT TYPE	TP P	TP P	TP P	TP F	TP P	TP P	TP P	TP P	TP P
ROOM LOCATION	A	A	A	A	A	A	A	A	A

Table 1. Generic Enclosures Survey

ROOM NUMBER	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103
ENCLOSURE CLASS	C	V	V	V	V	C	C	V	V	V	V	V	V	C	C	V	V	V
EQUIPMENT	C,P	G,P	G	P,C	G,C	G	G,C	G,C	P,C	P,C	P,C	P,C	P,C	P,C	G,P,C	C,P	G,P	C,G
FUEL LOAD CABLE OIL TRANS/MISC.	NF 12,340sf	NF >0	NF	NF 4,8x8sf	NF >0	NF >0	NF 24lb.	NF 140g	NF >0	NF >0	NF >0	NF >0	NF >0	NF	NF 320g	NF	NF 28g & 30lb	NF 5lb
DOORS	N,E,S,W NUMEROUS	1N		1E 2W		1E		1NW 1SW		1N 0/1S 0/1E	1S 0/1N 0/1E	1S 1E	2N 0/1E	1N	2NE 2SE 0/1SW 1NW	0/1W		
ACCESS	N/2,5x7	W/50x2? S17-1/2 x22			N/38x18	E/pc												N/S
STAIRWELLS	2	2		1			1	1	2	1	1						1	
HATCHES																		
VENTILATION RATE	FAN 26,4	N/A	N/A	AC 8,3	N/A	FAN 1,3	2 FANS 2,3	2 FANS 20,0	FAN 12,3	SP/EX 11,1	SP/EX 11,1	SP/EX 4,4	SP/EX 4,4	3 FANS 91,4 EA	4 FANS # 91,4	NONE	RB VENT 8,2	3,0
VENTILATION ORIENTATION						2E/4x4				EX/NW 4x4	EX/SW 4x4	EX/NW SP/SE	EX/SW SP/2/NE	EXB/W/4x4 SPB/E/4x4	EXB/W/4x4 SP/NS/ 16/12		EX/NW	
GEOMETRY	26,1 1,0 11 7	2,8 2,2 22,5	1,3 0,5 24	4,7 3,5 14,5	2,1 1,9 18	2,4 0,5 19	6,7 1,5 15	5,3 1,8 19	8,8 3,3 20	1,4 1,1 26,5	1,7 1,1 26,5	2,6 1,3 17	2,6 1,3 17	7,1 0,5 17	10,4 1,7 17	0,8 0,6 17	1,7 1,5 34,5	3,8 3,1 15
PLANT TYPE	TP P	TP P	TP P	TP P	TP P	TP P	B B	B B	B B	B B	B B	B B	B B	B B	B B	B B	B B	B B
ROOM LOCATION	A	T	T	C	R	R	SW	SW	DG	DG	DG	DG	DG	DG	DG	DG	R	R

Table 1. Generic Enclosures Survey

ROOM NUMBER	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121
ENCLOSURE CLASS	V	V	V	V	V	V	V	V	V	V	V	V	V	C	V	B,V	C,B	C,B
EQUIPMENT	G,C	G,P	G,F	C,P,G	G	G	G,C	G,C	P,C	G,P	C	P,C	C	G,P,C	C,G	C	C	C
FUEL LOAD CABLE OIL TRANS/MISC.	NF 155g&25lb	NF 28g&41b	NF 30g&31b	NF 3lb	NF 60lb	NF 45lb	NF 21lb	NF 5lb	NF 6lb	NF	NF	NF 30g	NF 30lb	NF 40g&112lb CHAR. 120lb	NF 45lb	NF	NF	NF
DOORS			1E	1W		1NE 1SE	1S	1N			eNW 1N	1S 1E		1E 1W eNE	1E 1W	1W	1S 1E	
ACCESS			E/28'	E/25'	PLUGS				N/S	E/W	S/30' W	N/30' W	N/S/40'					
STAIRWELLS		1	1	1			1	1		1		1		4				
HATCHES	1NE 1S						WALLS CEILING	WALLS CEILING						NE/20x20				
VENTILATION RATE	7.0	2.5	5.5	1.5	SP/EX 7.5	SP/EX 5.0	10.5 EX SP1.0&9.5	14.4EX/SP	5.0	8.2	1.0	2.5	N/A	Avg. 2.0	12.0	N/A	N/A	N/A
VENTILATION ORIENTATION		SP/ FLOOR				SP/S+#	SP/S& FLOOR	SP/N& FLOOR										
GEOMETRY	2,6 2,1 19	1,5 1,5 34,5 Δ	1,6 2,4 29 L	1,8 1,6 29 L	1,1 1,0 29	2,2 2,0 14,5	1,4 0,7 28,5	1,4 0,7 29	1,7 1,2 29	2,5 1,5 29,5	2,1 0,8 29 L	1,6 1,0 29 L	2,9 2,9 15	11,4 1,6 29 C	2,1 1,7 24	0,4 0,4 25,5	1,4 0,4 25,5	1,2 0,4 25,5
PLANT TYPE	E B	B B	B B	B B	B B	B B	B B	B B	B B	B B	B B	B B	B B	B B	B B	B B	B B	B B
ROOM LOCATION	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	C	C	C

Table 1. Generic Enclosures Survey

ROOM NUMBER	122	123	124	125	126	127	128	129	130	131	132	133	134
ENCLOSURE CLASS	B,V	B,V	C,B	C,B	V,B	V	V	V,B	V	V	C,B	V	V
EQUIPMENT	C	C	C	C	C	C	C	G,C	C	P,C	C	P,C	G,C
FUEL LOAD CABLE OIL TRANS/MISC.	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF 5,0 C'	NF 20 lb C'	NF	NF 28g&41b
DOORS	1N 1E	1W	1S 1E	1N 1W	1E	0/1F	1E	1E	1S	0/1E	1E	1N 1S 1E 7/3W	
ACCESS													
STAIRWELLS													1
HATCHES													
VENTILATION RATE	N/A	N/A	N/A	N/A	N/A	0,6	0,7	N/A	AC 0,6	N/A	0,4	SP/EX 34,2	2,5
VENTILATION ORIENTATION						NE/SE	NE/SE		N/E		E		SP/ STAIRS
GEOMETRY	0,5 0,4 25,5	0,6 0,5 19	2,0 0,5 19	1,8 0,5 19	0,7 0,5 19	1,2 0,8 20	0,8 0,8 20 L	0,4 0,4 20	3,4 1,7 9,5	1,8 0,8 19	0,9 0,2 19 L	11,6 2,0 19	1,3 1,3 34,5Δ
PLANT TYPE	B B	B B	B B	B B	B B	B B	B B	B B	B B	B B	B B	B B	B B
ROOM LOCATION	C	C	C	C	C	C	C	C	C	C	C	C	R

Table 1. Generic Enclosures Survey

Survey of Existing Research Results. BNL has assisted in the compilation of mass and energy release characteristics of probable source fuels encountered in critical fire areas. Typical fuels identified were cable insulation, lubricating oil and grease, fuel oil along with more well-categorized combustibles such as cellulose. Typical loadings of these combustibles are given in Table 1.

Experiments to Augment Existing Data. These preliminary experiments are the responsibility of SNL. BNL has provided consultation and input (Table 1) to aid in the selection of candidate source combustibles for testing.

B. FIRE ENVIRONMENT DETERMINATION PROGRAM

Fire Environment Model and Computer Code Selection. This project involved two basic phases: (1) the determination of features required in the fire environment model and (2) the selection of a computer code which best fulfilled the requirements set forth in the model.

The first phase of this project is best typified as a set of criteria which any candidate model must meet:

(1) The analysis/numerical code must have already been utilized in realistic enclosures similar to what may exist in NPPs.

(2) The code should already have the capability to predict the spatial and temporal variation of those fire-induced parameters deemed necessary to appraise the vulnerability of NPP safe-shutdown equipment.

(3) The code should already have the capability to assess the effects of NPP enclosure geometry complexity, such as obstacles and openings, on the movement of the fire-induced thermal energy flux, mass flux, and momentum flux field.

(4) The effects of forced ventilation and its attendant impact on the redistribution of the flux field must also be an aspect that the code can address.

(5) The code must have the flexibility for analyzing fires resulting from the burning of complex solid fuel configurations.

(6) Exposure fires initiated at various locations within the enclosure (e.g., centrally located or against a wall or corner) must be within the realm of the code's capability. Thus mapping of the three-dimensional, fire-induced thermal energy field is mandatory.

(7) The fire-induced flow should be treated as three dimensional and elliptic, i.e., flow in one part of the building can be affected by changes in conditions in other parts, as well as conditions outside the building.

(8) Subsequent combustion of pyrolzate products may be addressed with the unit-models employed in the code.

(9) Restrictive constraints imposed by the Boussinesq approximation should not be included.

(10) The boundary conditions and field-grid structure inherent in the code should be such that the effects of internal solid objects, such as interbay walls, columns, horizontal working platforms, etc., on the flow field can be readily investigated.

Given the above set of criteria, five potential codes/sources were reviewed as candidates for selection: PHOENICS/CHAM, UNDSAFEII/UND, DRAGON/EPM, (Unnamed)/NBS, and COBRA/EPRI.

A matrix (Figure 1) comparing the various attributes of each of the numerical codes was prepared to aid in the second phase of this project, viz., code selection.

	1	2	3	4	5	6	7	8	9	10
PHOENICS/CHAM	*	*	*	*	*	*	*	*	*	*
UNDSAFEII/UND		*					*		*	
DRAGON/EPM		*		*	*		*			
(Unnamed)/NBS		*					*		*	
COBRA/EPRI				*			*			*

Figure 1. Code Comparison Matrix

The CHAM-developed fluid flow analysis code PHOENICS was selected as the model to be further developed.

CHAM of North America, Inc., specializes in the development and application of mathematical models of fluid flow, heat transfer, and chemical reaction processes. Its primary business is to provide technical services, computer software and support in the field of fluid flow simulation. Adaptations of the numerical model utilized in PHOENICS[3] have been previously applied to fire hazard analysis within the complex geometrical enclosures of NASA's vehicle assembly building (VAB).[4] The aim here was to determine the thermal environment in the VAB following accidental ignition of solid rocket motor(s). An additional fire-related study was performed by CHAM's sister organization in the United Kingdom: CHAM, Ltd. This study[5] involved simulation of fire tests conducted to address questions of smoke movement in shopping mall corridors. The following conclusions were drawn regarding the application of the model in the two cases:

(1) All results were qualitatively plausible.

(2) Calculated temperatures and velocities were in fair agreement with measured data, where applicable.

(3) These applications, though demonstrating the potential usefulness of the model/code, were not typical of cable insulation fires in NPP enclosures.

Computer Code Demonstration/Development. Included within the framework of this project was the preliminary validation of the computer code, PHOENICS, via comparison with fire test results conducted with NPP environs in mind. Prior to these test comparisons a summary of the numerical model is presented.

For purposes of the following analysis, a field model based on the solution of governing partial-differential conservation equations of mass, momentum, and energy is used. Gas flow is treated as three-dimensional, transient, and elliptic. The fluid is assumed to be a perfect gas with constant physical properties pertinent to that 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. The turbulence effects are accounted for by using the two-equation k-ε model of turbulence,[6] with known refinements for buoyant flows.[7-9] Cable tray assemblies are simulated as combinations of perforated plates and blocks. The porosities of these plates and blocks are determined from the available information on packing of cables. Thus, the presence of a cable tray disrupts the flow. Heat transfer to and from the redundant (target) cable trays is neglected. The calculation domain includes the whole room and some volume outside the door so as to account for the effects of the canopy over the door and to avoid the need of prescribing boundary conditions at the doorway. The fire heat source and wall heat losses are prescribed as functions of time. Further specific details of boundary conditions are presented later along with the discretization details.

The 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 general time averaged form:

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

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

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

where $\Gamma_{eff,\phi}$ is the effective exchange coefficient for the transport of property ϕ. The values of Γ_{eff} and S for different ϕ's are listed in Table 2.

TABLE 2

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

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

From the table:

$$\mu_{eff} = \mu_t + \mu_\ell \quad , \tag{3}$$

$$\mu_t = C_\mu \; \rho \, k^2/\varepsilon \quad , \tag{4}$$

$$G_k = \mu_t \; \{ 2 \; [(\frac{\partial u}{\partial x})^2 + (\frac{\partial v}{\partial y})^2 + (\frac{\partial w}{\partial z})^2]$$

$$+ \; [(\frac{\partial u}{\partial z})^2 + (\frac{\partial w}{\partial x})^2] + [(\frac{\partial w}{\partial y})^2 + (\frac{\partial v}{\partial z})^2] \tag{5}$$

$$+ \; [(\frac{\partial u}{\partial y})^2 + (\frac{\partial v}{\partial x})^2] \} \quad , \quad \text{and}$$

$$G_b = \frac{\mu_t}{\rho} \, g \, \frac{\partial \rho}{\partial z} \quad . \tag{6}$$

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 constants which are assigned the following standard values[6]:

$$C_1 = 1.44 \; ,$$

$$C_2 = 1.92 \; ,$$

$$C_\mu = 0.09 \; , \tag{7}$$

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

$$\sigma_\varepsilon = 1.3 \; .$$

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 generates local predictions of temperature, velocity, species concentrations, and pressure. These calculated values were then compared with the measured data from two series of tests conducted to simulate cable fires in NPP enclosures to provide a preliminary validation of the computer model.

The first set of tests[2] were cable insulation burning experiments conducted by FMRC under the sponsorship of the EPRI. From this series of tests, a particular case was chosen for analysis: (designated as Test #2 in Reference 2). This test was performed in the enclosure depicted in Figure 2. Forced ventilation was rated at 6 room changes per hour, and the cable tray array was placed in the center of the room and was arranged parallel to the ventilation flow (N to S in Figure 2). The exposure fire consisted of 4 gal of methanol in a 36 in. diameter by 3 in. deep pool placed directly below the cable array. The total pool fire heat release rate was 286 kW. The cable array consisted of both horizontal and vertical cables which were interconnected. The total burn time for the test was to be 1200 s although sprinkler actuation occurred sometime prior to this set experimental duration. Boundary conditions for velocities are determined by the flow rates at the ventilation source(s). Initial conditions for density and pressure are those of ambient air. In order to establish

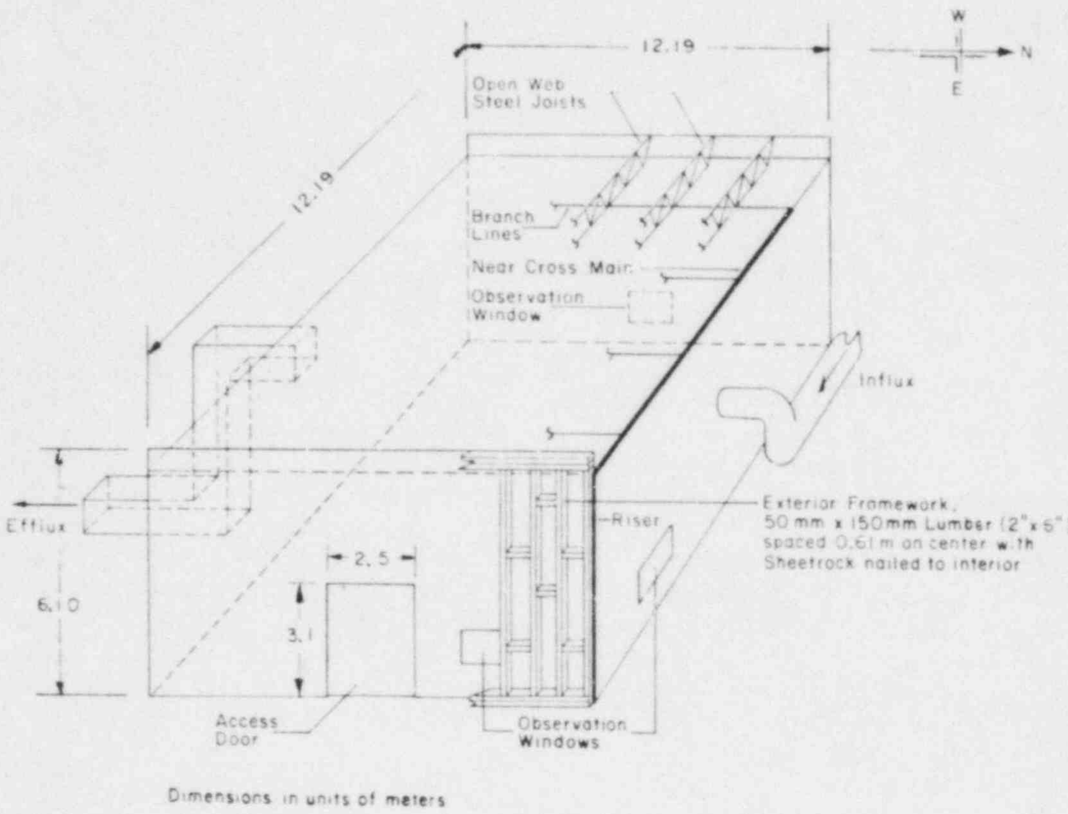


Figure 2. Three-dimensional view of FMRC test structure.

initial conditions for other properties a "cold-flow" case is simulated with no heat source present. Reported data utilized in the computational validation were (1) total heat release rate vs. time (input to code) and (2) one ceiling gas temperature vs. time (used to compare with code predictions).

Problem formulation began with the setting up of grid structure simulation of the test enclosure. Due to symmetry within the room (at the plane of the ventilation inlet and exhaust) only half of the room was considered as the calculation domain. A total of 3368 control cells were utilized in the x,y,z grid structure. The load cell, supporting the methanol pan, was represented as a solid block. Cable trays were represented as solid blocks and plates (perforated and/or impervious). The exposure fire was represented as a heat source spread over a region of computational cells. The heat and mass sources released gases having the same thermophysical properties as air (molecular weight of gas and enthalpy/temperature relation similar to air). Gaseous fuel was released with specific heat and heat of combustion values as stated in Reference 2. Instantaneous chemical reactions (SCRS) were presumed. A total of seven cases were modeled:

Case 1.1: Simulated fire test room with nominal heat release rate and ventilation rate, but without any cable trays. Calculated 3 time steps to give solutions at t=10, 20 and 60 s.

Case 1.2: Same as Case 1.1, but with cable trays. Calculations performed up to t=180 s.

Case 1.3: Same as Case 1.2, but with zero porosity of the top two rows of cable trays. Calculations up to t=180 s.

Case 1.4: Same as Case 1.3, but with refined simulation of fire source, i.e., finite mass release considered with heat release. Also, heat source is spread over smaller volume (both height and width are reduced). Calculations up to t=180 s.

Case 1.5: All cable trays simulated as impervious plates and blocks. Instead of using heat release rate directly as input, it is assumed that gaseous fuel was released with specific heat and heat of combustion values as reported in Reference 2. Instantaneous reaction (SCRS) was assumed. The mass release rate is determined as a function of the heat release rate and the heat of combustion. The region of mass release changes (increases) with time in accordance with Reference 2. Total heat release rates were reduced to 85% to neglect the radiative component since it should have no effect on gas temperature as determined by the code. Calculations performed up to t=240 s.

Case 1.6: Heat release rate determined from the following expression:

$$\dot{Q} = \min(\dot{Q}_A, (\dot{Q}_m + 1/2(\dot{Q}_A - \dot{Q}_m)))$$

where $\dot{Q}_A$ is the measured heat release rate reported, and $\dot{Q}_m$ is the heat release rate of methanol in the equilibrium burning state (286 kW).

Case 1.7: Heat release rate adjusted to take an approximate account of the pyrolysis process. In Reference 2 it is indicated that there is a critical rate of mass release ($\dot{m}''_{cr}$) below which no cable combustion takes place. By using the values of $\dot{Q}_A$, $\dot{Q}_m$, $\dot{m}_{cr}$, H (the heat of combustion for the cable), and A (the surface area of the cable exposed to nominal heat fluxes), the following expressions are derived to estimate the heat release rate:

$$\dot{Q}_A < \dot{Q}_m \; ; \; \dot{Q} = \dot{Q}_A$$

$$\dot{Q}_A > \dot{Q}_m \; ; \; \dot{Q} = \dot{Q}_m + \dot{m}_b H$$

where $\dot{m}_b$ represents the mass release rate of the cable which is in excess of $\dot{m}''_{cr}A$ and, hence, combustible.

Cases 1.6 and 1.7 were run subsequent to the other five cases. These two cases were necessary because the code was overpredicting ceiling gas temperature as a function of time utilizing the actual heat release rate as input. The improvement effected in Cases 1.6 and 1.7 produces temperatures much more nearly approximating the measured data.

Output from the code is illustrated in Figures 3 and 4. Figure 3 depicts the flow velocity field at various times during the test. Flow exhaust port and load cell are depicted in the figure. The entrainment of cold air into the fire plume is clearly shown. Figure 4 shows isotherm contours for 50°C and 60°C at t=240 s. into the fire. This figure illustrates quite well the formation of a stratified layer within the test enclosure.

Calculated velocities and temperatures show plausible trends, i.e., consistent with inputs and assumptions, for all cases. For example:

a) larger velocities in the plume region,

b) zero velocities across impervious plates (trays),

c) a large recirculation region (eddy current) above the entrance of ventilation air,

d) small recirculation regions in the lower corners,

e) highest gas temperatures in the fire source area,

f) high gas temperatures in the plume,

g) temperatures near the ceiling are much higher than those near the floor,

h) in the corners, near the ceiling, temperatures are lower than in the central parts, and

i) exhaust gas temperature increases with time; average room temperature is lower than the exhaust temperature.

Comparison of calculated and measured gas temperatures, near the ceiling and directly above the fire course, reveals the following:

a) all cases show good agreement with experimental data up to t=60 s.

b) all cases predict higher gas temperatures at t>60 s. The experimental data shows a slower rate of temperature rise during 60<t<200 s. No such reduction is seen in the calculated temperatures. The discrepancy is quite large, but the refinements in heat release rate specification in cases 1.6 and 1.7 greatly reduce this difference.

The results of this first attempt at validation were encouraging. However, doubts as to the physical interpretation of the measured heat release data led to the need for a second set of validation analyses wherein the heat release rate could be more clearly specified. A second series of fire tests,[1] conducted to investigate the 20-foot separation criteria, provided the experimental data for further validation comparisons. These tests were conducted by Underwriters Laboratories in conjunction with SNL under the aegis of the NRC. Figure 5 shows a schematic of the test enclosure. The enclosure was 14 ft wide, 25 ft long,

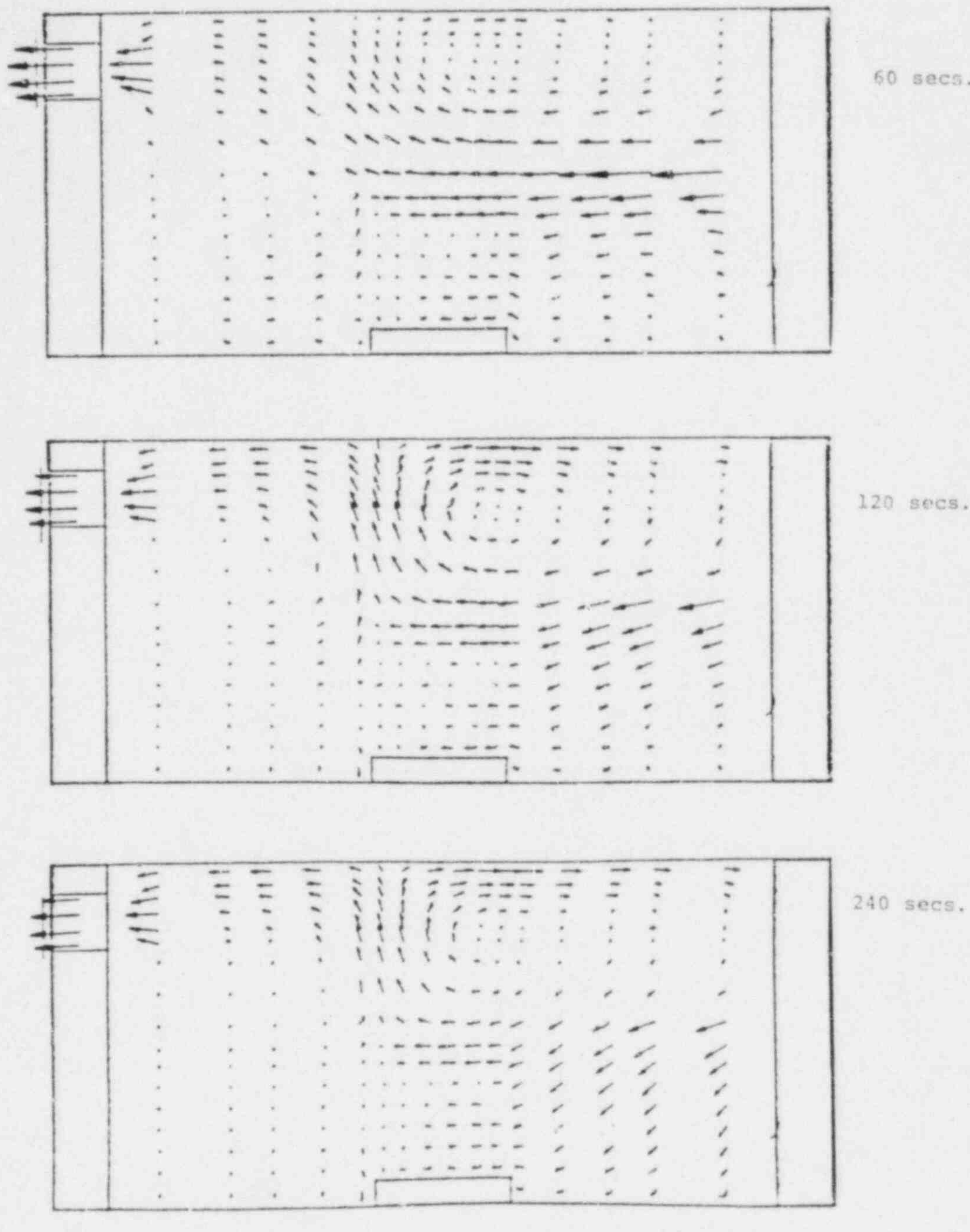


Figure 3. Velocity vector field through central vertical plane during fire growth.

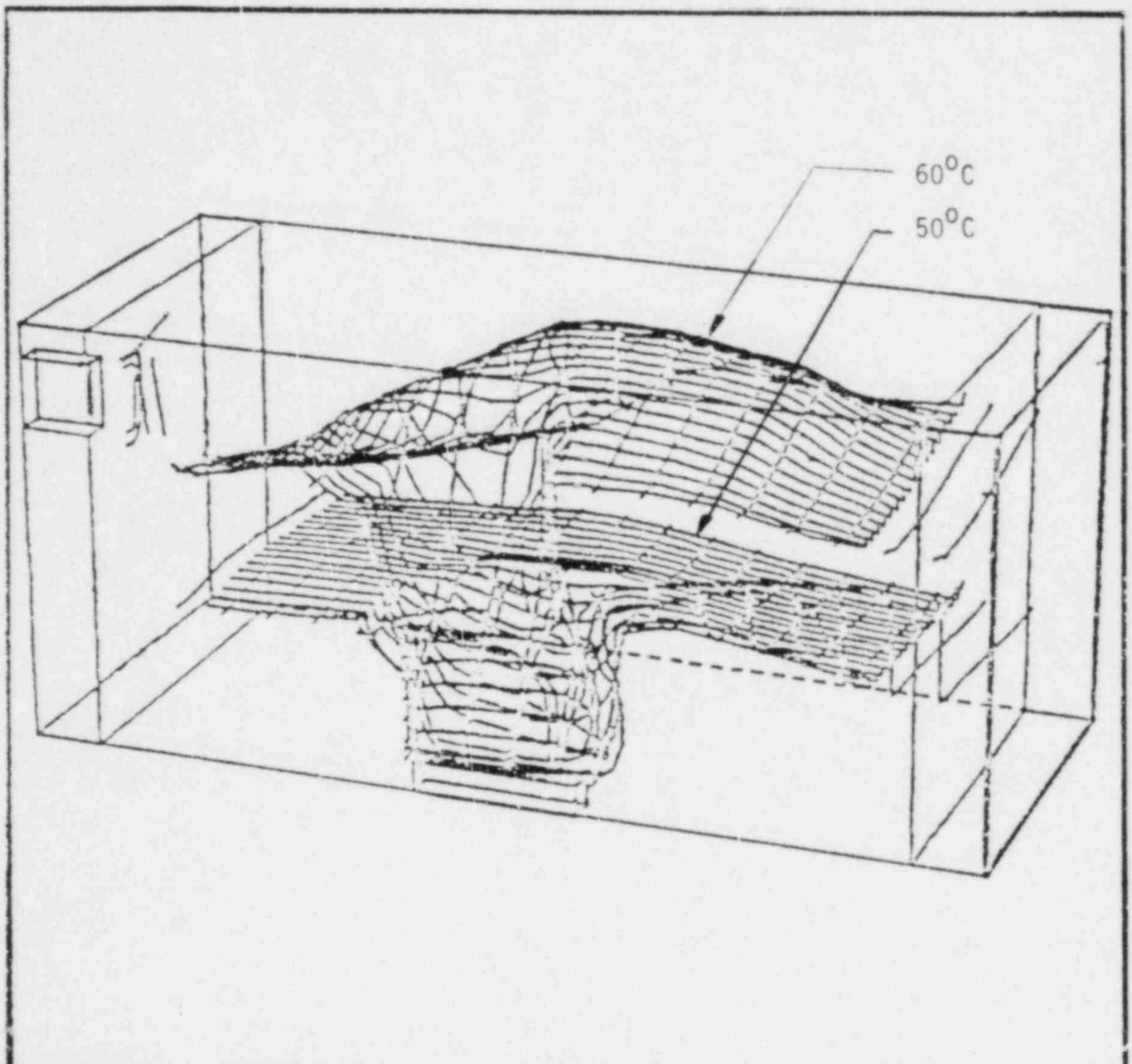


Figure 4. Isotherm contours (T=50°C, T=60°C) at 240 secs. into fire.

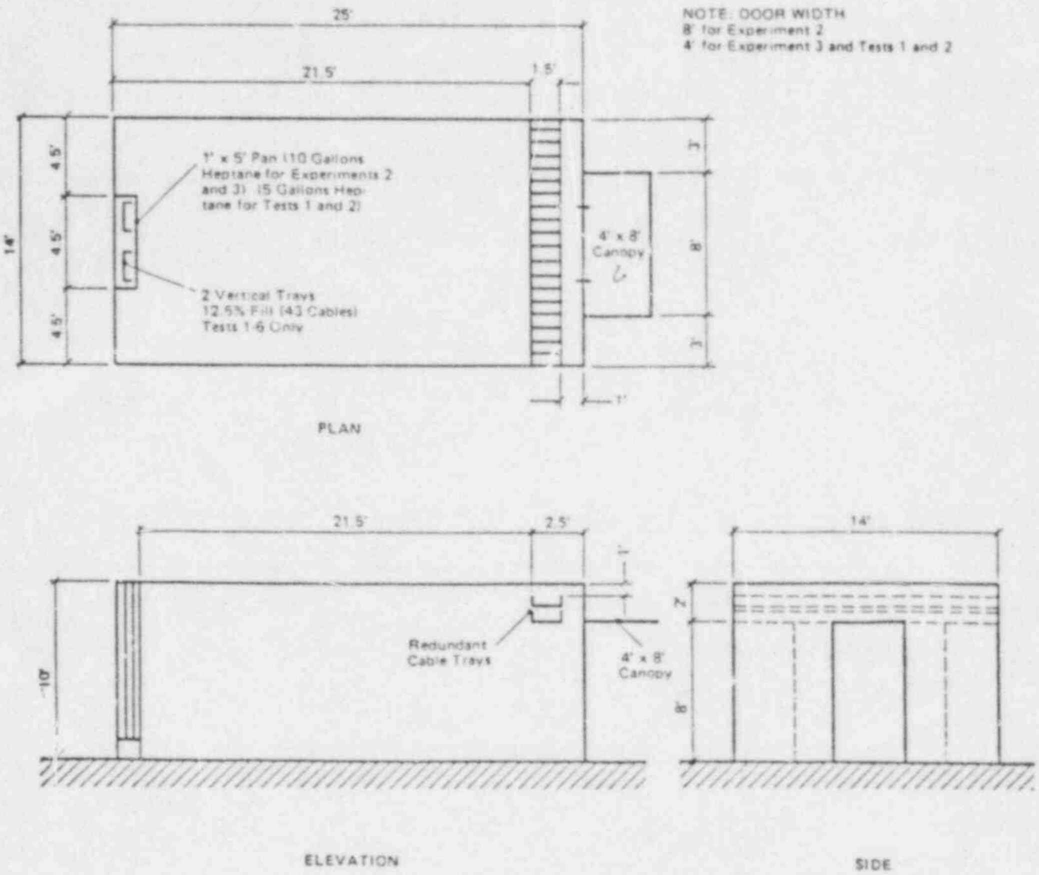


Figure 5. Fire enclosure details: preliminary fire experiments No. 2 and 3 and full-scale tests 1 and 2.

and 10 ft high, with a doorway in one of the 14x10 ft walls. Four preliminary experiments and six tests were conducted. Measured data consisted of wall and gas temperatures and heat fluxes at various locations. Vertical thermocouple rakes were installed at predominately three locations: 4 ft, 20 ft, and 25 ft from the wall near the source fire. Fuel mass and heat release rates were not measured. Subsequently, in order to use the test data for the verification of numerical models, heat release rates were calculated[10] for four cases: Experiments 2 and 3 and Tests 1 and 2. In this present analysis all four cases have been simulated numerically by using the calculated heat-release rates as prescribed input. The salient features of these four cases are described below.

In Experiment 2 the doorway was 8 x 8 ft while in the other three cases the doorway width was 4 ft. Experiments 2 and 3 involved 10 gal heptane pool fires with no other combustibles. The pool was rectangular (1 x 5 ft) and was placed along the wall opposite the doorway. Tests 1 and 2 each had a 5 gal heptane pool fire with electrical cables as an additional combustible, all placed against the wall opposite the door. The cables were placed in two vertical

trays, suspended above the heptane pool, each loaded with 43 10-ft lengths of cable (12.5% fill). This amount of cable was estimated to equal 5 gal of heptane in total heat release. Two horizontal cable trays (the redundant division) were also located near the ceiling and 20 ft away from the fire source. In Test 1 all cables were unqualified and unprotected. In Test 2 the cables were qualified but remained unprotected.

Because of the geometrical symmetry of the problem considered, only half of the room was simulated. As illustrated in Figure 6, a total of 950 control cells, with 5, 19, and 10 cells in the x, y, and z directions, respectively, were used for all four cases. The grid distributions are non-uniform in each coordinate direction, permitting good resolution of the solution in the particular area of interest. No-slip boundary conditions are applied at all solid surfaces, while at the calculation-domain boundaries outside the room, free boundary or constant-pressure conditions are applied. Heat source variations with time as determined in Reference 10 are shown in Figure 7. Figure 8 depicts heat release and loss rates for Experiment 2. Similar data are available for other cases. Figure 9 illustrates the manner in which heat release and heat losses

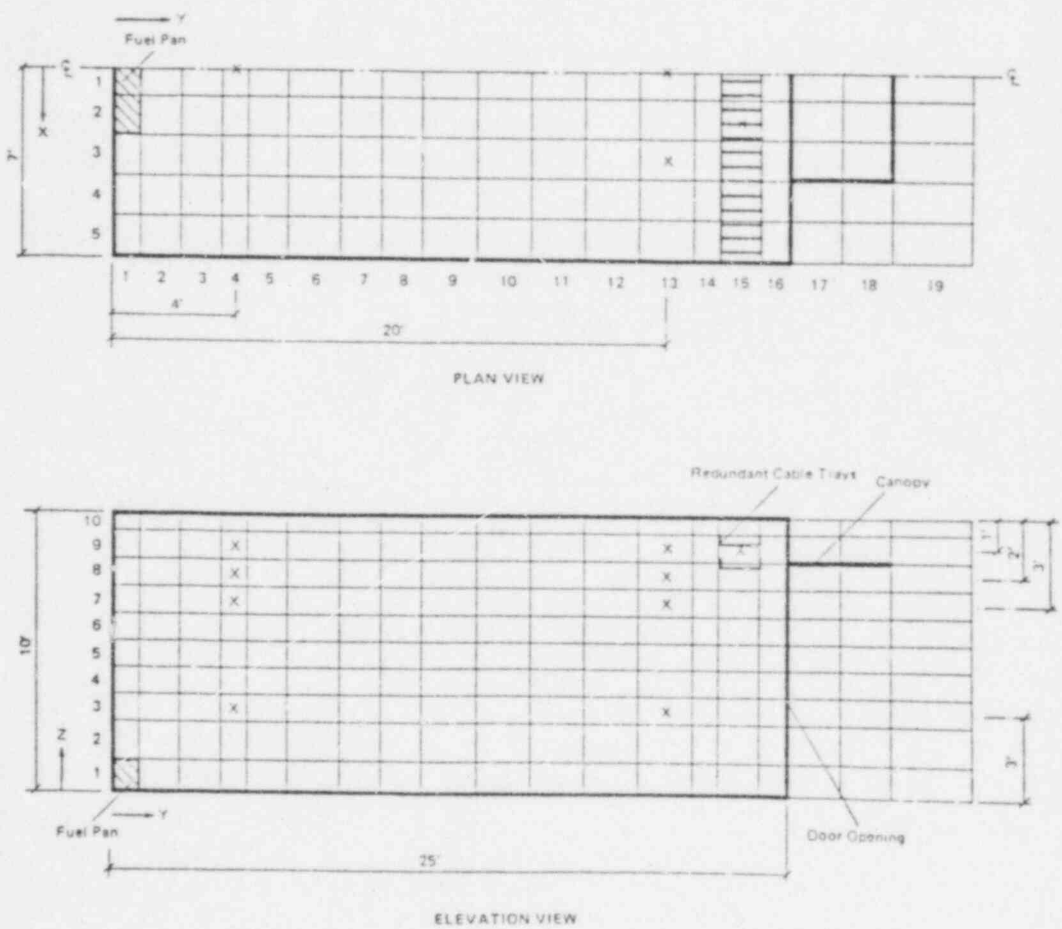


Figure 6. Grid distributions, coordinate directions and thermocouple positions (shown by "X").

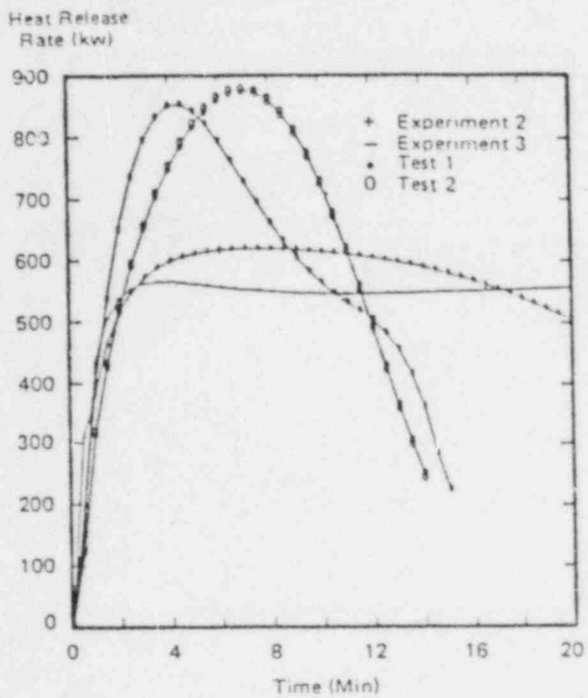


Figure 7. Total Heat Release Rates for Experiments 2 and 3, and Tests 1 and 2.

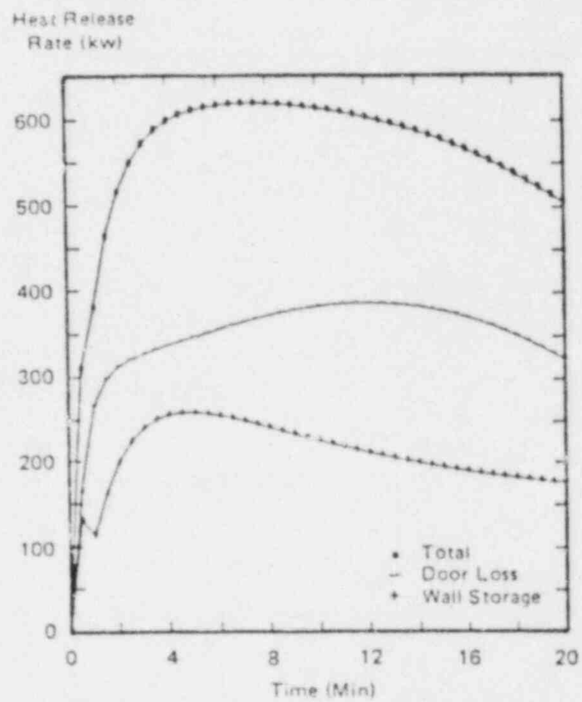


Figure 8. Heat Release Rates and Losses for Experiment 2.

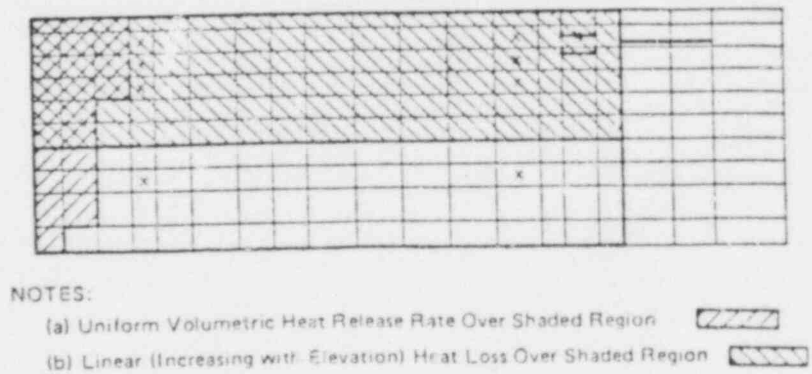


Figure 9. Volumetric Heat Release and Heat Loss Distributions

were modelled across the enclosure volume. As noted in Case 1.4 of the previous set of simulations, decreasing the size of the volume containing the heat source has little or no effect on the accuracy of results while increasing computer time. Likewise the effect of allowing the heat source to spread in a realistic manner also has a negligible effect on the temperatures of concern (located ~20 ft. from the fire). While the fire was not permitted to spread, the heat release rate did follow the temporal distribution calculated from the experimental data[10].

All computations reported have been performed with the aid of a general purpose finite-difference flow analysis computer code, PHOENICS[3]. An implicit, successive substitution algorithm, SIMPLEST[11], has been employed. SIMPLEST is a modified form of the SIMPLE algorithm. In both cases, global and species continuity is satisfied through solution of a Poisson-type pressure correction equation.

Computations for Experiments 2 and 3 were performed up to 960 s in nine time steps with Δt=60 s for the first two time steps and Δt=120 s for the last seven time steps. For full scale Tests 1 and 2, smaller time steps (Δt=60 s versus Δt=120 s) were used since transient heat release rates were larger and steeper than those of Experiments 2 and 3. All computations were performed on a 32-bit mini computer (Perkin Elmer 3251), which is about ten times slower than a CDC-7600 or at least twenty times slower than a CRAY-1. For each time step 100 overall iterations (sweeps) were performed. All solutions were well converged, i.e., residuals were reduced by at least two orders of magnitude, and all flow variables settled within 1%. Computer time requirement was about thirty minutes per time step on the mini computer.

Figure 10 illustrates predicted transient development of doorway velocity and temperature profiles for Experiment 3. At t=960 s these profiles are well developed. The fire strength at this time is 548 kW. In order to assess the similarity of profiles, data from Steckler's NBS room fire experiments[12] are shown in Figure 11. The comparison of Figures 10 and 11 provides a qualitative verification of the calculated profiles. Figure 12 shows the comparison of predicted temperature near the horizontal (redundant) trays with the data of Experiments 2 and 3. The agreement is most satisfactory. There is a measurable increase in temperature of the environment when the door width is decreased from 8 ft (Expt. 2) to 4 ft (Expt. 3). Figure 13 shows the comparison of predicted temperature variations within the stratified hot layer as a function of distance below the ceiling for Experiment 3 data. The stratified layer structure observed in Experiment 3 is well predicted by the present model. Comparisons between predictions and measurements of temperatures recorded at several vertical locations, 4 ft and 20 ft from the fire source, are shown in Figures 14 and 15, respectively. The agreement is quite good in Figure 15. Figure 14 illustrates a combination of two effects: 1) thermocouples, which were not shielded from flame radiation, indicated higher gas temperatures than actually present, and 2) quantification approximations made in the calculation of the heat release rate have their greatest effect close to the source fire.

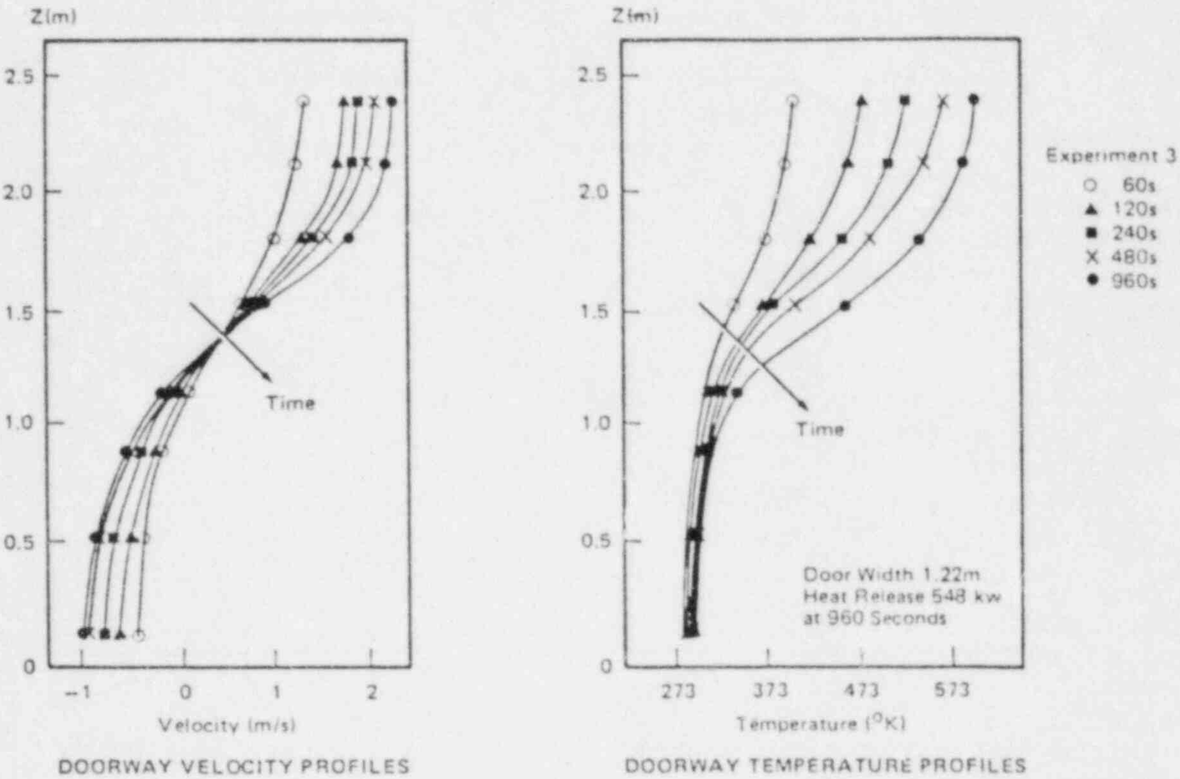


Figure 10. Calculated development of doorway velocity and temperature profiles for Experiment 3.

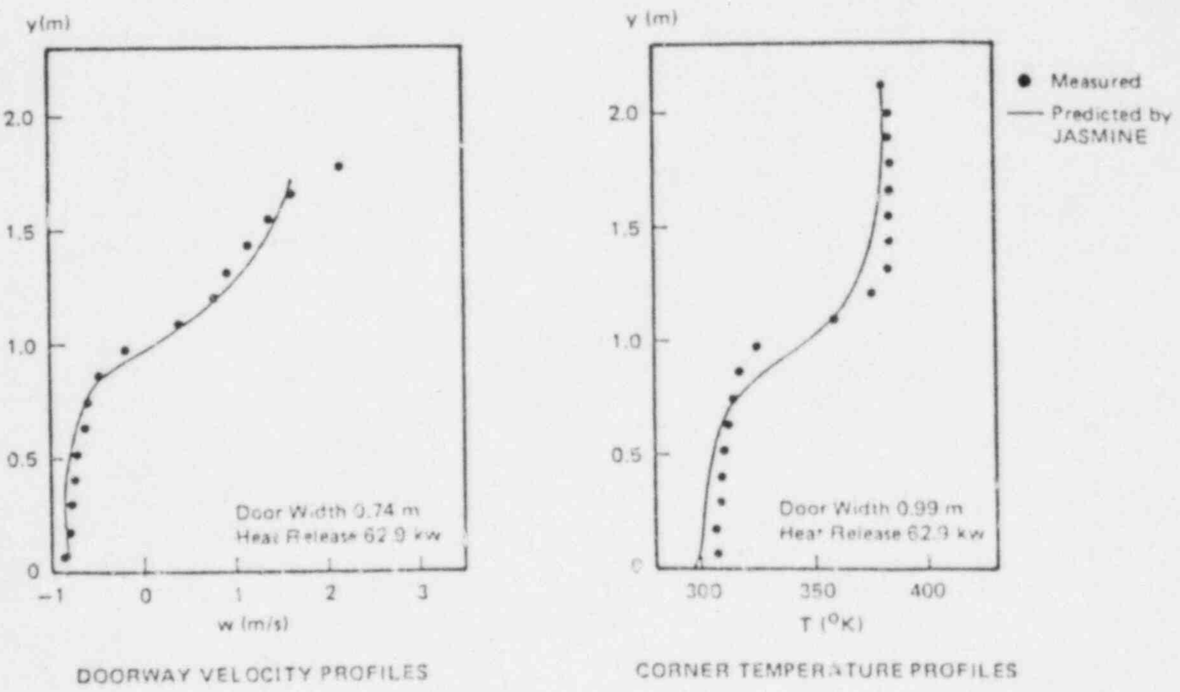
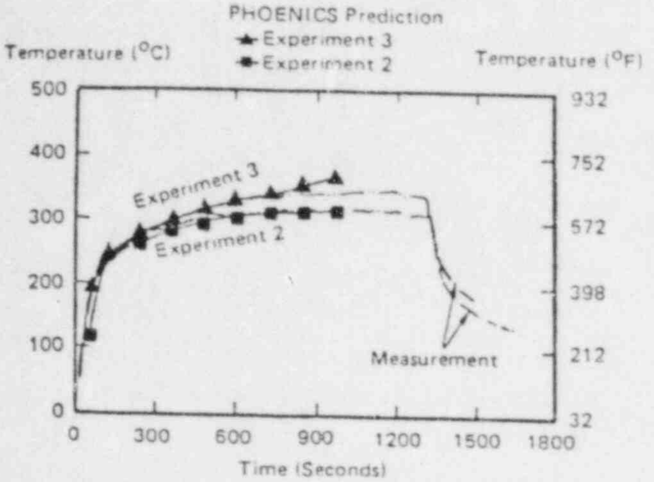
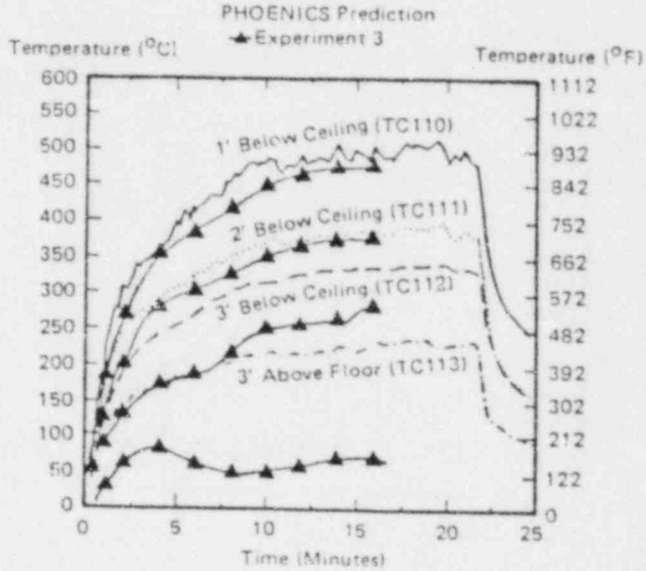


Figure 11. Measured doorway profiles in Steckler's (NBS) Steady-State experiments.



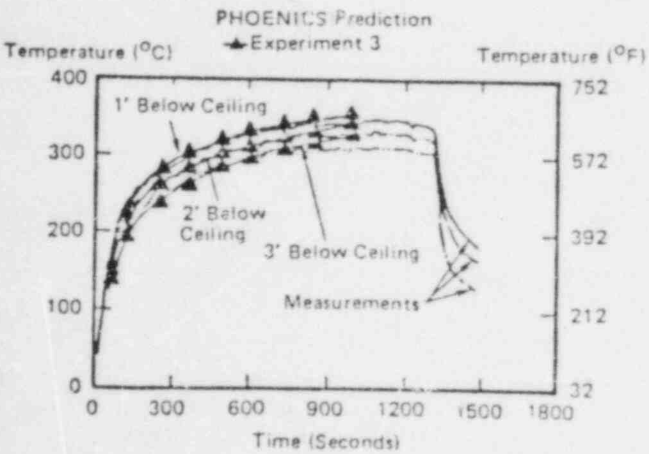
Temperatures are the Average of Thermocouples 69, 73 and 77. (1' Below Ceiling and 2' from the Tray)

Figure 12. Predicted and measured temperatures for Experiments 2 and 3.



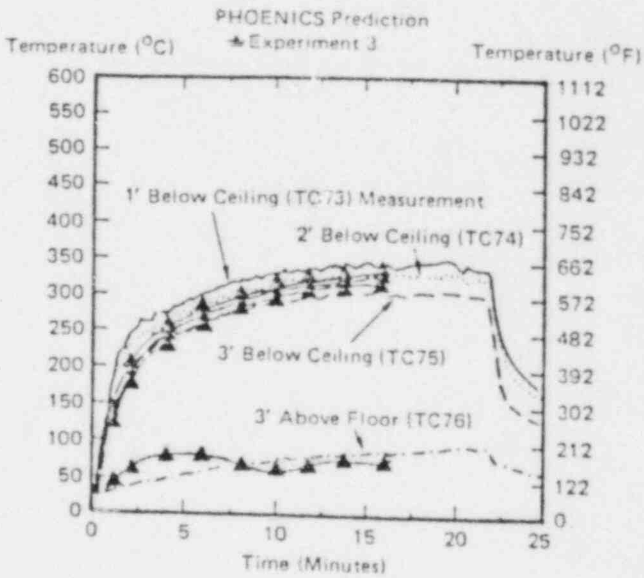
4' FROM SOURCE FIRE

Figure 14. Predicted and measured temperatures at several levels for Experiment 3.



Thermocouples are 2' in Front of Horizontal Tray

Figure 13. Predicted and measured temperatures at several levels for Experiment 3.



20' FROM SOURCE FIRE

Figure 15. Predicted and measured temperatures at several levels for Experiment 3.

To illustrate the overall flow pattern, a calculated velocity field for Experiment 2 at t=360 s is presented in Figure 16 in two longitudinal vertical planes. Inspection of the velocity fields which are generated by the code reveals the following.

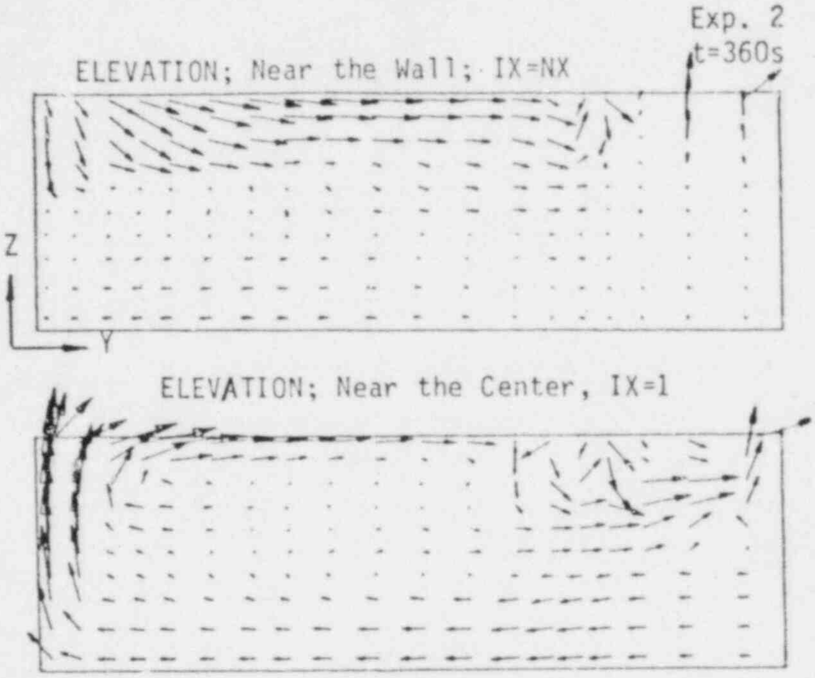


Figure 16. Velocity Distributions in Two Longitudinal Vertical Planes (Experiment 2)

- Strong upflow motion, induced by the fire source, impinges on the ceiling and is deflected outward along the ceiling.

- The hotter air is removed from the enclosure through the upper part of the doorway.

- Cold air is drawn into the enclosure through the lower section of the doorway. As expected, a recirculation eddy is observed between the door and the side wall.

Full scale Tests 1 and 2 were similar to Experiment 3 in all respects except for the presence of vertical cables above the heptane pool. These cables also burned, and as a result the heat release rates were higher and steeper than those of Experiments 2 and 3 (Figure 7). Figures 17 through 22 show the comparisons of calculated and measured temperatures at various horizontal and vertical locations. The difference between predicted gas temperature near the cable and the measured temperature (the thermocouples were located on the cable skin) shown in Figures 18 and 20 is plausible since it is is due to the thermal inertia of the cables, which has not been included in the computational model. As

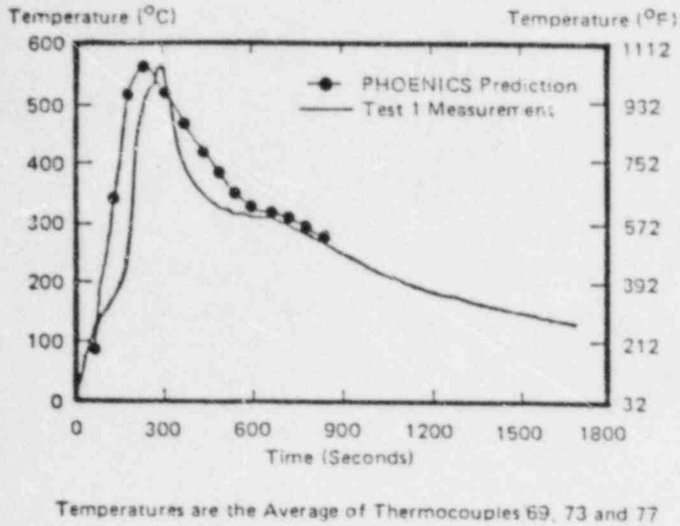


Figure 17. Predicted and measured temperatures at 1' below ceiling and 2' from the tray (Test 1)

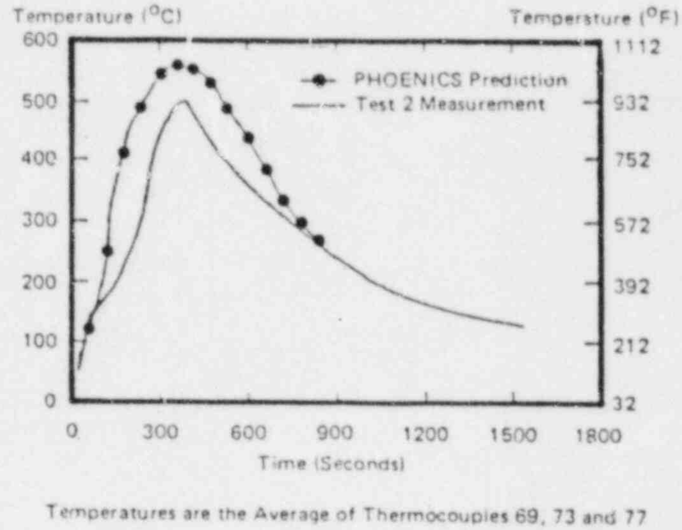


Figure 19. Predicted and measured temperatures at 1' below ceiling and 2' from the tray (Test 2)

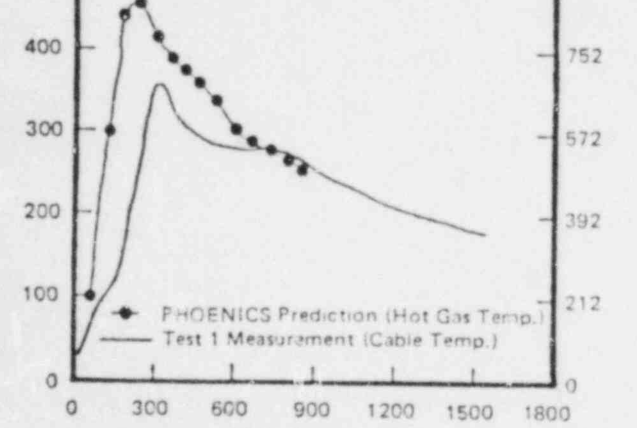


Figure 18. Predicted and measured temperatures at redundant target (Test 1).

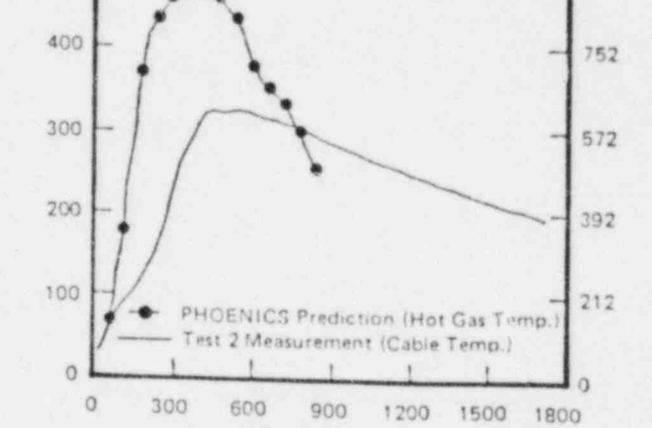


Figure 20. Predicted and measured temperatures at redundant target (Test 2).

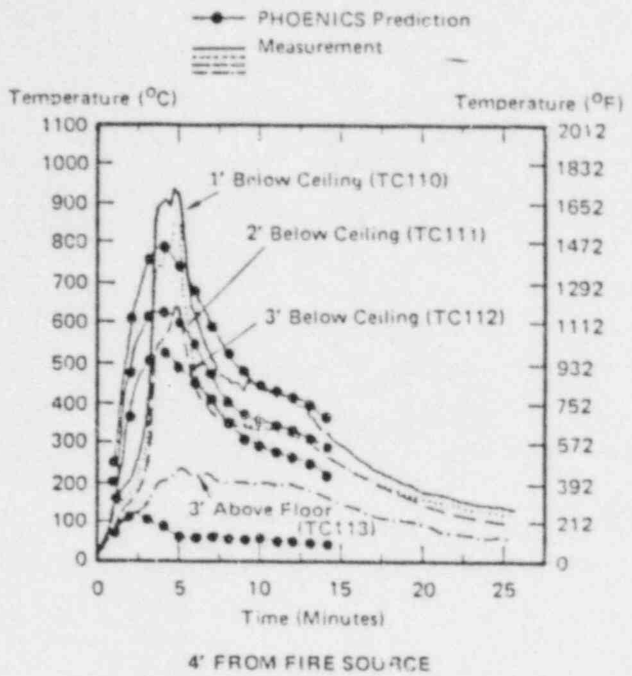


Figure 21. Predicted and measured temperatures at several locations for Test 1.

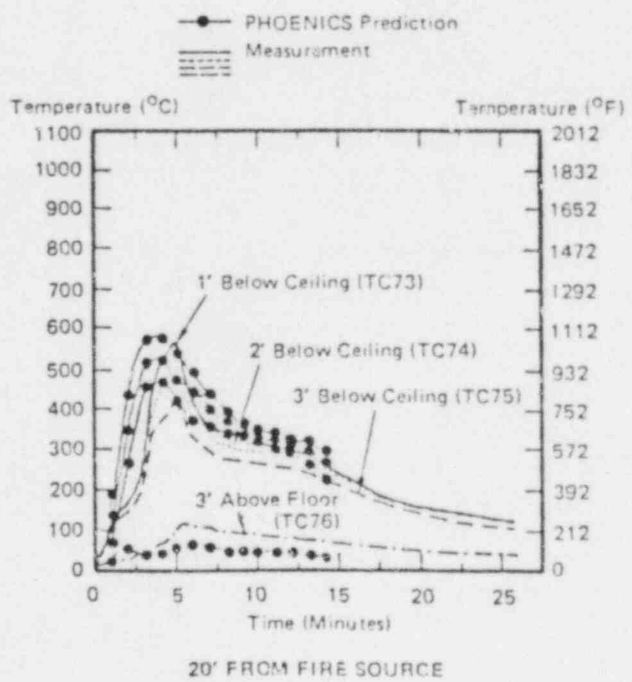


Figure 22. Predicted and measured temperatures at several locations for Test 1.

expected, the predicted temperature is higher during the fire development period and lower thereafter. In general, the predicted temperatures conform to the measured ones. Early in the burn the hot layer is seen to develop very rapidly due to highly non-linear heat release from the cable burning (Figure 7). Near the end of the tests the hot layer temperatures reduce significantly due to the diminishing fire strength.

Graphical representations of selected isothermal surfaces for Experiment 3 and Test 1 are displayed in Figures 23 and 24. The progressive emergences of hot stratified layers are clearly observed. These results show physically plausible trends, e.g., early in the burn higher temperatures are developed in Test 1 compared to Experiment 3. Similarly, near the end of the tests, a lower temperature environment is observed for Test 1.

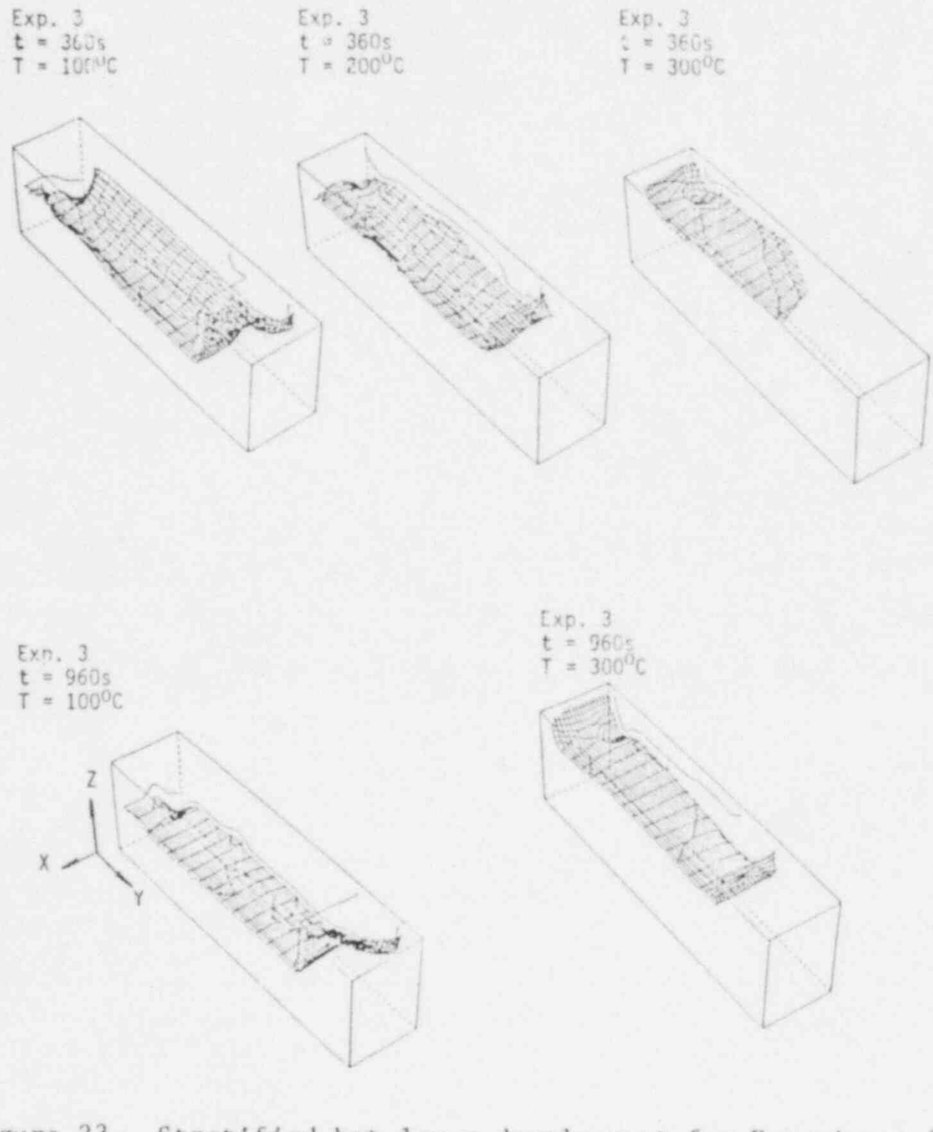


Figure 23. Stratified hot layer development for Experiment 3.

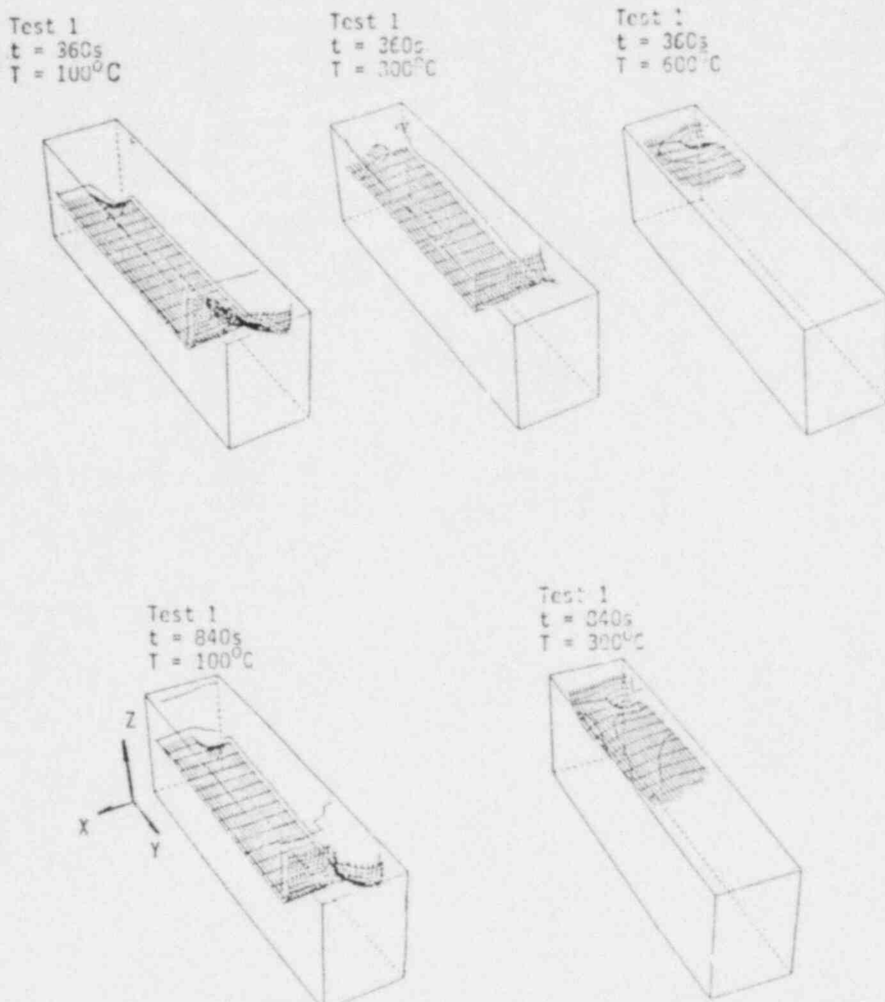


Figure 24. Stratified hot layer development for Test 1.

Calculated flow fields and temperatures are physically plausible. Velocity and temperature profiles across the doorway are similar to those reported by Steckler[12] for similar tests. In most respects, agreement between the calculated and measured temperatures is excellent. Differences in agreement are due to the effects of using unshielded temperature probes in areas dominated by radiative heat flux. The exercise has demonstrated the capability of this field model for prediction of the thermal environment within enclosures subjected to pool/cable fires.

Benchmark Testing. The responsibility for the fire tests lies with Sandia National Laboratory. BNL's contribution to this project consisted of assistance in establishing test matrices for the two cases of benchmarking tests to be performed: (1) baseline validation tests and (2) cabinet/control room tests. Additionally, BNL has provided input to aid in the selection of a test facility wherein these validation tests will be performed.

BNL's primary contribution in this project has been via assistance in the determination of the necessary physical properties for validation of the mathematical model described previously. Interactive meetings with both SNL and the NRC have produced a set of requirements for test output data. The most prominent of these properties are temperature, heat release rate of the source fire, convective and radiative heat fluxes, flow velocities at various locations and combustion species concentrations at several locations. Given these required properties, instrumentation needs for the test enclosure have been specified. This process specified an important set of considerations to be utilized in the selection of a test facility.

Test matrix development was also performed within the interactive meeting framework outlined above. Once the required physical test output data had been identified, decisions were reached regarding the number and type of tests needed to specify the properties within the matrix parameter space consisting of geometry, flow conditions, source fire type and strength, and obstacle configurations within the test enclosure. Both the physical matrix requirements and the time factors generated by the matrix design represent prominent additional factors in the test site selection process.

C. CONTROL ROOM HABITABILITY AND FIRE SAFETY STUDY PROGRAM

An additional application of the computational model recently initiated is the study of the fire environment within the LaSalle NPP control room which is being performed in conjunction with the PRA analysis of the RMIE project. Figure 25 presents an example of the computational cell model of the LaSalle control room. Objects, such as cabinets, control consoles, etc., are modelled as solid blocks. The plan view shown is at floor level and depicts such items as consoles, desks, chairs and other flow obstacles present at this level. The complete conputational model consists of several (7) horizontal slices covering

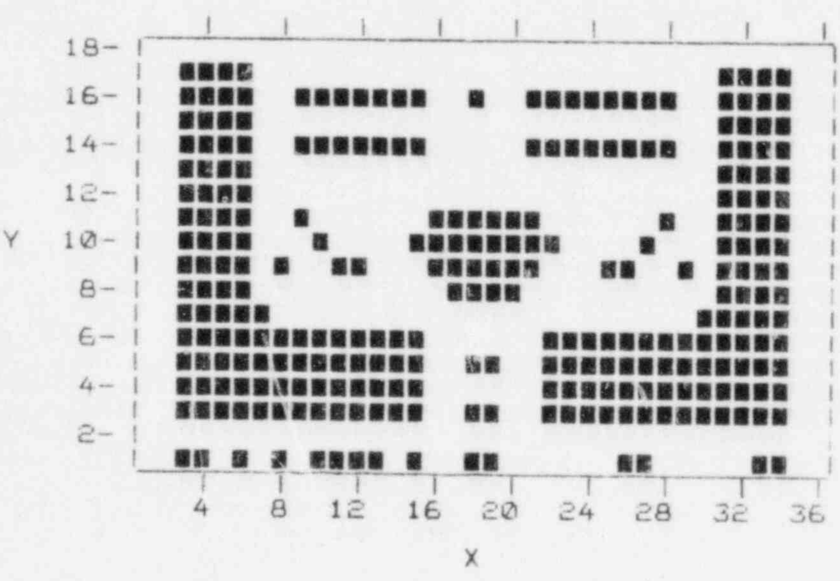


Figure 25. Horizontal Cross-Section

the entire room height from floor to ceiling. The grid depicted in Figure 25 is 36x18, however, in the computational analysis the grid was modified slightly to 32x19 to produce a total of 4256 control cells within which the governing conservation equations and constituent relations (see Table 2) are numerically solved.

Figure 26 depicts a detailed view of the cabinet structure within the valance frames of the control room. The LaSalle control room is unique in that these two L-shaped areas are actually exhaust plenums for the ventilation system. The forced ventilation inlets are distributed throughout the control room though there are none in the plenums. There are exhausts located in each plenum near the corner of the "L" at ceiling level and one additional small exhaust located outside in the control room. Air is drawn into the plenums through vents in the bottoms of cabinets and consoles which form part of the boundary of the plenums. Steel valances extend from the tops of the boundary cabinets to the control room ceiling thus isolating the exhaust plenums from the main portion of the control room. In addition to the forced ventilation exhausts, there are five doors leading out of the control room. Although these doors remain closed,

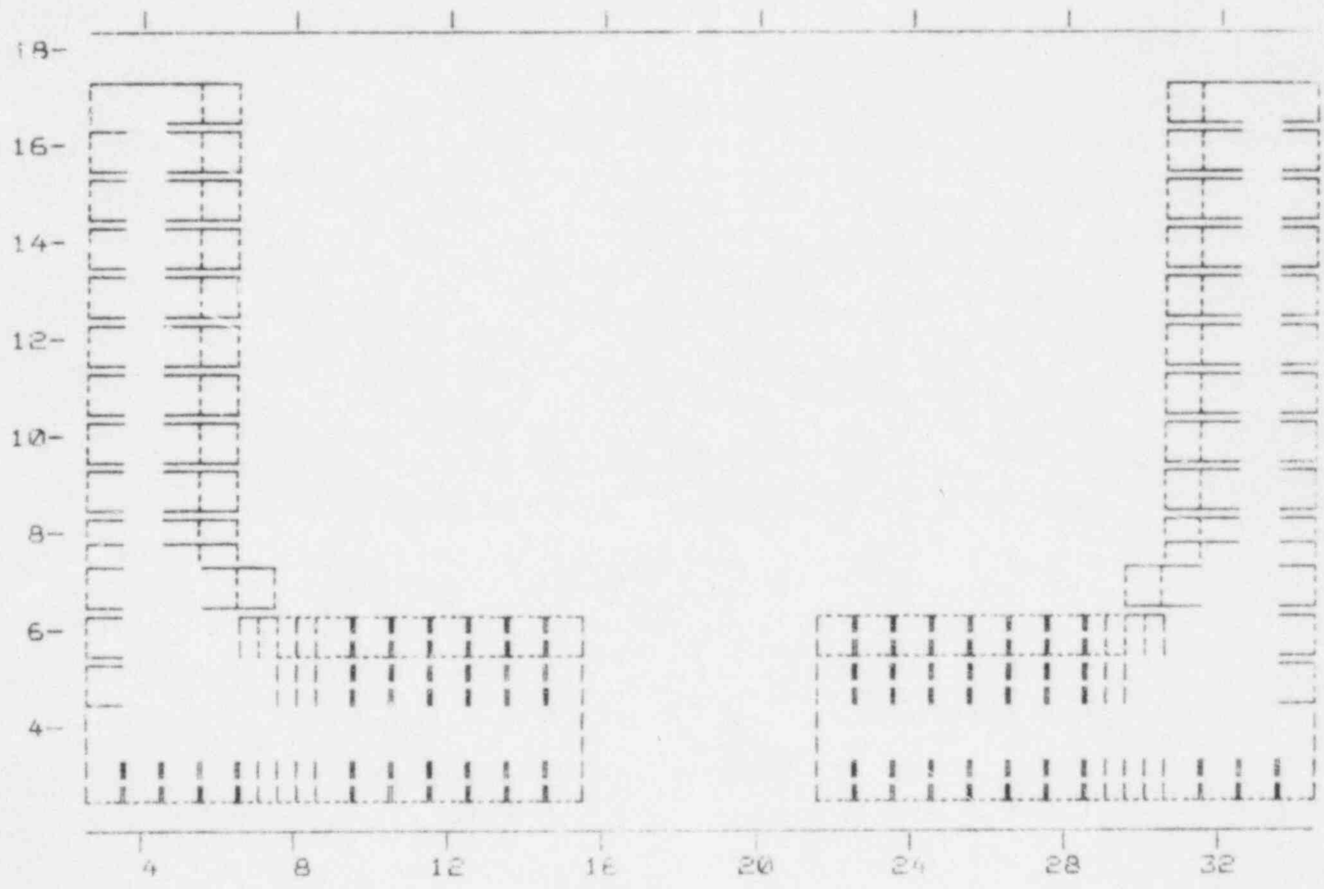


Figure 26. Valance Horizontal View

there is a total exfiltration rate of 1500 CFM out of the control room through these doorways. Total forced ventilation into the room is 24020 CFM. Room dimensions are 60 ft x 120 ft x 16.5 ft high, yielding an approximate 12 room changes per hour ventilation rate.

Two cases have been examined in the initial phases of this study:[13] (1) steady-state cold flow with no source fire, and (2) 6 min realtime simulation of a source fire located at (25,16) on Figure 25. The analyses of these two cases, while preliminary in nature, illustrate the expected physical properties which occur in enclosure fires.

The first of the above cases (cold-flow) was analyzed as a baseline case to establish the flow patterns within the control room under nominal steady-state state conditions. Flow is seen to proceed downward from the inlets in the cabinets and consoles at the plenum boundaries and up into the plenums and out the ventilation exhausts. Additional flow components also exit the control room through leakage from the five external doorways. Physically realistic flow patterns and velocities are observed at all obstacle boundaries.

In the second case above, a source fire modelled after the work of Williamson et al.[14] is utilized. This fire is not placed at a plenum boundary so the environmental effects are entirely whole-room effects and do not substantially perturb plenum conditions thermally or otherwise. Figure 27 depicts the flow conditions at floor level. For simplicity, flow obstacles such as cabinets, control consoles, etc., are not depicted in this figure as well as in Figure 28. Entrainment into the plume is clearly shown as is air flow into the exhaust plenums. Note that air flow through doorways is now into the control room as additional cold air is drawn in due to the buoyant action of the fire source. Figure 28 illustrates the thermal history of the environment at three time steps following fire initiation. At t=6 min it should be noted that the 150°C isotherm has not descended below 10 ft at any room locations other an very near the fire source, although some thermal mixing is observed even at floor level due to the ventilation jet induction. A critical time in fire history may be the time where the hot layer drops below the ventilation ducts and becomes substantially mixed with cooler air below. This time represents a critical stage in dispersion of toxic and thermal effects throughout the main body of the control room.

The preliminary examination of these two cases once again illustrates the physical applicability of the computational model. All of the primary characteristics of enclosure fires are present and modelled realistically. The usefulness of the model is demonstrated again via the thermal mapping and flow pattern analysis presented. Three-dimensional thermal and toxicity profiles are readily constructed from code output, and effects on equipment and personnel may be determined therefrom. However, until this phase of the study is completed no conclusions will be drawn regarding control room habitability and equipment damageability.

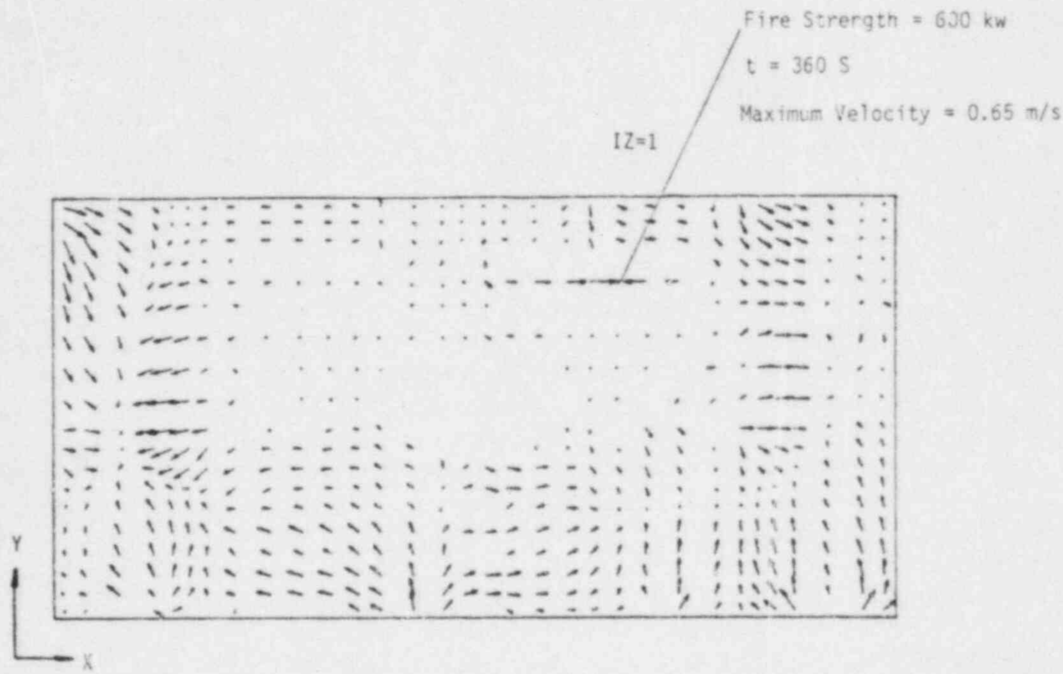


Figure 27. Velocity distributions in horizontal plane IZ=1 at t=360S

D. PLANT-SPECIFIC CODE APPLICATION

As part of the on-call assistance program BNL is called upon to review licensee-submitted requests for exemptions to Appendix R of 10CFR50. The thesis is that a postulated, probable fire in one of the Reactor Coolant Pump (RCP) bays would not affect the operation of redundant safe shutdown equipment. Fire-induced containment temperatures and pressures were calculated, through the models employed, to stay within acceptable limits. The scope of our review entailed answers to the following questions:

- Are the fire scenarios analyzed, albeit somewhat simplified, reflective of what may realistically occur? In other words, does the physical model employed represent an adequate replication of the major fire-related phenomena?

- Concomitantly, does the mathematical model portray adequately these major physical processes?

- Does the actual scenario analyzed bound the overall problem?

- Are the conclusions drawn from the calculated results valid, uniformly, with the assumptions made to provide a tractable analysis?

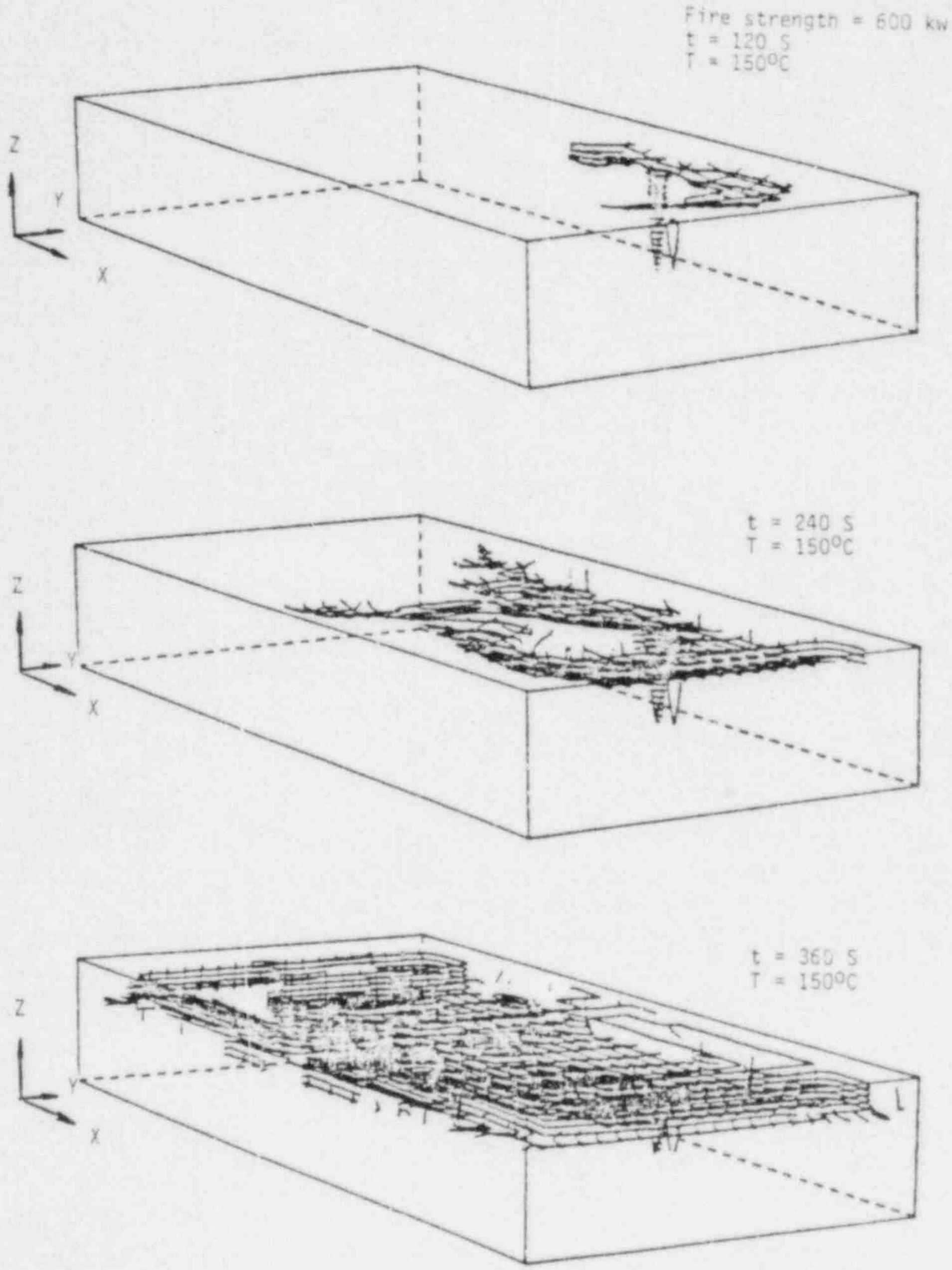


Figure 28. Development of temperature field at various times.

Our review of the fire models employed is through direct comparison of reported results using, in lieu of a quasi-steady, zone-model approach as employed by the licensee, a more fluid-dynamically detailed, two-dimensional, transient analysis. By definition and by solving a more accurate representation of the transfer of mass, momentum, and energy through convection and diffusion, assurances are provided that, indeed, the mathematical/physical model employed (for direct comparison of the numerical results) is a truer representation of the fire scenario. The analysis attempts to model the vertical temperature profile inside the containment building resulting from the combustion of 80 gal of lube oil on the floor of an RCP bay. The licensee uses a one-dimensional fire plume model coupled to a one-dimensional stratification model. This is supplemented by a ventilation flow model for buoyancy driven flow through RCP bay openings near the bay floor and ceiling. The objective of the analysis is to show that hot combustion products do not enter neighboring bays because of a chimney effect and that temperatures and pressures in the containment building do not represent a hazard to safe shutdown equipment short-term operation.

The plume model is assumed to be steady-state. This is justified because the plume response time is one or two orders of magnitude faster than the heat-up response time of the containment as a whole. However, the stratified layer model is dynamic in that the growth of the layer with time is simulated, starting at the top of the containment and moving downward. The one-dimensional nature of the model ignores the effects of the lateral placement of the fire within the containment and requires the model elements to be visualized as being axisymmetric about the containment building centerline. Also, toroidial vortex development within the stratified layer as a result of bouyancy induced forces and vertical plume momentum transfers resulting from containment wall interaction, is not considered. Basically, the analytical modeling provided in the submittal can be asociated with what is termed as the "classical filling-box" model.

We used the PHOENICS code to simulate the 80 gal lube oil fire. The code was run in two dimensions, axisymmetric about the containment building centerline, using the geometry given in Figure 29 on a computational grid of 10 by 15 cells. A constant heat flux of 7644 kW (convective heat release rate of the 12 ft diameter lube oil fire) was input at the center floor cell of the model RCP bay for a total of 10 minutes, with the results printed each minute.

Using the simplified analysis, the temperatures in the containment were computed to be 450K near the ceiling, 429K at 66 ft and 350K near the floor. The PHOENICS results show a similar flow field with temperatures (interpolated to 10.5 min) of 440K, 428K and 385K, respectively. The PHOENICS results therefore support the simplified analysis for this geometry.

The flow field vectors are shown in Figure 30. The vectors are plotted on a two-dimensional cross section of the containment building and are magnified seven times to aid visualization of the complete flow field. The flow out of and into the RCP bay is clearly shown, as is the entrainment into the plume. The return circulation causes the temperature near the containment base to be hotter than that computed by the simpler analysis.

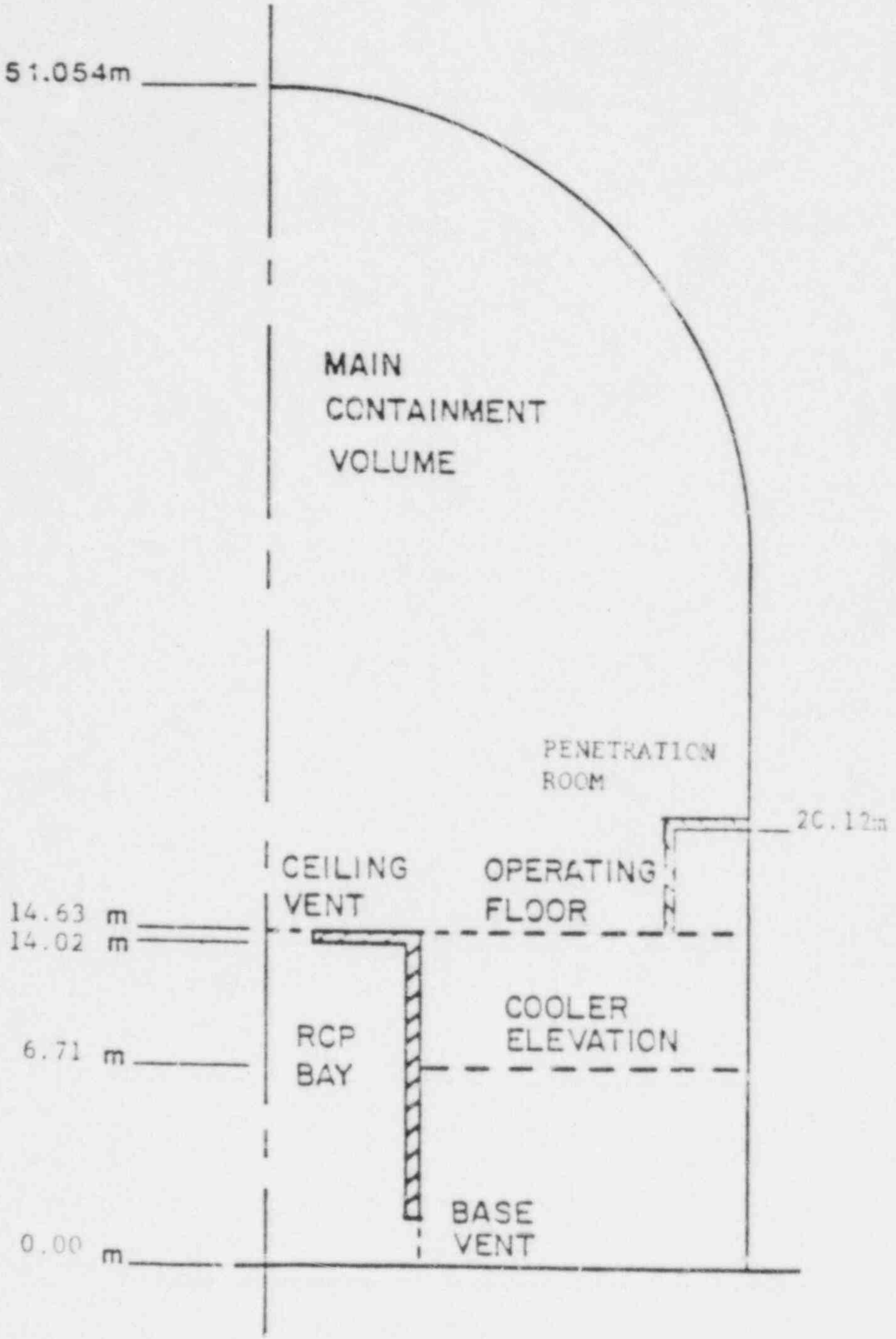


Figure 29. Containment model geometry.

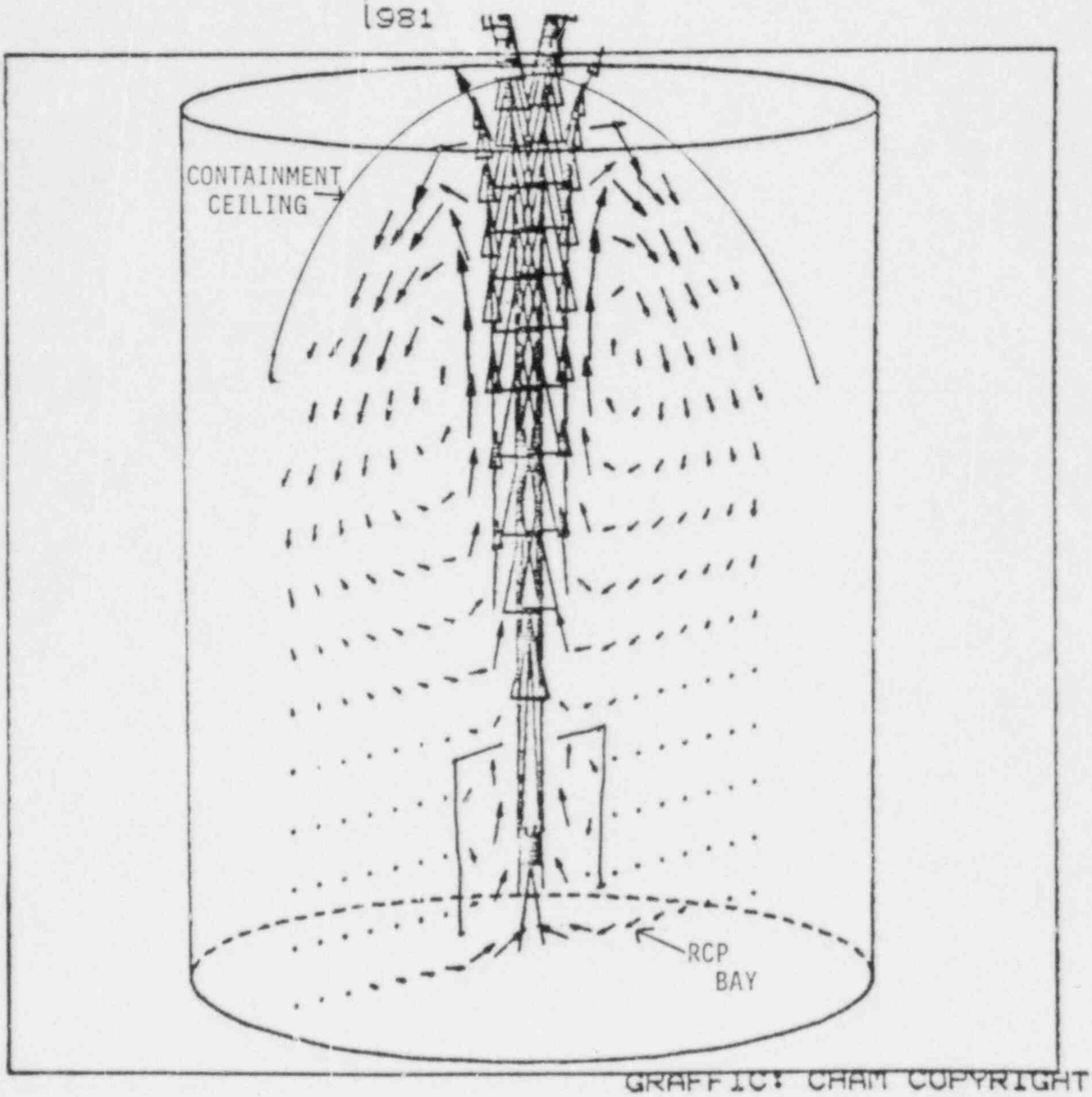


Figure 30. Flow vectors plotted on a 2-D cross section of the containment building. The vectors are magnified seven times for details. The plume updraft is 6 M/S, the downdraft is 5-10 cm/s, and the inflow at the RCP bay base is 1 M/S. (Graffic: CHAM Copyright)

A comparison of the temperature profiles in the containment outside the plume are shown in Figure 31. In Figure 32, we have plotted the isotherms in the containment building at the end of the fire. The lines are contours from 386K to 450K in 2K increments and show the resulting stratification.

This comparative study has shown that PHOENICS can be used to benchmark simplified analysis. By using a more fluid-dynamically detailed, two-dimensional, transient analysis, we were able to closely produce the results of the quasi-steady, zone-model approach employed and feel confident that the model adequately portrays the major physical processes under the assumption of a simplified geometric portrayal of the containment building.

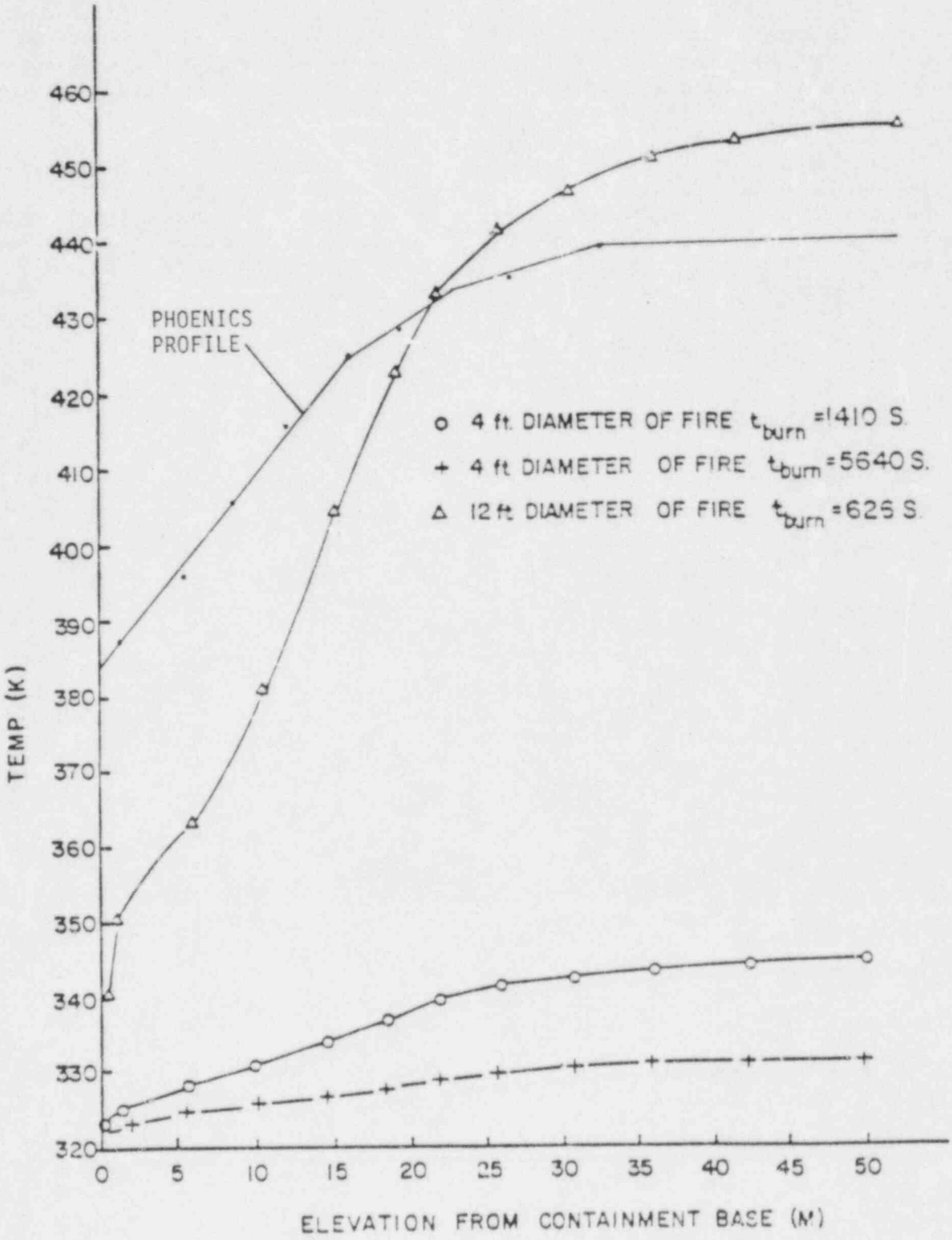


Figure 31. Containment temperature profile at end of variously sized lube oil fires.

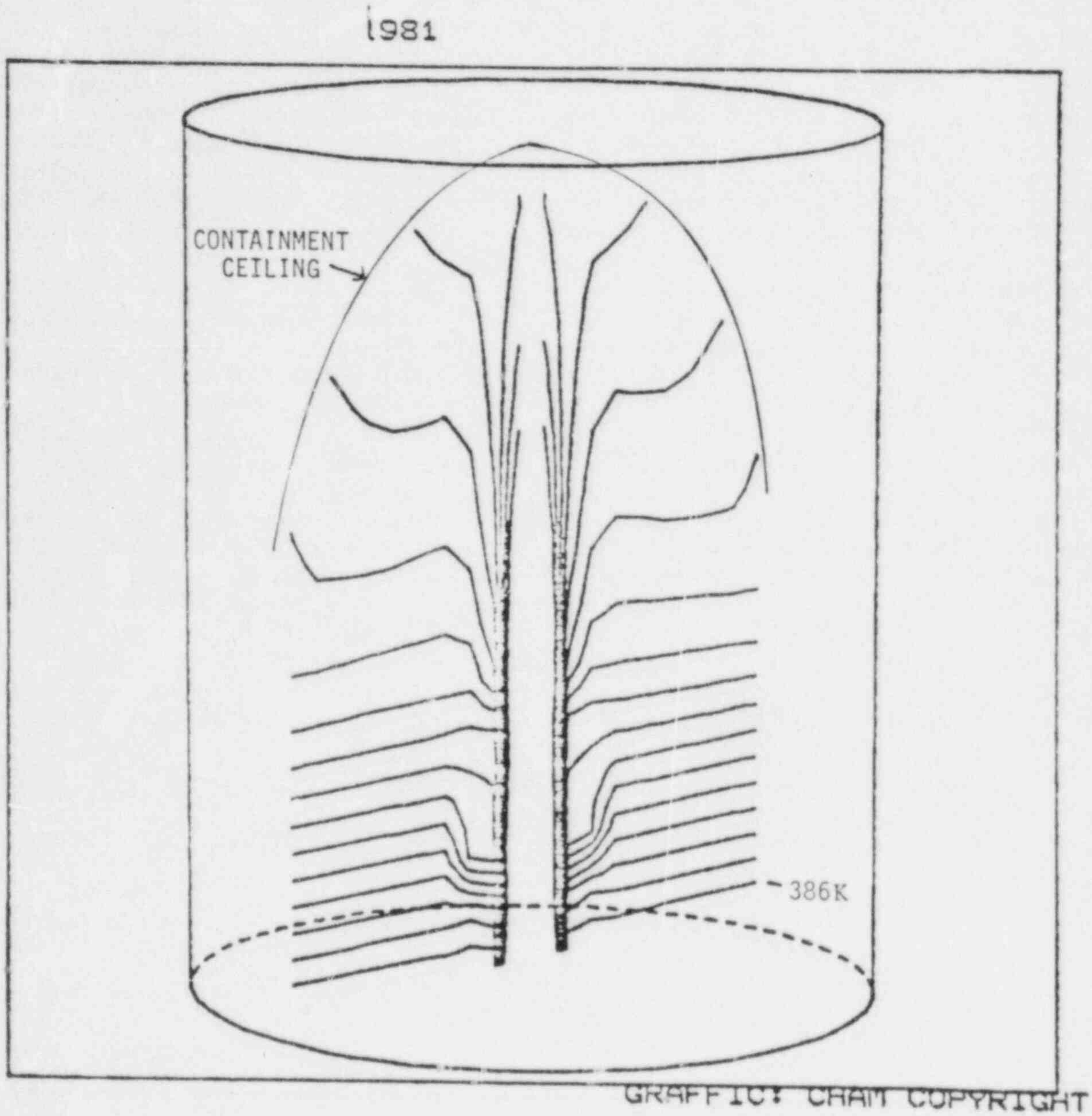


Figure 32. Lines of constant temperature in the containment building after the postulated fire. The contours range from 386K to 450K in 2K increments.

IV. FUTURE DIRECTIONS - BNL

A. Validation with Cabinet/Control Room Test Data

This phase of the study awaits the output from the cabinet/control room tests. These tests will enable the final set of validation simulation studies within the program. Additionally, these tests will provide the basis of comparison for including a series of upgrades within the framework of the computational model. These upgrades include (1) modifications for chemical reactions, and (2) modifications for heat losses to enclosure boundaries and objects within the enclosure. Modifications for chemical reaction include provisions for the following: transport of toxic gases, chemical reaction with SCRS (Simple Chemical Reaction System) model, and one-step, finite-rate reaction model. The second and third portions of this task enable the elimination of the need to specify heat release rate data as input to the code. Modifications for heat losses include the effects of both convective and radiative heat transfer. Radiative heat losses will be calculated eventually by the incorporation of a six-flux radiation model. These heat loss modifications will enable the detailed examination of heat flux effects on sensitive equipment located within the enclosure.

B. Parametric Study of Fires Within NPP Control Rooms

Of concern in both this study and also the RMIEP probabilistic survey is a fully involved cabinet fire and its effects on adjacent and non-adjacent control room systems. BNL and CHAM are to utilize the code described above to model this control room scenario. The control room will be divided into a three-dimensional grid as detailed above, and various source fire strengths and locations will be examined in the context of both deterministic and probabilistic analyses. The effects of both the thermal environment and the toxic gas environment will be determined by utilizing the analytical techniques developed to date in this project.

V. CONCLUSIONS

Primarily, this study has shown the following:

1. Existing field model fire codes, namely PHOENICS, are readily available to assist in appraising the effects of prespecified fires within complex nuclear power plant enclosures under both normal and forced ventilation conditions.

2. By direct comparison with enclosure fire experiments, reported herein as well as in the open literature, the PHOENICS code and its solution algorithm has been adequately demonstrated with regard to its capability of reasonably predicting spatial and temporal variations of fire-induced environments.

3. Suggestions made by PRA practitioners and PRA reviewers regarding the wide uncertainty associated with fire risk analysis, indicate that the modeling effort described in this report can be utilized to "benchmark" deterministic fire models/codes presently employed in analyzing fire risk.

4. The ability of the code to map the thermal and toxic gas environment within complex enclosures, given the energy release rate and toxic gas mass source rate of the initiating fire, indicates that the output of the code can be used to better scope enclosure fire experiments and provide "boundary-condition information" for component fire vulnerability (fire fragility) test programs. Critical areas where enclosure fire test instrumentation should be concentrated can be easily defined through examination of these thermal maps.

Based upon these efforts and the findings reported herein, it is concluded that not only are the future directions described in Section IV warranted and doable, but the present state of the code has the requisite, built-in features to address the fire-protection issues that have been identified and thus better assure realistic, cost beneficial, and continuation of the Fire Protection Reseach Program.

REFERENCES

1. Cline, D.D., Von Riesemann, W.A., and Chavez, J.M., "Investigation of Twenty-Foot Separation Distance as a Fire Protection Method as Specified in 10CFR50, Appendix R," NUREG/CR-3192, SAND83-0306, October 1983.

2. Hill, J.P., "Fire Tests in Ventilated Rooms-Extinguishment of Fires in Grouped Cable Trays," EPRI Project RP 1165-1-1, Report NP-2660, prepared by Factory Mutual Research Corporation, Norwood, MA.

3. Spalding, D.B., "A General Computer Program for Fluid Flow, Heat Transfer and Chemical Reaction Processes," presented at the International FEM-Congress, Baden-Baden, Germany, November 17-18, 1980.

4. Planning Research Corporation, "Solid Rocket Motor/Vehicle Assembly Building Inadvertent Ignition Effects Study," NASA KSC-DF-441, September 1981.

5. Cox, G., "A Field Model of Fire and its Application to Nuclear Containment Problems," Proceedings of the CSNI Specialist Meeting on Interaction of Fire and Explosion with Ventilation Systems in Nuclear Facilities, LA-9911-C, Vol. I, p. 199, April 1983.

6. Launder, B.E., and Spalding, D.B., Mathematical Models of Turbulence, Academic Press, London, 1972.

7. Markatos, N.C., Malin, M.R., and Cox, G., "Mathematical Modeling of Buoyancy-Induced Smoke Flow in Enclosures," Int. J. Heat Mass Transfer, Vol. 25, No. 1, pp. 63-75, 1982.

8. Markatos, N.C., and Cox, G., "Turbulent Buoyant Heat Transfer in Enclosures Containing a Fire Source," Seventh International Heat Transfer Conference, Munchen, 6, p. 373, 1982.

9. Eagnaro, M., Lauuisset, M., and Lockwood, F.C., "Field Model Prediction of Some Room Fires: Steady and Transient," The 21st National Heat Transfer Conference, pp. 107-114, Seattle, WA, July 1983.

10. Nowlen, S.P., "Heat Release Rates During the Sandia/UL 20 Foot Separation Tests," Letter Report prepared for Electrical Engineering Branch, Division of Engineering Technology, Office of Water Reactor Safety Research, U.S. Nuclear Regulatory Commission, DOE 40-550-75, NRC FIN-A1010, June 1984.

11. Spalding, D.B., "Mathematical Modeling of Fluid Mechanics, Heat Transfer, and Chemical Reaction Proceses," CFDU, Report No. HTS/80/1, 1980, A Lecture Course, Imperial College.

12. Steckler, K.D., Quintiere, J.G., and Rinkinen, W.J., "Flow Induced by Fire in a Compartment," NBSIR-82-250, National Bureau of Standards, 1982.

REFERENCES (Cont'd)

13. Singhal, A.K., and Tam, L.T., Progress Report: "Fire Modeling for Nuclear Power Plant Enclosures - Three Dimensional Calculations," CHAM of North America, Inc., Prepared for BNL, Feb. 1985.

14. Williamson, R.B., Mowrer, F.W., and Fisher, F.L., Final Report: "Fire Safety of Electrical Cabinets," Lawrence Berkeley Laboratory, Prepared for NRC, Jan. 1984.

NRC FORM 335 (2 84) NRCM 1102, 3201, 3202

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

SEE INSTRUCTIONS ON THE REVERSE

1. REPORT NUMBER (Assigned by TIDC add Vol No., if any)
NUREG/CR- 4479
BNL/NUREG- 51948

2. TITLE AND SUBTITLE
THE USE OF A FIELD MODEL TO ASSESS FIRE BEHAVIOR IN COMPLEX NUCLEAR POWER PLANT ENCLOSURES: PRESENT CAPABILITIES AND FUTURE PROSPECTS

3. LEAVE BLANK

4. DATE REPORT COMPLETED

MONTH	YEAR
November	1985

5. AUTHOR(S)
JOHN L. BOCCIO AND JOHN L. USHER

6. DATE REPORT ISSUED

MONTH	YEAR
December	1985

7. PERFORMING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)
BROOKHAVEN NATIONAL LABORATORY
UPTON, NEW YORK 11973

8. PROJECT/TASK/WORK UNIT NUMBER

9. FIN OR GRANT NUMBER
FIN A-3252

10. SPONSORING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)
DIVISION OF ENGINEERING TECHNOLOGY, RES
OFFICE OF NUCLEAR REGULATORY RESEARCH
U.S. NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555

11a. TYPE OF REPORT

b. PERIOD COVERED (Inclusive dates)

12. SUPPLEMENTARY NOTES

13. ABSTRACT (200 words or less)

This report provides a summary of the work conducted during FY84 by Brookhaven National Laboratory (BNL), under FIN A-3252 "Fire Protection Research Program." It was undertaken under the cognizance of the Electrical Engineering Branch in the Division of Engineering Technology within the Office of Nuclear Regulatory Research. The report describes a mathematical model for predicting the thermal environment within complex nuclear power plant enclosures. It demonstrates the capability of the existing numerical code by direct comparisons with electrical cable fire/large enclosure tests performed by Factory Mutual Research Corporation (FMRC) for the Electric Power Research Institute (EPRI). It further demonstrates the potential usefulness of the existing code in addressing fire-protection issues. This is done through a parametric study of the thermal environment resulting from a series of fires within cabinets in a nuclear power plant control room (similar to LaSalle). Also, it presents an example of how the code can be utilized by addressing an Appendix R exemption request which deals with the vulnerability of containment fans to a fire emanating from a reactor coolant pump bay. Recommendations are also given as to how the model/code can be further enhanced and where current effort is proceeding.

14. DOCUMENT ANALYSIS – a. KEYWORDS/DESCRIPTORS

fire protection
computer codes
control rooms
nuclear power plants
cable fires
pool fires
field models
cabinet fires
forced ventilation
complex geometry

b. IDENTIFIERS/OPEN ENDED TERMS

15. AVAILABILITY STATEMENT
Unlimited

16. SECURITY CLASSIFICATION
(This page)
Unclassified
(This report)
Unclassified

17. NUMBER OF PAGES

18. PRICE

120555078877 1 1AN1R7
US NRC
ADM-DIV OF TIDC
POLICY & PUB MGT BR-PDR NUREG
W-501
WASHINGTON DC 20555