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A Summary of the Fire Testing Program at the German HDR Test Facility

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**Prepared for
U.S. Nuclear Regulatory Commission**

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Abstract

This report provides an overview of the fire safety experiments performed under the sponsorship of the German government in the containment building of the decommissioned pilot nuclear power plant known as HDR. This structure is a highly complex, multi-compartment, multi-level building which has been used as the test bed for a wide range of nuclear power plant operation safety experiments. These experiments have included numerous fire tests. Test fire fuel sources have included gas burners, wood cribs, oil pools, nozzle release oil fires, and cables in cable trays. A wide range of ventilation conditions including full natural ventilation, full forced ventilation, and combined natural and forced ventilation have been evaluated. During most of the tests the fire products mixed freely with the full containment volume. Macro-scale building circulations patterns which were very sensitive to such factors as ventilation configuration were observed and characterized. Testing also included the evaluation of selective area pressurization schemes as a means of smoke control for emergency access and evacuation stairwells.

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Acknowledgements

To a large extent this report represents a consolidation of information gleaned from various reports published by the HDR experimental staff and others. The author gratefully acknowledges these reports as the source of much of the material presented here. In addition, the author thanks Herr Müller, of KfK, for his friendship, and for his insightful support of the SNL/NRC cooperative efforts. Thanks also to Herr Wenzel and the rest of the HDR staff for their kind and patient hosting of the author's various visits to the test facility during the course of this undertaking, and for their help in extending the authors limited German language skills. Finally, the author acknowledges the contributions of Bill Farmer, of NRC/RES (retired), for his recognition of the importance and unique nature of the HDR fire test program and for his support of these efforts.

Executive Summary

The purpose of this document is to provide an overall description of the fire tests which have been performed under the sponsorship of the German Government in the Heißdampfreaktor (HDR) test facility. This document focusses on the physical characteristics of the tests including test design, test performance, data gathering, and other similar topics. To a more limited extent, the major results and findings of the tests are also discussed.

The HDR facility is an inactive pilot nuclear power plant project east of Frankfurt, Germany. While the plant actually was operated for approximately one month, operational instabilities quickly lead to the permanent shutdown and defueling of the reactor. The plant containment building has been used for a number of years as a test bed for a variety of experimental studies. The particular studies of interest to this report are those involving fire safety.

A variety of fire tests have been performed in this facility. These tests have utilized a range of fuel sources including gas burners, wood cribs, liquid fuel pools, nozzle release oil fires, and electrical cables in cable trays. Fires have been set in three different locations within the containment building, and tests have been performed under natural, forced, and combined ventilation conditions. The tests generally involved the full containment structure in the circulation of fire products; however, in the case of the cable fires only a limited subsection of the containment was involved.

In reviewing the structure and design of the fire tests performed, one should keep in mind the fact that the German researchers have their own set of objectives and questions, some of which are somewhat unique to facilities in Germany. As an example, the HDR tests have focussed considerable effort on the evaluation of smoke control strategies which might be used in maintaining smoke-free emergency access and evacuation routes during a fire event. This results from the fact that the German building codes require that such protected access paths be provided in all manned or potentially manned structures, including reactor containment buildings. In the U.S., there are as yet no stringent corresponding codes, and hence, the smoke control issue has not been a high priority research topic. The results of such investigations are nonetheless of interest, particularly as they might apply to advanced reactor design strategies, and to the fire protection community at large.

The fire tests performed at HDR are unique in several respects. First and foremost, they represent the most extensive testing of fire in a complex, multi-compartment, multi-level structure performed to date. The response of this complex structure to the fires is extensively characterized. Macro-scale involvement of the containment volume has been demonstrated and characterized. The fire tests are also unique in their extensive evaluation of ventilation system interactions and effects including the performance of selective pressurization schemes, the impact of ventilation system configuration on macro-scale circulation patterns, and the impact of smoke on ventilation filtration systems.

In addition, it should be noted that the overall testing program included an international fire model validation effort. In particular, the fire test have been designed and implemented so as to allow for the direct comparison of test results to computer fire modeling predictions. Extensive efforts have been undertaken to evaluate the performance of a variety of existing fire models in both blind and semi-blind calculations of the fire effects. This included a variety of fire models developed in a number of countries. The current report includes only minimal discussion of these fire modeling efforts which are described in detail in a separate document [5.2.1].

1 Introduction

1.1 Project Overview

The Heißdampfreaktor (HDR, which translates as Heavy Water Reactor) is an inactive pilot nuclear power plant project east of Frankfurt, Germany on the banks of the Main river. While the plant actually was operated for approximately one month, operational instabilities quickly led to the permanent shutdown and defueling of the reactor. The plant remains, administratively, a licensed nuclear power plant. However, it is unlikely in the extreme that operations there would ever again be initiated.

For a number of years, the plant, and in particular the containment building, has been used as a test bed for a variety of operational safety experimental studies. These studies have included, seismic simulations, aircraft impact, high pressure steam blowdowns, hydrogen burn, and fire. At the time of this writing, this phase of the HDR experimental program has been experimentally completed and no further operational safety experiments are planned. Efforts to close out the analysis and reporting of the final experiments continue. (It is likely that at some time in the future, the plant will be used as a test bed for evaluation of plant decommissioning techniques. However, funding of these activities remains an issue.)

The particular studies of interest to this report are those involving fire. A number of fire tests have been performed in the containment building over the course of several years effort. These experiments have been divided into groups or series in which each series of tests would typically involve a set of 3-14 tests performed in a given location within the containment structure. Testing has involved various fuel sources including gas burners, wood cribs, liquid fuel pools, nozzle release oil fires, and electrical cables in cable trays.

The actual performance of testing at HDR has been sponsored by the German government, in particular the German Ministry for Research and Technology (BMFT), and has involved a number of organizations within Germany. The primary operational oversight has been provided, alternately, by Battelle Institute Frankfurt and by Kernforshungzentrum Karlsruhe (KfK, which translates roughly as the Nuclear Research Center in Karlsruhe). In general terms, these two groups have alternately managed the facility for periods of five years at a time. Other groups which have had a significant level of involvement, in particular, in planning for and analyzing the fire efforts, include Gesellschaft für Reaktorsicherheit (GRS, which translates roughly as Company (or Society) for Reactor Safety), and the University of Braunschweig. A wide variety of international organizations have also had some level of involvement in the HDR project, primarily as a result of interest in the experimental results and findings.

1.2 Scope of this Document

It should be noted at the outset that the Germans themselves have published numerous reports documenting various aspects of the HDR test program. The preparation of this report was based largely on the material available in these various German reports, supplemented by personal discussions with the project staff. Most of the important German reports have been translated to, and are available in, English; however, some of the reports, and particularly those reporting intermediate results or which represent planning documents, are available only in German.

The current report is not intended to replace these reference documents. Rather, the purpose of this document is to provide the United States Nuclear Regulatory Commission (USNRC) with a concise, English language document which consolidates the salient highlights of the overall HDR fire test program. In particular, this report provides an overall description of the physical characteristics of the tests (i.e., test design, objectives, and test performance). To a more limited extent, the report also includes a discussion of the principal objectives and the principal test results and findings for each test series.

Also note that in conjunction with the fire testing program, an international fire simulation model validation effort has also been pursued by the HDR researchers. However, this document intentionally minimizes the discussion of these computer modeling efforts. These efforts are addressed in a separate document [5.2.1].

2 The Test Program and Objectives

2.1 General Facility Description

The most important segment of the overall HDR facility is the containment building itself. It is within, or upon, this containment building that all of the operational safety tests have been performed. However, in addition to the containment structure itself, the HDR facility includes an attached, four-story control building, and other office and storage support structures.

The containment building is an elongated vertical cylindrical structure with a domed top and a below-grade hemispherical base. The cylindrical section measures approximately 20 m (66 ft) in diameter. The overall height of the containment structure is about 60m (197 ft), of which approximately 11 m (36 ft) is below grade. Levels within the containment are identified by their distance above or below grade. The total containment volume is 11,000 m^3 (about 388,000 ft^3). (Note that this is relatively tall and narrow as compared to typical U.S. containment structures.)

Figure 2.1 provides an overview of the containment structure. This structure is divided into about 8-9 primary levels (depending on exactly how one counts the below-grade levels). The highest level is the upper dome section and is basically a large open hemisphere beginning at the +30.85 m (+101 ft) level. Below the dome area are four additional levels which surround the central reactor vessel area. The next level below this is the primary access level at +4.5 m (+15 ft). Below the primary access level, the subdividing becomes less well defined, but basically, there are two-three additional levels, again depending on how one counts the individual levels.

Each level is further subdivided into a variety of small rooms or partially segregated spaces. Most of the areas are open and relatively few doors are present. Connections between the levels include an open switch-back style stairway, an open spiral stairway, and a closed personnel elevator shaft. In addition, the upper six levels are connected via a set of primary equipment hatches which form a shaft adjacent to the primary stairwell. Doorways located in these hatchways can be closed at each level. In most of the experiments performed, these hatchways were left open creating an open shaft between levels from the dome down to the primary access level. Finally, a secondary equipment hatch also connects the 25.3 m level to the dome in an area adjacent to the secondary spiral stairway. (This secondary equipment hatch played an important role in the T52 test series.)

Fire tests were performed in several locations within the containment. As will be described further below, tests were performed in the lower below-grade levels, in an upper level area adjacent to the secondary spiral stairwell, and on the primary access level. These locations are also highlighted in Figure 2.1. In all but the final series of tests, the entire containment structure was open and involved in the fire products migration.

The general containment ventilation system is comprised of external blowers (located in the adjacent control building) which provide fresh air intake and internal air exhaust. The fresh air intake is drawn from the environment, filtered, conditioned (heated or cooled), and introduced into the containment at various points through a system of distributed ducts. The exhaust air removed from the containment is drawn through various points via a similar distributed system of ducts, passed through a series of filter banks, and discharged to the environment through a ventilation stack.

For use in certain experiments supplemental localized ventilation systems were provided. Generally, these systems were associated with providing a localized source of fresh air to the fire source, or with creating isolated ventilation loops. These unique configurations are described as appropriate for each test series.

2.2 Project Objectives

Historically, most fire test programs have focussed on an investigation of one specific issue. While other questions or issues may be investigated, this is typically done on an "as possible" basis. The HDR tests are somewhat unique in this regard in that no one single issue or question has entirely driven test design and planning. Rather, the HDR fire test program has encompassed the investigation of a range of current fire safety research issues and questions.

The HDR test program has also taken particular advantage of its long-term nature in optimizing project planning. That is, fire testing began in 1982, and continued into 1992. Thus, a significant amount of time could be taken after one test series to plan and prepare for the next test series. During the interim, other experimental programs were executed so that nearly continuous testing took place. These other programs included steam blow-downs, seismic testing, aircraft impact, and limited decommissioning experiments. This allowed for the maintenance of a full time HDR site staff throughout the testing process.

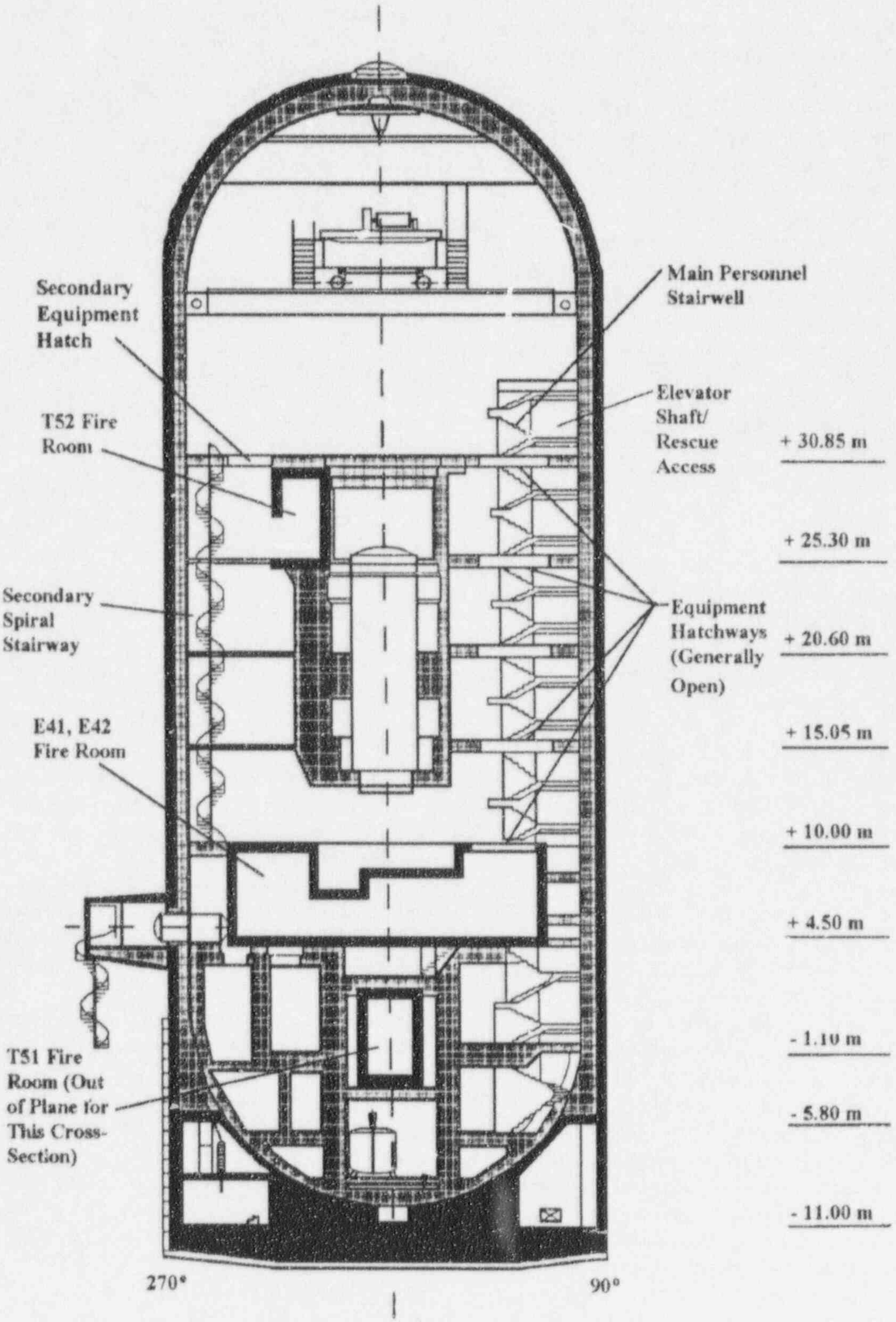

Figure 2.1: General Schematic View of the HDR Containment Structure.

However, at the same time one must recognize that this test program was first and foremost an undertaking of the German government. Hence, the issues which were investigated were primarily those associated with the resolution of German fire safety concerns and regulatory uncertainties. While many of these concerns parallel those of the USNRC, the match is not one-to-one. Hence, some aspects of the German test program will not be particularly relevant to current USNRC concerns.

It should also be noted that while all of the fire tests were performed within the HDR containment structure, the applicability of the results is certainly not limited to containment structures. In fact, the test results provide insights into the behavior of fire and fire products in any complex structure.

As identified by the German researchers [5.1.3], "(t)he purpose of the HDR studies lies mainly in the following fields:

- Improved understanding of the physical processes occurring during fires, such as temperature and pressure buildup, combustion behavior, fire propagation, smoke and fume development, fume aerosol behavior.
- Assessment of decisive parameters and boundary conditions, such as source of ignition, objects burning, oxygen supply, layout of rooms, ventilation conditions, etc.
- Improvement of our knowledge of the behavior of components in the containment (such as ventilation systems and filters).
- Verification and advancement of methods for computation of fires in the closed containment.
- Improved knowledge about fire fighting possibilities and rescue time (pressurized rescue stairways)."

While this appears on the surface to be a relatively short list of topics, the listing is actually deceptively broad. That is, each of these stated interests encompasses a broad range of more specific issues. Hence, it is recommended that the list be interpreted in the broadest sense in order to gain a proper perspective on the range of issues addressed by the HDR tests.

Of the specific areas of investigation, those which will have direct applicability to current operating reactors in the U. S. would include the following:

- The impact of smoke on ventilation system filters,
- The spread of smoke in a multi-compartment structure and macro-scale building behaviors,
- Smoke removal from a large building,
- Fire modeling assessment and results (addressed in a separate publication),
- Fire suppression effectiveness,
- General fire behavior results,
- Impact of fire on equipment, and
- Generation of toxic fire products.

In addition, the results obtained regarding the protection of access routes from fire products intrusion by selective pressurization (a major focus of the later German efforts) should be of interest in the design of the next generation of reactors, and to the general fire protection community. Current regulations in the U.S. do not require that such measures be undertaken, but considerable interest in this particular strategy does exist. In particular, the results would be of direct relevant to applications such as hospitals, high-rise structures, hotels, and military facilities. It is to be expected that such strategies will eventually become a common part of building design, and hence, it is likely that advanced reactor designs may also incorporate selective pressurization of vital areas as a means of fire protection.

2.3 General Matrix of Tests Performed

HDR fire tests have been performed in four groups or series. Each series of tests was performed in a different part of the overall containment structure. Each test was performed within the confines of a particular room within the containment which will be referred to as the "fire room." Within each test series, as many as 14 individual experiments have been performed. Each test series is identified by a one-letter, two-number general designation.

The individual tests within the series are then identified by the addition of a test number to this series designator. The general nature of each of the four test series is provided in Table 2.1 below. Each of these test series is discussed in greater detail in Chapter 3.

Table 2.1: General Matrix of Fire Test Series Performed in the HDR.

Test Series	Test Location	Fuel Sources	Comments
T51	Level -1.10m	Gas burners or wood cribs	Tests were performed on level just below the main access level. Mixed natural and forced ventilation was used. Fire source was gas burner or wood crib. Fire products interacted with the full containment volume. Tests primarily intended as feasibility study. Full containment involvement allowed and observed.
T52	Level +25.30m	Oil Pool Followed by Constant Oil Flow Rate	Test level was first level below dome. Tests involved both natural and limited forced ventilation conditions. Fire room outflow plume flowed directly into dome area. The fire room was relatively small for size of fire. Full flashover conditions observed with very inefficient burning. Full containment involvement allowed and observed.
E41	Level +4.50m	Oil Pool Followed by Constant Oil Flow Rate	Fuel source was similar to that of T52 series (oil). Tests performed in a room on the main access level. A variety of natural and forced ventilation conditions used, including changes in ventilation conditions during the course of each test. Full containment involvement allowed and observed.
E42	Level +4.50m	Cables Trays	Tests performed in the same room as that used in E41. Fires involved PVC cables in trays ignited by gas burners. Fire products largely confined to a subset of the containment volume, although confinement strategy not fully successful. Only one test in the series resulted in significant cable involvement. This one significant test has been designated the standard Commission of the European Community (CEC) international fire model validation problem.

3 Specific Test Series

3.1 Test Series T51

3.1.1 Series Specific Design Strategy and Objectives

Test Series T51 was the first series of fire experiments performed at HDR. The initial testing was performed with very general objectives in mind. One of the principal objectives of this test series was to simply demonstrate the feasibility of performing fire tests in the HDR facility. That is, the tests were designed in part to show that such tests could be performed in HDR without compromising the overall integrity of the structure or its usefulness as a continuing experimental test bed. The experiments were also designed to assess the impact of certain simple fire sources on the environment of the containment building and to provide initial data for the performance of computer simulations of HDR fire behavior.

No attempt was made to confine the fire products to any given sub-section of the containment. Some limited measures were taken to protect the containment's steel liner shell from direct exposure to the heat of the fire including the use of insulating drapes in certain areas near the fire. A second objective of this test series was to determine the extent to which the fire would impact the full containment structure and the containment volume. A third point of interest was the extent to which smoke would be produced and build up in the containment volume, and the effectiveness of the normal HDR containment ventilation system at removing the smoke.

3.1.2 Series Specific Facility Configuration

The first series of fire tests was run in one of the lower levels of the containment structure (see Figure 2.1 for a general identification of the fire room location). The fire room was constructed on level -1.10 m, the level immediately below the main access level. The volume of the fire room was approximately 35 m^3 (1236 ft^3), a small-to-modest size room in comparison to the experimental fire intensities. This room was connected to a long hallway via a relatively small door (approximately 1 m wide and 1.3 m tall), the bottom of which was located about .3 m above the floor of the outer hallway. This hallway, in turn, opened into the bottom of the column of primary equipment hatches located at the 90° point in the containment. These hatches extended all the way from the fire level to the dome level. In all of the tests, these equipment hatches were left open. Adjacent to this column of equipment hatches is the main personnel staircase. A temporary partition curtain was put in place to segregate the hatch column from this stairwell on the fire room level only. That is, the purpose of the curtain was to direct the fire products towards the equipment hatches, rather than towards the open stairwell. This strategy proved quite successful. An open gap at the floor around the bottom of this curtain, approximately 0.5 m (19") tall was left to allow for a natural convection fresh air return path. Figure 3.1 provides a schematic representation of the 1.400 containment level and the general layout of the fire area on this level. Figure 3.2 provides a three-dimensional view of the fire room and adjacent spaces to illustrate the general configuration of these areas, and to illustrate the stepped increases in ceiling height present.

In certain of the tests the fire room doorway was left open providing a natural ventilation path. This configuration allowed for fire products to spread upward through the equipment hatches and directly to the dome area at the top of the containment. In other tests, this doorway was closed and a localized forced ventilation system supplied fresh air drawn from the general containment into the fire room and removed exhaust air to the general HDR ventilation exhaust system. Other tests utilized a combination of forced air supply and natural convection circulation paths. All of the T51 fires involved either gas burners in the 200-1200 kW range or wood cribs with peak heat release rates of 800-2300 kW.

3.1.3 Series Sub-Matrix

A total of 14 experiments were performed in the T51 experiment series. These experiments are designated as T51.11-19 and T51.21-25. Each of the tests involved either a pre-mixed propane gas burner system (using 1-6 individual burners) or a wood crib fuel source. The wood cribs were formed using blocks of conditioned pine measuring approximately 5x5x35 cm arranged into a 3-dimensional rectangular mesh by stacking the blocks in layers of four blocks each with the block orientation rotated 90° between layers. An air gap equivalent to the width of one block (5 cm) was allowed between adjacent blocks in a given layer. The characteristics of each test are presented in Table 3.1.

Note that test T51.19 is only described briefly in some of the earliest fire testing reports and is not presented as a part of the series test matrix in later publications. Relatively sparse information regarding the exact nature of this particular test could be obtained from the test reports.

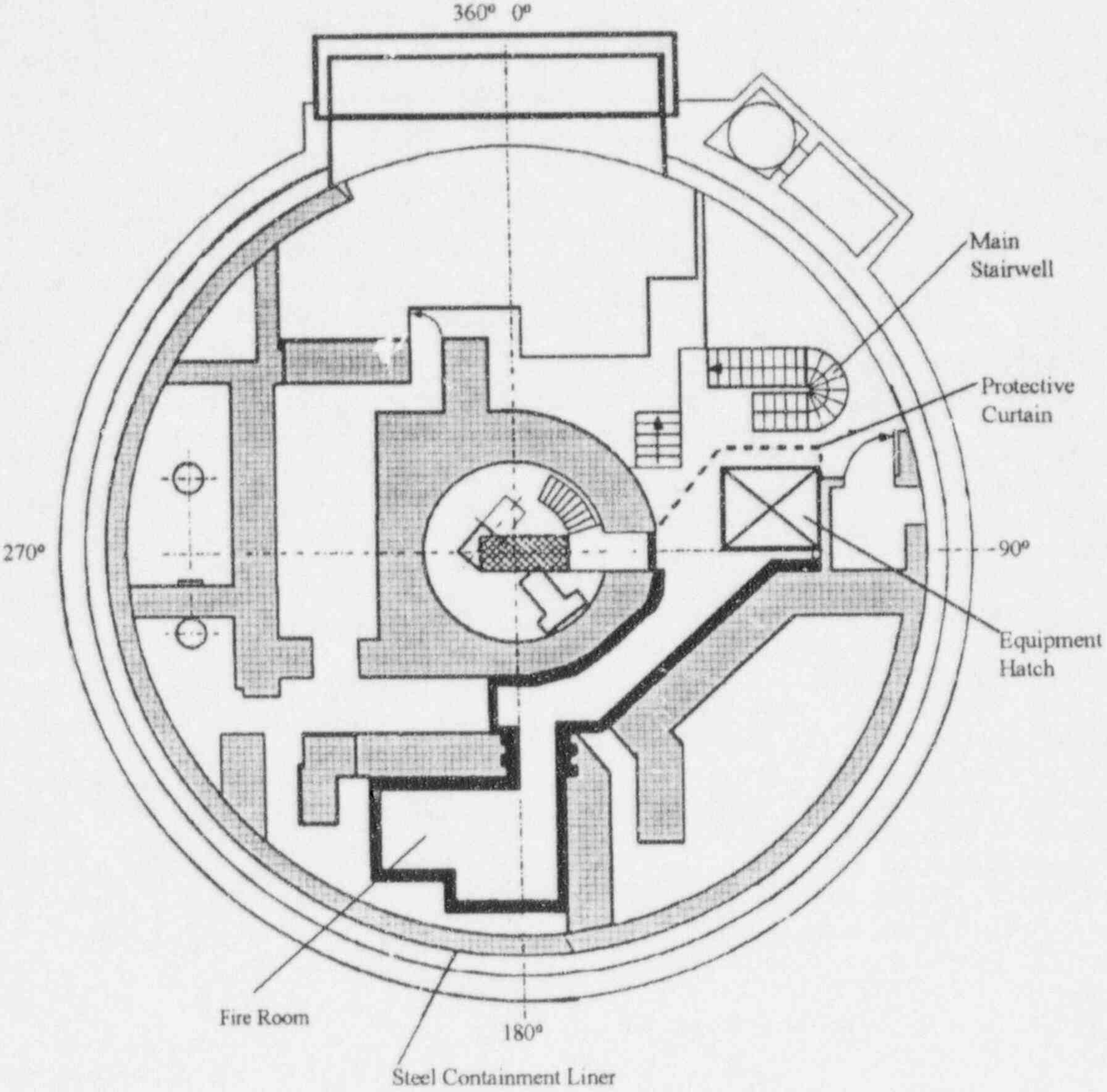

Figure 3.1: Schematic View of the Containment Fire Level for Test Series T51.

3.1.4 Summary of Tests Results and Observations

In general, the experimenters found that the temperatures experienced in the containment during the fires were relatively modest. That is, while the fire room and adjacent hallway temperatures were relatively high, these temperatures dropped off quickly away from the fire room. In no case was the temperature of the steel liner observed to exceed 30% of the established maximum allowable exposure temperature rise from ambient to the maximum allowable temperature.

The test conditions utilized resulted in a transition from material surface controlled burning to ventilation limited burning. Such a transition represents an important

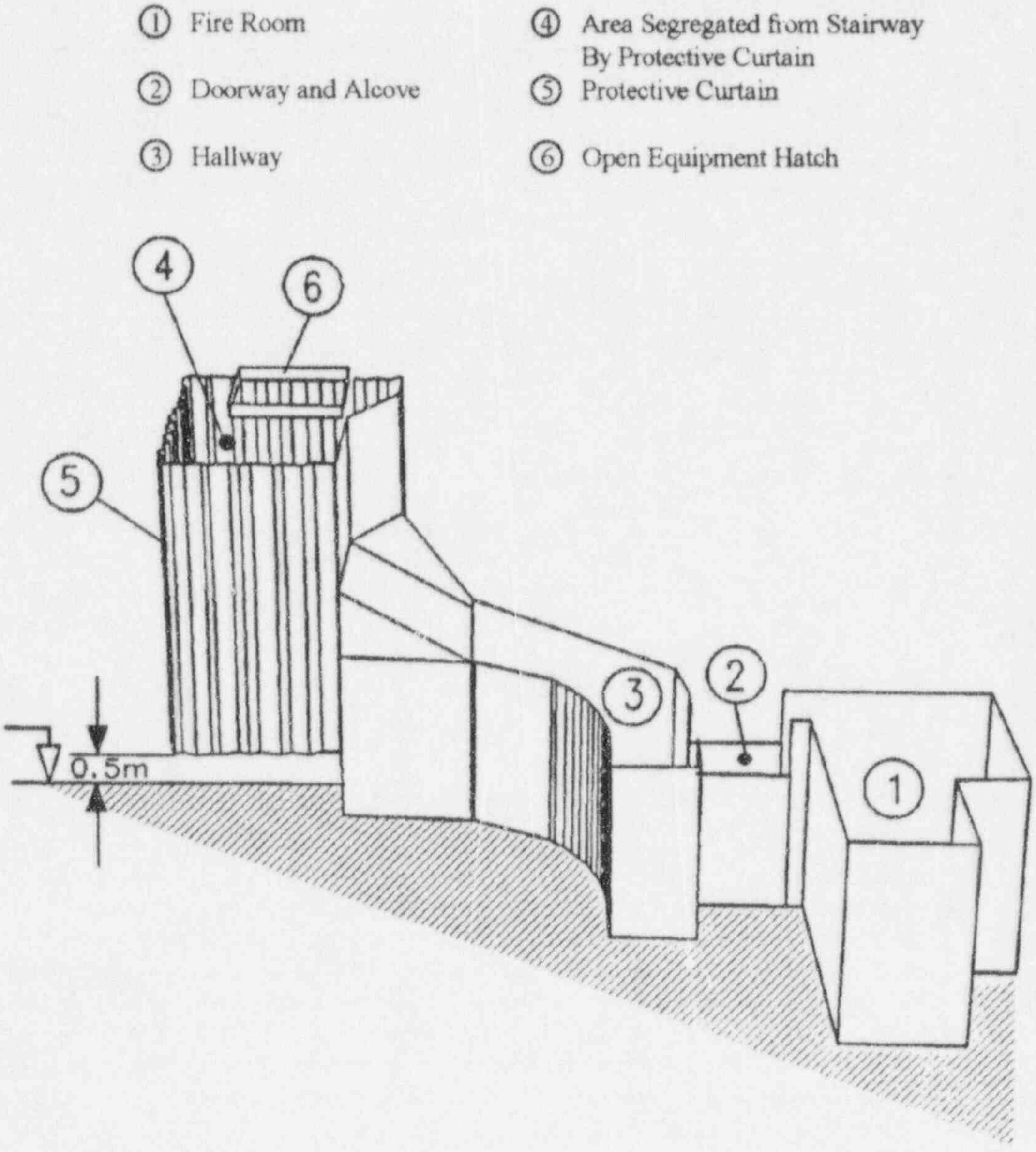

Figure 3.2: Three-Dimensional View of the T51 Fire Area and Adjoining Spaces

behavior in fires. In a surface controlled fire, the intensity of the fire is limited only by the available fuel surface area, and rapid fire growth will typically be observed. In a ventilation controlled fire, the fire intensity is limited by the available oxygen, and relatively little growth, and in some cases a retreat, in fire intensity is typically observed. As expected, it was observed that this transition also led to a significant increase in soot production due to the decrease in combustion efficiency. In the words of the experimenters, "an enormous soot production start(ed) at the same time (as this transition)" [5.1.2].

This test series resulted in a number of relatively unexpected results. First, the experimenters had expected

Table 3.1: Matrix of Tests in T51 Test Series.

Test ID	Fuel Source	Peak Fire Size (kW)	Fire Duration (min)	Ventilation Configuration
T51.11	Gas	229	60	Forced ventilation provided at a fixed rate.
T51.12		380		
T51.13		692		
T51.14		1025		
T51.15		380		
T51.16	Wood	1000	~35	Natural ventilation through open doorway involving hallway and balance of containment, no forced ventilation.
T51.17		1500		
T51.18		2300		
T51.19	Gas	~1200	Unknown	Unknown
T51.21	Gas	700	60	Combined forced and natural ventilation fires. The forced rate was varied from test to test and was also varied during certain of the tests (T51.22, 24, and 25).
T51.22		700		
T51.23		1010		
T51.24		950		
T51.25		980		

that the primary impact of the fire would be limited to localized effects immediately surrounding the fire room, with the additional expectation that the smoke and other fire products would flow directly to and be largely confined within the dome region of the containment. It had been anticipated that a relatively localized natural circulation path would develop. In contrast, the fire products were quickly spread throughout the containment structure, and a clearly observed natural circulation loop involving the entire containment developed. In particular, a hot gas plume extending out of the fire room, down the adjacent hallway, and up the open equipment hatches to the dome region quickly developed in each test. In parallel, a return air flow path developed down the open personnel stairwell adjacent to the equipment hatches.

It was also observed that this circulation pattern was very sensitive to the configuration of the forced ventilation system. In particular, in some of the tests, the localized forced ventilation system was activated to supply additional fresh air to the fire room. This air was drawn from the next higher level in the containment, from the area at the base of the secondary spiral stairway. Activation of this ventilation system "immediately" caused a shift in the circulation pattern [5.1.2]. In particular, it was observed that a return air flow path from the dome region down this secondary stairway quickly developed upon actuation of the system.

The experimenters were also somewhat surprised at the extent of smoke distribution within the containment. As mentioned above, an "enormous" quantity of smoke was generated. It had initially been expected that most of the smoke would accumulate in the dome region of the containment. In reality, it was observed that the "smoke density equalizes along the convection paths within minutes" [5.1.2]. This can largely be attributed to cooling of the fire products through contact with the massive containment structures, the loss of fire products buoyancy, and the resultant mixing of those fire products with the general air volume.

The normal HDR containment ventilation exhaust system proved inadequate to deal with this smoke; the HEPA filters in the exhaust gas stream quickly clogged. In the worst case, it eventually took on the order of two days to fully purge the containment, and in particular the dome region, of the residual smoke. It was concluded that, despite the relatively high air flow rates which could be achieved, the physical configuration of the exhaust system was not conducive to the effective removal of smoke. Further, the HEPA filters normal to the system were incapable of dealing with the copious amounts of smoke generated.

The smoke generated by the fire also resulted in certain unanticipated equipment problems. As mentioned above, a variety of experiments were ongoing or in preparation at HDR at any given time. During the clean-up after the first fire tests, it was found that several items of instrumentation left in place during the tests had been damaged by smoke deposition and corrosion. The relatively long time required to purge smoke from the containment clearly contributed to the severity of such problems. Several of the installed instruments required replacement after the fire tests.

Another problem identified during the post test clean-up efforts was the deposition of smoke particulate on the surfaces of the containment. Particular concern was expressed for areas near the fire source which received a combined exposure to moderately high temperatures and smoke deposition. A concern that long term exposure to these smoke deposits might weaken the containment structure was raised through corrosive attack. Extensive efforts were made during the post-test recovery operations to remove these deposits. These efforts achieved only limited success, and in the end, only a fraction of the deposits were considered to have been successfully removed, and those primarily from metal surfaces.

While the tests were judged to be a successful demonstration of the feasibility of performing fire tests in HDR, the smoke-induced equipment failures and smoke deposition problems led to restrictions being placed on the performance of subsequent fire tests. (Note that later test series reinforced these concerns.) Subsequent fire tests were performed only after completion of certain other test programs, and the removal of delicate test instruments from the containment. This led to significant fire test scheduling problems, significant delays in the completion of the fire testing program, and nearly resulted in the cancellation of the final E42 cable fire test series (see further discussion in Section 3.4 below).

3.2 Test Series T52

3.2.1 Series Specific Design Strategy and Objectives

The intent of the T52 fire test series was to simulate the behavior of a relatively large cable fire through the use of an "equivalent" oil fire. Based on the results of the T51 experiments, it was decided that the experiments would be moved to a higher level in the containment structure. A room adjacent to the secondary personnel stairwell one level below the dome section (level +25.30m) was selected (see Figure 2.1). It was expected that this configuration would minimize the extent of containment involvement in that the fire products were expected to accumulate directly into the dome area with relatively little circulation into the lower levels. As discussed further below, this did not prove to be a well-founded assumption.

As an additional objective, this test series introduced the first significant efforts to assess the effectiveness of selective pressurization for controlling smoke ingress into personnel access/escape routes. Selective pressurization is a proposed method by which the flow of smoke might be controlled through judicious application and control of the ventilation system. In this case, the intent is to provide a fresh air supply into the protected area alone which is of sufficient flow rate so that should the doors to the area be opened, no fire products would flow into the protected area, and instead, all flow through the opened doorway would be out of the protected area. In this manner, intrusion of the fire products into the protected area would be prevented or minimized. This smoke control strategy is generally considered to hold wide potential for future building designs, and was in fact considered as a part of early nuclear power plant fire safety investigations [5.2.2]. However, retrofitting of such a system to existing plants was considered unrealistic. Relatively little large-scale testing of these proposed methods has been performed to date. Hence, the HDR tests provide unique insights into the efficacy of these proposed methods.

In support of this objective, the elevator shaft located at the 90° point in the containment (adjacent to the primary equipment hatchways and main personnel stairwell) was used to simulate the response of a closed personnel access stairwell. This elevator shaft is equipped with a single hinged doorway on each level, and hence, is quite similar to, although somewhat smaller than, a typical stairwell. (Note that the use of such a hinged doorway is quite common in older elevators in Europe whereas most elevators in the U.S. utilize one or two sliding "pocket" doors.) A dedicated air ventilation source was provided to introduce fresh air into this isolated space at a prescribed rate. Testing included the variation of the ventilation rate of air introduced into this "stairwell," and the remote opening and closing of the access doors on certain levels to simulate personnel entry into or exiting from the area. Measurements of smoke infiltration into the "stairwell" were made.

3.2.2 Series Specific Facility Configuration

The T52 test series was conducted on the level immediately below the dome floor (Level +25.30 m). The fire room was relatively small, measuring approximately 22.5 m^3 (794 ft^3 which represents a cube just over 9 feet on a side), and was located directly adjacent to the secondary (spiral) staircase (at 270°) and to the secondary equipment hatchways located in the same area. Ventilation was provided to the fire room by natural convection through the open doorway and, in some tests, by supplemental air from a forced ventilation supply duct of variable and controlled flow rate. The doorway measured approximately 2.85 m^2.

The floor-to-floor secondary equipment hatchways immediately outside of the fire room were also left open. These open hatchways provided a second direct connection between each level from level +10.00 m all the way to the dome. These equipment hatchways were similar to the column of primary equipment hatchways located at the 90° point of the containment, but did not extend to the lower levels of the containment structure. With these secondary hatchways open, the fire plume would exit the fire room and flow up through the open hatchway and directly into the dome area. Figure 3.3 provides a schematic representation of the fire room level as configured for use in the T52 test series.

3.2.3 Series Sub-Matrix

Test series T52 was comprised of four individual tests designated T52.11-14. In all of the tests, the initial fire source consisted of a hydrocarbon oil pool. Once this initial pool was consumed, a small supply nozzle disbursed additional oil into the fuel pan at controlled flow rate. The total duration of each fire was approximately 30 minutes.

The only parameters varied between tests were those associated with the size of the initial fuel pool, the rate of fuel delivery after the initial pool was consumed, and the forced air supply flow rate. The peak fire intensities ranged from 2000-4000 kW. This is quite a large fire for the size of the test enclosure. The characteristics of each test in the T52 series are provided in Table 3.2.

3.2.4 Summary of Tests Results and Observations

In this series of tests, it was found that the relatively large fire size in a relatively small room resulted in ventilation-controlled burning being established quickly. In fact, in most tests severe oxygen starvation conditions were noted inside the fire room itself. In all of the tests, the fire room temperatures rose quite rapidly to full flashover

Table 3.2: Matrix of tests in the T52 test series.

Test ID	Pool Size (m^2)	Initial Pool Fuel Volume (liters)	Post-Pool Fuel Delivery Rate (liters/min)	Peak Fire Intensity (kW)
T52.11	1	25	3.72	2000
T52.12	1	50	5.57	3000
T52.13	3	75	7.43	4000
T52.14	3	50	5.57	~3500

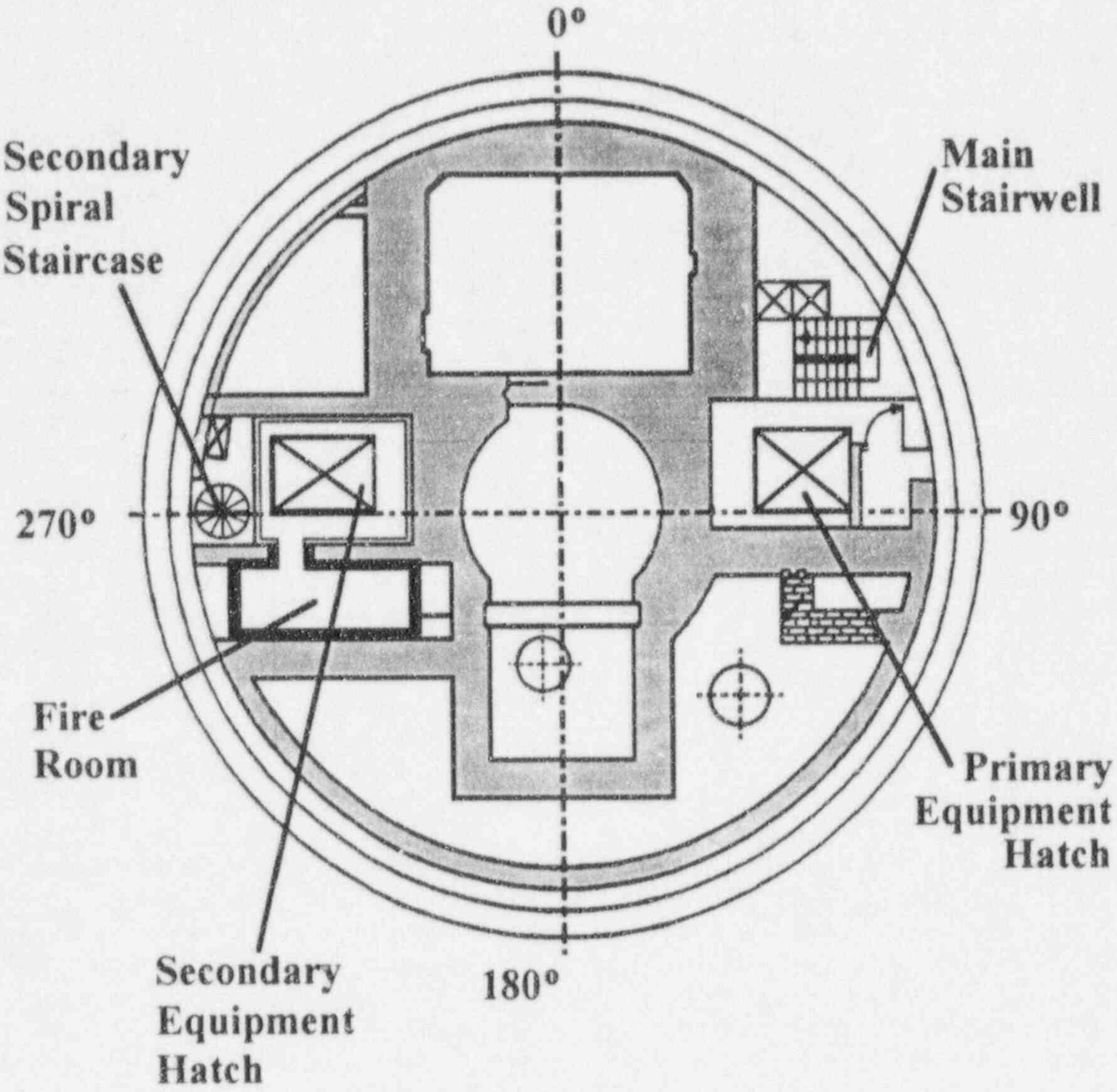

Figure 3.3: Schematic View of the Containment Fire Level for Test Series T52.

conditions. This caused the liquid fuel to vaporize at a rate much faster than the rate at which the fuel could be burned given the available oxygen. Hence, much of the actual burning took place in the effluent stream outside of the fire room itself.

This situation also led to quite inefficient and incomplete combustion, and the generation of copious amounts of heavy soot. The quantity of smoke generated during the liquid pool fire tests were much greater than those observed in the earlier gas burner and wood crib fire tests.

As expected, the fire plume was observed to exit the fire room and feed directly into the dome area primarily through the open secondary equipment hatchway and in part through the secondary spiral staircase. A somewhat unexpected result was that a macro-scale natural air circulation loop throughout the containment was created. That is, hot combustion products rose with the fire plume directly into the dome area through the secondary hatchways and spiral stairway (at 270°). A downward flow of relatively cool air formed in both the primary stairway and the adjacent open primary equipment hatches (at 90°). To complete the loop, an upward convective flow from the lower levels of the containment (level 1.60) up the secondary staircase and the secondary equipment hatchways to the fire room was observed. As a result of the macro-scale convective flow, the entire containment structure was eventually filled with soot-laden air.

The development of such an extensive convection loop had not been anticipated. Initial estimates had suggested that only the upper section of the containment would become involved in the macro-scale convection patterns. However, the final results clearly demonstrated involvement of the lower containment levels was likely, even for fires confined to the upper levels of the structure.

It was also found that the simulated stairwell pressurization schemes worked well, provided that fresh air was supplied to the area at a sufficient rate. That is, even when doors were opened (simulating accessing the "stairwell") smoke was unable to significantly penetrate the protected interior space, provided that the ventilation rate was sufficient to overcome the buoyancy driven flow of smoke. In effect, by increasing the flow rate of fresh air available to the protected area, the "neutral plane" of the open doorway (that is the level at which the direction of air flow changes from cool make-up air flow into the room to hot fire products air flow out of the room) could be driven beyond the top of the door thus preventing fire products intrusion into the protected area. The testing showed that a direct relationship between the over-pressure in the protected area induced by the excess fresh air supply and the level of the doorway neutral plane could be established. (The results of these tests are presented in detail in the test reports for both Test Series T52 and E41.)

3.3 Test Series E41

3.3.1 Series Specific Design Strategy and Objectives

As compared to the T52 experiments, the E41 tests were performed in a larger room and under more variable ventilation conditions. The fire room constructed for use in the E41 test series (and later used in the E42 test series as well) was located on the main access level of the containment structure (level +4.50 m). While the fuel source was essentially the same as in the T52 tests (namely, liquid fuel pool fires followed by a nozzle release oil fire) the size of the fire was somewhat reduced. In addition, provisions were made for a fresh air supply in the immediate vicinity of the fuel source through a localized forced ventilation system.

Another significant change was that the fire room was equipped with doors which could be opened and closed remotely. The prior tests had all been conducted in rooms in which the doorway was either open or closed, but not repositioned during any given test. One objective of the E41 tests was to explore various effects of a fire in a closed room, and the impact of opening the door on the fire behavior. This was of particular interest as this configuration simulated the expected behavior should a fire be initiated in a closed room, and after a certain period of fire development, the fire brigade might arrive and open the doors to access the fire.

This test series also continued testing of the selective pressurization smoke control strategy which was initiated in the T52 test series. In particular, the elevator shaft at the 90° point of the containment was again configured to simulate an emergency access and evacuation stairwell. Again, doorways into this protected area on various levels of the containment were opened for varying lengths of time at specific points during the tests. Ventilation flow to the protected area was again varied.

Other factors of interest in the performance of this test series included (1) the impact of the fire on containment structural safety (i.e., on the steel liner temperature), (2) the temperature observed in the ventilation ducts, (3) pressure buildups due to the fire, (4) smoke/soot loading rates for various ventilation filters, and (5) the impact of fire suppression generated steam on fire room and HDR pressures.

3.3.2 Series Specific Facility Configuration

In test series E41, the fire room was located on level +4.50 m, the main access level. A roughly cubical fire compartment with a volume of about 110 m^3 (3885 ft^3) was constructed from open web cement blocks on this level. This room was connected through a doorway alcove with a lower ceiling height and a pair of doors (each about 1x3 m) to an outer hallway which, in turn, was open to the main stairwell and equipment shaft. Thus, fire products were allowed to spread throughout the full containment structure. Figure 3.4 provides a schematic representation of the fire room level as configured for use in the E41 test series.

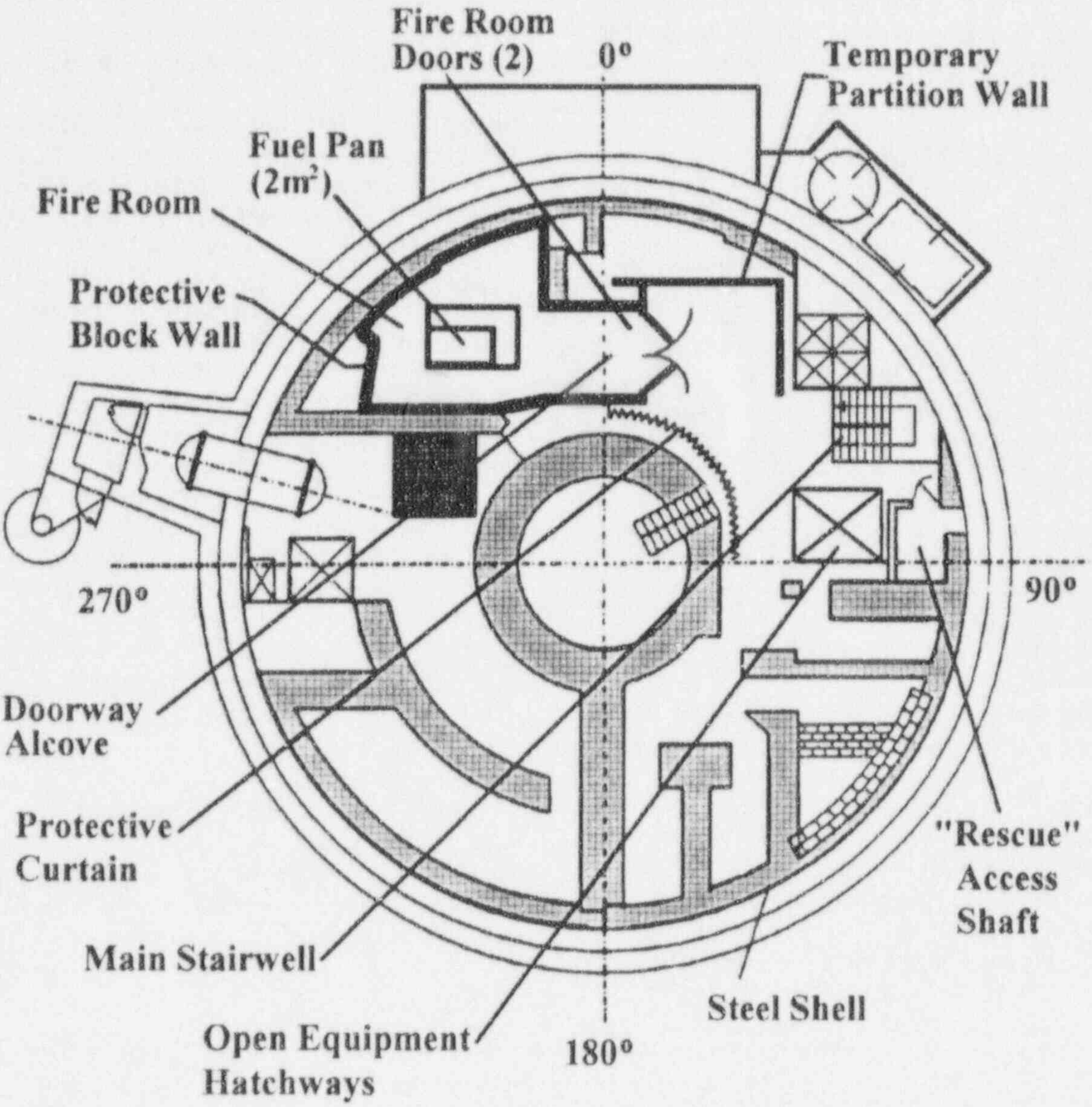

Figure 3.4: Schematic View of the Containment Fire Level for Test Series E41.

The fire room was also provided with a localized ventilation system which could draw air from the upper reaches of the fire room, and fresg make-up air at the bottom of the room near the fire source using the general containment volume as an air source. That is, the inlet air was drawn from the general containment, and the exhaust air could be released either to the general containment or through the normal HDR containment exhaust filtration system.

As in the T52 experiments, the personnel elevator was again configured to simulate the behavior of a closed emergency access and evacuation stairwell. As in previous tests, the capability to remotely open and close access doorways on certain levels of the containment was provided. The fire room also included a simulated fire sprinkler system located directly above the fire source pan. This sprinkler system could be remotely actuated on demand.

3.3.3 Series Sub-Matrix

A total of 10 fire tests were conducted as a part of the E41 test series. These tests are designated E41.1-10. These tests were actually performed in two parts. The first part included Tests E41.1-4. These first four tests were performed, primarily, to assess the behavior of a fire in the newly constructed fire room, and as scoping tests. The second part involved Tests E41.5-10, and it is these six tests which represent the main body of the E41 test series.

In Tests E41.1-4, the fire source was a liquid fuel (oil) pool fire. The fuel pool surface area was either 1, 2, or 3 m^2. Each of these tests was conducted under natural ventilation conditions only with both of the fire room doors fully open. These were relatively simple tests with no variation of test parameters during any given test. Table 3.3 provides a description of the test conditions during each of these four tests.

Table 3.4 provides a description of the test conditions and variations employed in each of the remaining six tests. Note that this matrix is based on pre-test planning documentation [5.1.4]. In general, the tests were performed as planned, although only minimal post-test documentation was available describing the exact progression of each individual test. Hence, this matrix should be viewed as only a limited and general outline of the anticipated progression of each individual test.

Each test in the E41.5-10 series was initiated with a given quantity of fuel (oil) placed in a fuel pan of either 2 or 1.7 m^2 surface area. Once this fuel had been consumed, a controlled flow of additional oil was released from a nozzle into the pan to continue the fire.

The final parameters of interest were associated with the simulated rescue/safe access stairway. One rescue stairway parameter which varied during testing was the flow rate of fresh air delivered to this protected area. Also, one of the doors into the protected area could be opened for short periods of time during the fire test. Typically, this doorway would be opened for periods of from 30 seconds to 5 minutes, and then closed. These door openings were intended to assess the extent of smoke infiltration into the stairwell upon opening of the doorway for various air flow conditions.

3.3.4 Summary of Tests Results and Observations

The most unique aspect of the E41 tests was that the ventilation conditions could be altered during the performance of a given test. The conditions were able to simulate effects ranging from a fully closed room, to a closed room with forced ventilation, to an open room, and finally to an open room with forced ventilation.

Table 3.3: Test conditions for Tests E41.1-4.

Test ID	Pool Size (m^2)	Fuel Volume (liters)	Peak Intensity (kW)	Fire Duration (min)
E41.1	3	224	~8000	20
E41.2	1	150	6500*	23
E41.3	2	224	6500	28
E41,4	2	224	6500	25

* Note that this is an apparent discrepancy in the original report [5.1.3]. With the smaller pool size, one would expect a lower fire intesity. Given the total fuel content and burn duration, the fire size was likely on the order of 4500-5300 kW.

Table 3.4: Test conditions for Tests E41.5-10

Test ID	Sub-section	Time	Fire	Door	Ventilation Status (ACH = Room Air Changes Per Hour)
E41.5	E41.51a	0-5 Min.	2 m^2 pool, 1cm oil	closed	Local: 5ACH in, 5ACH out to HDR exhaust HDR: On, filtering fire room out flow Rescue: No Flow
	E41.51b	5-20	0.01 kg/s	closed	Local: same as previous HDR: same as previous Rescue: same as previous
	E41.52	20-35	0.01 kg/s	closed	Local: 10 ACH in, 10ACH out to internal HDR filter bank "A" HDR: On, filtering general exhaust only Rescue: same as previous
	E41.53	35-50	0.02 kg/s	closed	Local: same as previous HDR: same as previous Rescue: same as previous
	E41.54	50-65	0.05-.07 kg/s	closed	Local: 30 ACH in, 30 ACH out to internal HDR filter bank "U" HDR: same as previous Rescue: same as previous
	E41.55	65-90	0.07 kg/s	one door half open (45°)	Local: 30 ACH in, out flow duct closed HDR: same as previous Rescue: No Flow, Door open 30 sec
E41.6	E41.61	0-15	2 m^2 pool, 2-3 cm oil	closed	Local: 5ACH in, 5 ACH out to HDR exhaust HDR: On, filtering fire room out flow Rescue: No flow
	E41.62	15-30	0.01 kg/s	one door half open (45°)	Local: 5ACH in, out flow duct open to HDR exhaust HDR: same as previous Rescue: same flow, door open for 30 sec and then for 1 min.
	E41.63	30-45	0.02 kg/s	one door half open (45°)	Local: 5ACH in, 5ACH out to HDR exhaust HDR: same as previous Rescue: LW2, door open for 1 min. and then for 3 min.
	E41.64	45-60	0.02 kg/s	one open	Local: 10ACH in, out flow duct open to internal filter bank "A" HDR: On, filtering general exhaust only Rescue: same flow, same door openings
	E41.65	60-75	0.01 kg/s	both open	Local: same as previous HDR: same as previous Rescue: same flow, same door openings
	E41.66	75-80	no fuel	both open	Local: In and out flow ducts closed HDR: same as previous Rescue: same flow, doors closed
E41.7	E41.71	0-15	2 m^2 pool, 15 min burn	closed	Local: 30ACH in, out flow duct open to internal filter bank "U" HDR: On, filtering general exhaust only Rescue: No flow
	E41.72	15-30	0.1 kg/s	one open	Local: Same as previous HDR: Same as previous Rescue: 5ACH, door opened for 1 min. then for 2 min.
	E41.73	30-45	0.02 kg/s	closed	Local: 10 ACH in, out flow duct open to internal filter bank "A" HDR: Same as previous Rescue: Same flow, door opened for 30 sec. 1 min., and then 3 min.

Table 3.4: Test conditions for Tests E41.5-10 (continued).

Test ID	Sub-section	Time	Fire	Door	Ventilation Status
E41.7 (cont.)	E41.74	45-60	0.1 kg/s	both open	Local: In and out flow ducts closed HDR: same as previous Rescue: Same flow, no door openings
	E41.75	60-75	0.03-.05 kg/s	one open	Local: Same as previous HDR: Same as previous Rescue: 10 ACH, no door openings
	E41.76	75-90	0.03-.05 kg/s	one, half open (45°)	Local: Same as previous HDR: Same as previous Rescue: No flow, no door openings
E41.8	E41.81	0-15	2 m^2 pool, 15 min burn	both open	Local: No flow, system off HDR: No flow, system off Rescue: 10 ACH, door opened for 1 min then for 3 min
	E41.82	15-30	0.1 kg/s	both open	Local: Same as previous HDR: On, filtering general exhaust only Rescue: Same flow, door opened for 5 min.
	E41.83	30-45	0.1 kg/s	one open	Local: Same as previous HDR: Same as previous Rescue: 5 ACH, no door openings
	E41.84	45-60	0.03-.05 kg/s	one open	Local: Same as previous HDR: Same as previous Rescue: Same flow, door opened for 1 min. then for 3 min.
	E41.85	60-75	0.03-.05 kg/s	one open	Local: 10 ACH in, 10 ACH out to internal filter bank "A" HDR: Same as previous Rescue: Same flow, no door openings
	E41.86	75-90	no fuel	closed	Local: Maximum inlet and outlet flow through main HDR HDR: Filtering fire room exhaust Rescue: Same
E41.9	E41.91	0-15	1.7 m^2 pool, 15 min burn	both open	Local: No flow, system off HDR: No flow, system off Rescue: No flow, door opened for 1 min. then 3 min.
	E41.92	15-30	0.1 kg/s	both open	Local: Same as previous HDR: Same as previous Rescue: 2 ACH, no door openings
	E41.93	30-45	<0.1 kg/s	one open	Local: 30 ACH in, 30 ACH out to internal filter bank "U" HDR: On, general HDR exhaust only Rescue: 5 ACH, no door openings
	E41.94	45-60	0.05-.07 kg/s	closed	Local: Same as previous HDR: Same as previous Rescue: 10 ACH, no door openings
	E41.95	60-75	0.01 kg/s	closed	Local: 10 ACH in, 10 ACH out to internal filter bank "A" HDR: Same as previous Rescue: No air flow, no door openings

Table 3.4: Test conditions for Tests E41.5-10 (continued).

Test ID	Sub-section	Time	Fire	Door	Ventilation Status
E41.9 (cont.)	E41.96	75-90	no fuel	closed	Local: 5 ACH in, 5 ACH out to HDR exhaust HDR: On, filtering fire room exhaust Rescue: Same as previous
E41.10	At the time of test series planning, it was anticipated that the "most interesting" aspects of previous tests would be repeated. The actual progression of testing in E41.10 is unknown and has not been documented in any of the reports made available to this study.				

Recall that the fire was provided by, basically, a controlled fuel source. In several of the tests, the fuel delivery rate was sufficient to generate a very large fire. In several instances, it was observed that the the local oxygen levels within the fire room were severely depleted. Hence, much of the actual combustion took place in the fire room hot layer and in the fire room outflow plume, rather than at the fuel source pan. This behavior is typical of fully developed high-intensity ventilation-controlled fires. The net effect of such fires in a confined space is often a pulsating "fire ball" effect, and such behavior was noted in certain of the E41 tests.

This mode of combustion is also, in general, very inefficient. Hence, very large amounts of smoke were again generated. As with previous tests, the full containment volume quickly became involved in macro-scale air circulation and the smoke was distributed virtually throughout the containment. In these tests, it was also noted that alteration of the ventilation configuration would have an immediate impact on the nature of the macro-scale air circulation.

A number of parameters were varied both between tests, and during a given test. In particular, each test was subdivided into as many as six separate intervals, typically of 15 minutes duration each. These intervals represent specific time periods during which the test parameters were held constant. One parameter varied was the flow rate of fuel, which controlled the post-pool fire intensity. Another parameter varied involved the opening and closing of the two fire room doors.

A third set of parameters was associated with the flow rate and configuration of the localized fire room ventilation system. Recall that the fire room was provided with a fresh air inlet at the floor near the fire source, and with an exhaust port located in the upper reaches of the room. Both the inlet and outlet flow rates were controlled separately. Further, the exhaust gases could be channeled to one of four potential exhaust pathways. One exhaust path was to the main HDR containment exhaust filtration stream. The other three possible paths involved passage through one (or both) of two filtration banks followed by release of the filtered air to the general containment. Each of these pathways could be independently controlled.

For example, under natural ventilation conditions, the hot fire products would rise through the primary equipment hatches (at 90°) up into the dome region. Simultaneously, cooler return air gases would flow downward through both the primary (90°) and secondary (270°) stairwell areas and back to the fire room. However, when the localized forced air ventilation system fire room exhaust stream was activated, hot, filtered gases from the fire room were released into the area near the base of the secondary spiral stairwell. It was observed that upon initiation of this system, the direction of air flow in the spiral stairway area (270°) quickly reversed, and an upward flow of hot air was quickly established. At the same time the rate of air flow down the primary stairwell increased to maintain the overall air circulation balance. Once the forced exhaust flow was stopped, the air circulation in the spiral stairway again quickly reversed itself and the original air flow pattern was reestablished.

One of the concerns which these tests were designed to assess was the response of the containment steel liner shell to the fire. In particular, while the steel liner was protected locally in the area immediately adjacent to the fire, the balance of the shell, and in particular the dome region, remained unprotected. In no case did the observed temperature of the shell approach the shell's temperature safety limits. These results were as expected, but served to confirm certain containment heat transfer calculations which had been performed prior to testing.

This test series also confirmed and expanded the findings of the T52 test series regarding the effectiveness of the selective pressurization smoke control strategy in protecting the simulated protected stairwell area. Recall that in the T52 test series the fire room was located near the dome and on the opposite side of the containment building from the protected "stairwell." In the E41 tests, the fire products exiting the fire room were generally directed to the primary equipment hatch located immediately adjacent to the protected "stairwell." Hence, the smoke exposure potential for opened "stairwell" doorways was somewhat greater in the E41 tests. Nonetheless, the tests again demonstrated that a direct relationship between the level of the doorway neutral plane and the over-pressure in the protected area could be established. Tests again demonstrated that if sufficient fresh air supply flow was provided, smoke could be prevented from entering the protected area even when doorways were opened.

Another important finding of this test series was on the impact of smoke on the ventilation filters. In previous tests, considerable difficulty had been experienced in maintaining flow through the primary facility HEPA filtering systems in the exhaust gas stream. These filters were observed to become clogged with soot rather quickly causing an unacceptable increase in filter pressure drops. In most of the previous tests, the filters had to be bypassed in order to maintain an exhaust flow. In the E41 tests attempts to devise an alternate scheme involving the use of coarser HEPA filters as a pre-filter proved only partially successful. In particular, one scheme utilized the primary filter banks in series, with the first bank in line fitted with relatively coarse HEPA filters. The second bank was then fitted with the more typical fine particle HEPA filters. In this configuration, the filter system could be operated for a significantly longer period of time. The coarse filters captured much of the particulate while maintaining a marginal flow capability. However, in the end, the filter banks were eventually overwhelmed and had to be bypassed. Cleaning of these filter banks between tests proved to be a difficult and tedious task.

3.4 Test Series E42

3.4.1 Series Specific Design Strategy and Objectives

The primary objective of the E42 test series was to burn realistic materials, namely cable insulation, under realistic conditions. Note that all of the prior experiments had involved gas burners, wood cribs, and oil fires. The E42 cable fire experiments were intended to provide a direct link between the experiments and the actual fires expected to occur in a nuclear power plant. The E42 tests were to involve burning of an extensive array of Poly-vinyl Chloride (PVC) cables in cable trays. (Note that while PVC is no longer used extensively as a cable insulation in U.S. reactors, it remains the insulation of choice throughout Europe.) These tests were expected to range from relatively small fires to quite extensive fires.

The design strategy and objectives of Test Series E42 underwent considerable revision before the tests were ultimately performed. This revision was much more extensive and fundamental in nature than had been experienced in the prior test series. In fact, the E42 test series was nearly canceled due to concerns associated with the highly acidic and toxic nature of PVC fire products. When the E42 tests were being planned, initiation of a new phase of decommissioning technology demonstration experiments was anticipated. Hence, it was critical that no experiments which might compromise the integrity and accessibility of the HDR containment structure be undertaken. The E42 cable fire experiments were perceived to hold such potential.

The German researchers had identified a set of test results which indicated that one possible product of PVC combustion was dioxin. The highly toxic nature of dioxin in even minute quantities raised significant concerns. Contamination of the HDR containment structure with deposits including dioxin would compromise the accessibility of the HDR structure to future experimental efforts. In the end, the wider implications of these results further supported the need to proceed with the E42 tests. That is, PVC is a widely used material throughout the world, and in particular, is still widely used as a cable insulation material in Europe. The potential generation of dioxin contaminants during a PVC fire could significantly impact manual fire fighting and post fire recovery strategies.

Ultimately, it was determined to go forward with the E42 experiments. However, it was also required that the tests be performed in such a manner as to insure that the overall containment structure was not contaminated, and in such a way as to ensure personnel safety. The E42 tests were purposely scheduled as the last of the operational safety experiments so that the potential impact of smoke contamination would be minimized.

In the initial planning for the E42 tests, it was expected that the fires would involve a series of cable tray fires in the containment dome region with fire products interacting with the full containment structure. However, due to the contamination concerns, the E42 test series was moved to a relatively small and isolated sub-section of the overall containment structure. The same fire room as that utilized in the E41 test series was utilized in the E42 tests. However, as discussed further below, additional measures were taken to isolate this area from the balance of the containment volume. These measures proved only partially successful (see further discussion below).

In the end, the primary objective of the E42 tests became an assessment of the dioxin issue. To this end, extensive soot collection and evaluation efforts were undertaken. However, the earlier objectives also remained. In particular, it was also desired to perform tests in HDR using realistic cable fuel fire sources. This test series was also intimately tied to the ongoing international fire model validation effort. It was expected that one of these cable fire experiments would eventually be designated as the standard fire modeling problem for use in the ultimate evaluation of fire model performance. One final objective of this test series was to assess the impact of cable fire smoke on the ventilation system's exhaust filters, and a variety of exhaust filter configurations were to be tested. This required the installation of a localized and dedicated fire room ventilation and exhaust gas scrubber system.

3.4.2 Series Specific Facility Configuration

The final test series, E42, was performed in basically the same fire area as the E41 test series. This included the fire room itself, the adjacent hallway and the smaller doorway alcove section which joined the two areas. The volume of each of these three areas was approximately 83.8, 105.2, and 18.8 m^3 (2959, 3715, and 664 ft^3), respectively. As in the E41 tests, the fire room itself was equipped with two doors which could be opened and closed remotely so as to control the connection between the fire room and the hallway. However, in this case this overall fire area, including the fire room and the adjacent hallway, was isolated from the balance of the containment volume. This isolation involved the construction of additional floor-to-ceiling partitions to isolate the hallway area from the adjacent main stairwell and the balance of the containment volume. In addition, a fire products collection hood was constructed at the far end of the hallway. The general configuration of the E42 fire area is illustrated in Figure 3.5.

In addition to the physical partitioning, the ventilation system was also specifically configured to provide fire area isolation for these tests. As mentioned above, a fire products collection hood had been constructed at the far end of the hallway section. This collection hood utilized the open hatchway at the end of the hall as a fire products collection point, and was literally built into this opening. The collected gases were routed directly to an elaborate system of water spray and cyclone scrubbers to remove smoke particulate and acid gases, and through internally located charcoal filter banks before being routed to the primary HDR ventilation exhaust system. This entire treatment system was intended to protect both the containment and its general ventilation system from potential dioxin contamination.

The fire area was also provided with a localized forced ventilation system comprised of two inlet ports and two exhaust ports. One of each of these ports was located inside the fire room itself while the second was located in the hallway area immediately outside the fire room. The forced ventilation inlet inside the fire room was located near the floor, and a flexible metal duct was used to direct the air flow to the immediate vicinity of the fire ignition source. The inlet port for the hallway area was located on the wall immediately to the left of the fire room doors (left and right are defined here as when looking into the fire room from the hallway), and approximately 0.6 m off the floor. The fire room exhaust port was located in the upper reaches of the room, approximately 1.6 m below the ceiling level. The exhaust port in the hallway area was located at a similar height in the wall to the right of the fire room doors. Each of these ports was comprised of a round duct approximately 12 cm in diameter and mounted flush with the wall.

This local ventilation system could be operated in several configurations. The flow rate for each inlet and outlet port could be separately controlled. Fresh air for the two inlet ports was drawn directly from the general HDR containment volume on the level directly above the fire room. Each of the two exhaust ports was directed to one of two local banks of charcoal filters installed within the containment. When in use, the exhaust gases leaving these local charcoal filter banks would be released to the general HDR containment. In addition, gases from the exhaust port located within the fire room could be routed directly to the primary HDR exhaust system bypassing the local charcoal filter banks. Figure 3.6 illustrates the general configuration of the ventilation system.

The only open, uncontrolled linkage between the fire area and the general containment was an open strip (approximately 0.5 m (18") tall and 2.4 m (7.9') wide) in

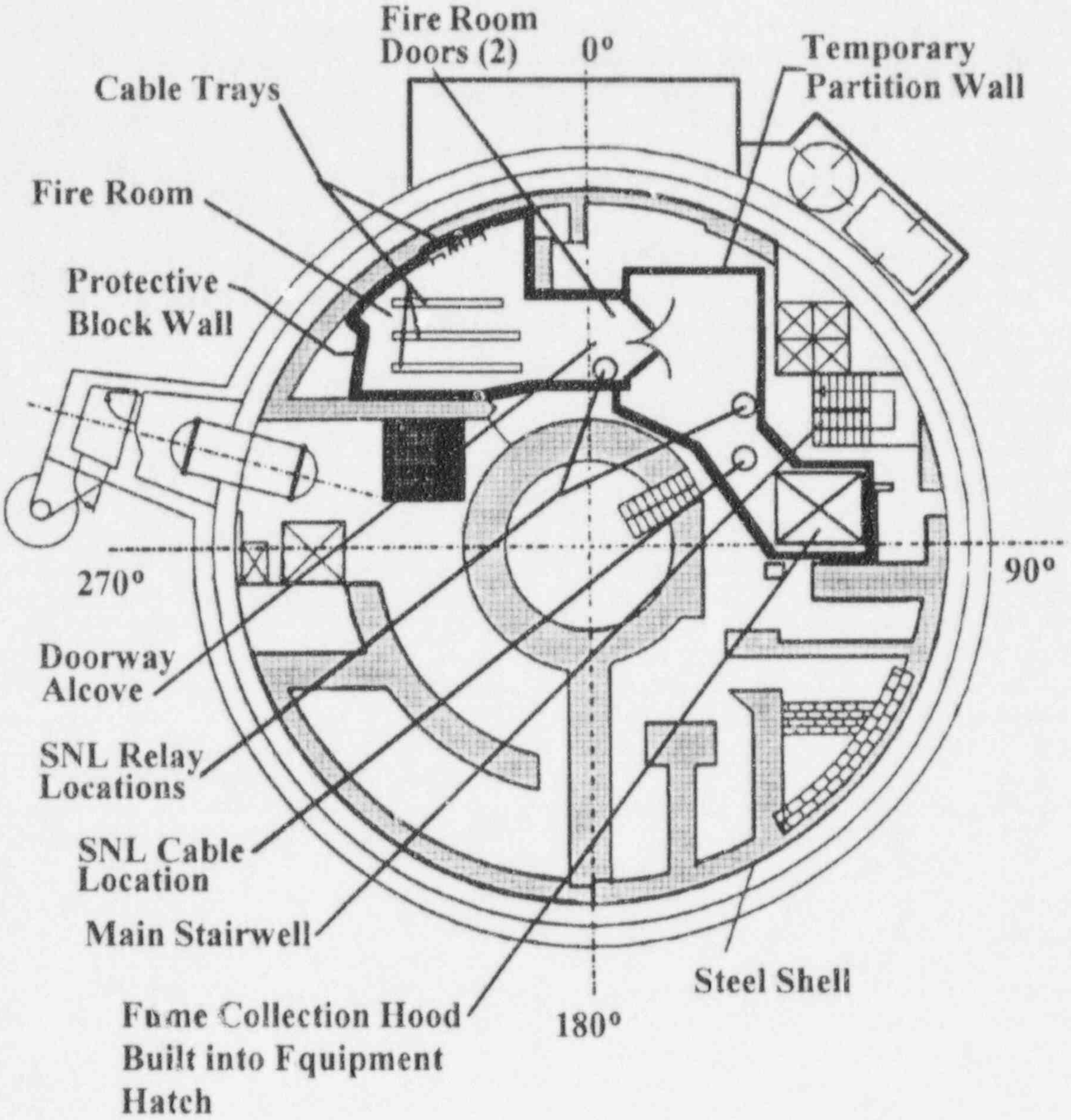

Figure 3.5: Schematic View of the Containment Fire Level for Test Series E42.

the bottom of one of the hallway partition walls (at the base of the hallway partition wall directly opposite the fire room doors). This opening was intended to provide for natural recirculation of fresh "make-up" air (to replace that routed to the HDR exhaust system) from the general containment to the fire area. By placing the opening at the floor level it was expected that little or no fire products would be released to the containment, but that an adequate supply of fresh air would be available to support combustion (the forced ventilation inlet supply was not expected to be sufficient to fully support combustion in the event of a fully involved fire).

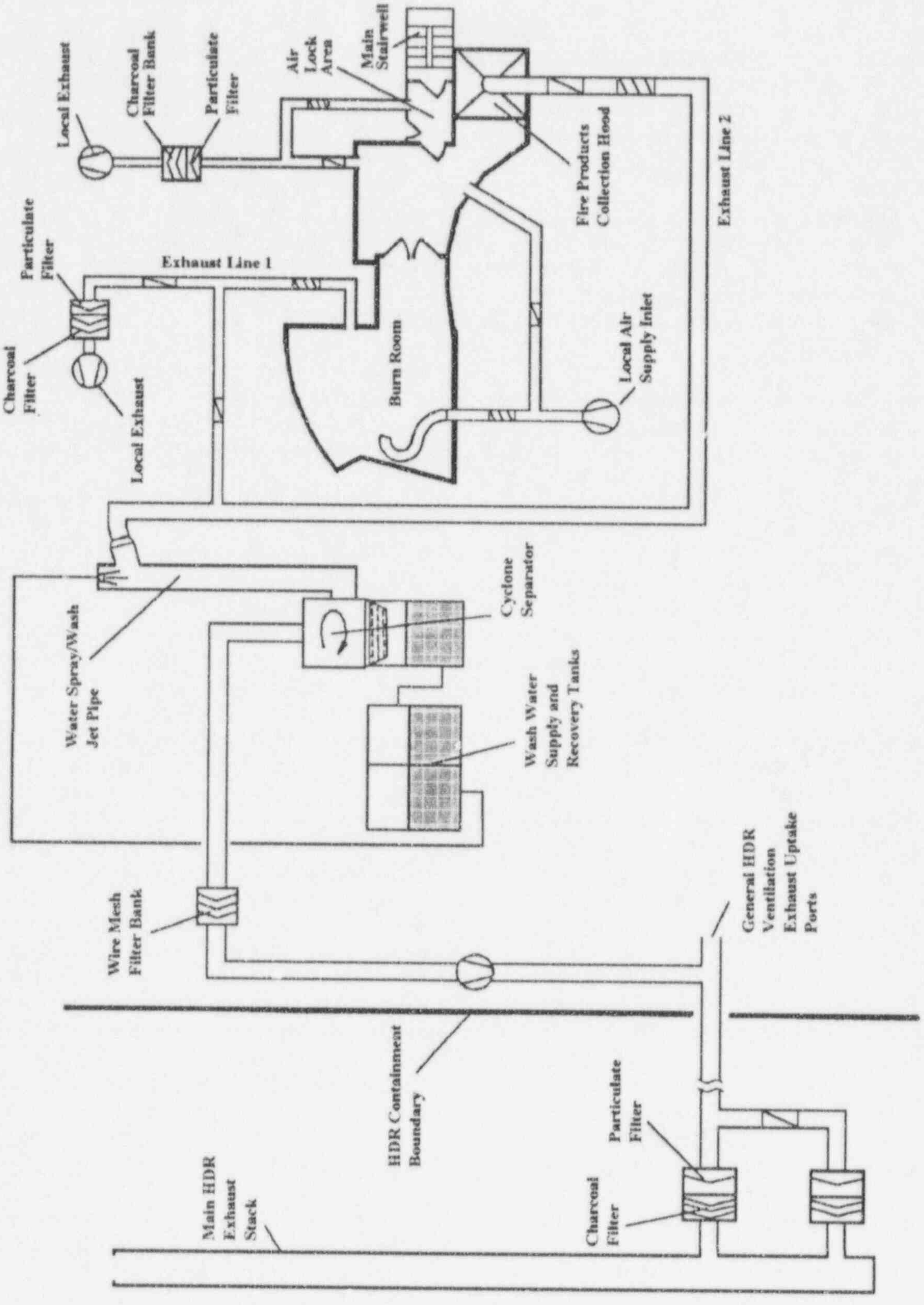

Figure 3.6: Configuration of the Ventilation System for Test Series E42.

3.4.3 Series Sub-Matrix

The E42 test series was initially expected to include approximately 5-6 tests, depending on the extent of fire growth observed in each individual test. Because of the concerns regarding dioxin contamination, all of the cable tray fuel elements required to support all of the various tests were installed at the outset in order to minimize the extent of personnel activity required between tests. (As a result of the dioxin concerns, all personnel entering the containment after the first fire test would be required to wear cumbersome full coverage environmental suits with externally supplied air. This would make any activity significantly more difficult.)

The cable tray fuel array was comprised of three stacks of horizontal cable trays and three vertical cable trays. The cable tray arrangement is illustrated in Figure 3.7. Each tray measured 30 cm (12") wide. Stacks I and II were each comprised of trays 4 m (13') long while the Stack III trays were each 3.5 m (11.5') long. The three vertical trays each measured 4.5 m (14.8') long. Each tray was loaded with, basically, a single layer of cables installed in a random fashion. A variety of cables were used including 16 different types of power and 7 different instrumentation cables. Each individual tray was loaded with either power or instrument cables, and in many cases were loaded with just one particular type of cable. Karwat, et.al. [5.1.7] provides a complete description of the cable loadings and cable characteristics.

The fire ignition source was a three-legged (trident shaped) gas burner which could be located at any given point in the array. The intensity of this gas burner was 2.8 kW, and in each test it was activated for 30-60 seconds. (Note that a 2.8 kW burner is relatively small. For comparison, consider that the burner used in the IEEE383 standard flame spread test utilized for the qualification of cables in the U.S. nuclear industry provides a 20.5 kW exposure fire intensity [5.2.3].) The test plan called for the majority of the cable tray array to be protected from the fire using insulating blankets (Alsiflex), and only a small subset of the array to be fire exposed in any given test. As testing progressed other sections of the cable tray array would be exposed and burned. The final test was expected to be the largest, involving all of the remaining unburned fuel elements.

As it turned out, three tests were performed in this test series. Of these three tests only one, E42.2, resulted in any significant fire development. The following sections provide descriptions of each of the three E42 fire tests performed.

3.4.4 Test E42.1

As is inevitably the case with cable fire testing, the fire tests did not go entirely as planned. The first cable fire test, Test E42.1, involved the exposure of just three of the cable trays (stack III or trays 20-22 as identified in Figure 3.7). All of the remaining trays were protected using a ceramic fiber blanketing material (Alsiflex) with the exception of the top three trays in Stack I, Trays 1-3. The fire source was placed under the lowest of the Stack III trays at the end furthest from the fire room doors. Very little propagation of the fire beyond the region immediately above the fire source was observed. The fire remained quite limited and self extinguished over a relatively short time period, and the test was terminated.

It is unclear as to the extent to which the cable insulation in these three trays was consumed during this first test. The fire reportedly remained quite small and did not propagate. However, statements made in the description of test E42.2 imply that all of the fuel in these three trays was consumed. That is, the descriptions of Test E42.2 include statements to the effect that there was no fuel available in these trays during test E42.2 as a result of the E42.1 test fires. This appears to be an apparent conflict with the E42.1 test descriptions, and with the available test data which indicates only very minor temperature deviations during each of the E41.1 fire attempts. One of two explanations are likely. First, the insulation may have been consumed through a prolonged smoldering combustion process initiated during the fire test. Second, it is also possible that relatively little insulation was consumed, but that the partially burned cables were removed from these three trays during the preparations for the second test. This would have been a relatively simple operation as the cables had not been secured to the tray in any way, and only three trays were involved. In either event, the test was largely considered a failure in that no significant temperature deviations were recorded and no significant fire spread was observed.

3.4.5 Test E42.2

In test E42.2, the fire source was relocated to a position just below tray 5 in stack I. The burner was placed approximately 1 m (3') from the end of the trays furthest from the fire room doorway. Trays 1-5 in Stack I, Trays 12-13 at the top of Stack II, and the vertical tray identified as Tray 23 (Stack IV) were unprotected for

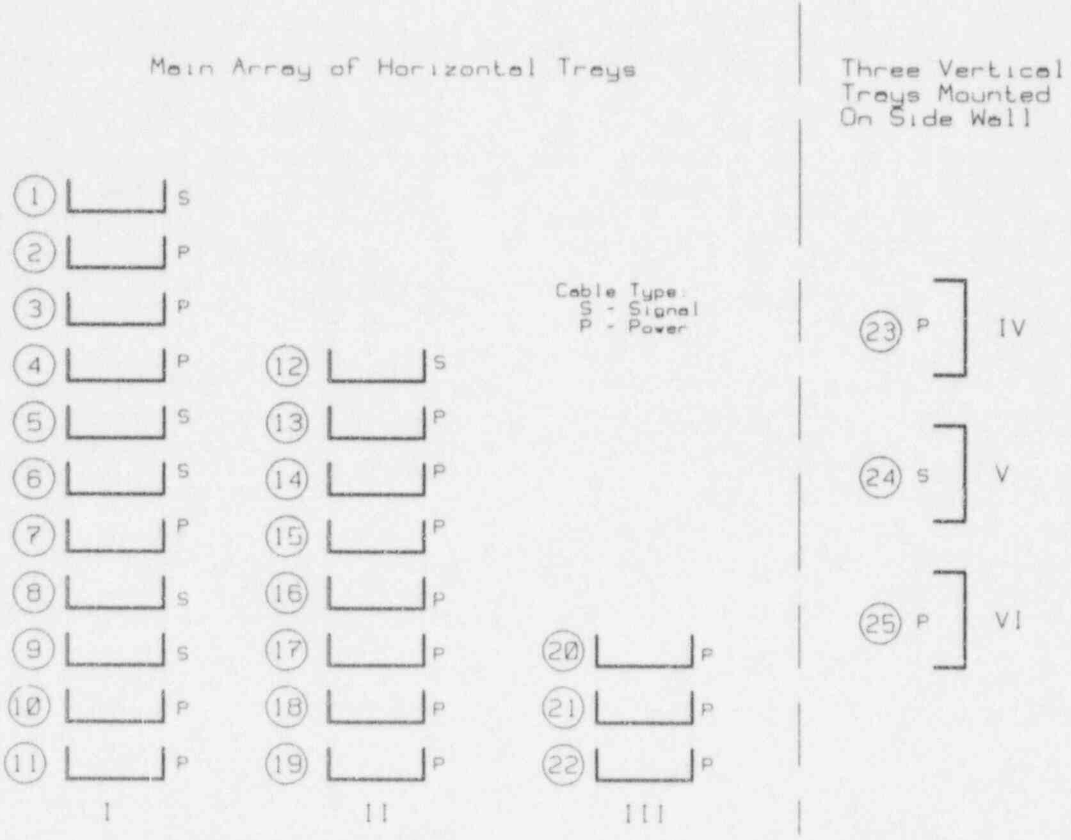

Figure 3.7: Array of Cable Tray Fuel Elements for Test Series E42.

this test. (Trays 20-22 in Stack III were also uncovered, but there was reportedly no unburned fuel remaining in these previously burned trays as discussed above.) The description which follows is based largely on that provided by Karwat, et.al. [5.1.7] and Karwat [5.1.8], with supplemental information provided through personal communications with the test personnel.

At the start of the test, the doors to the fire room were closed. A flexible duct was positioned so as to direct the flow of fresh air from the fire room forced ventilation inlet port directly along the length of the cables in Tray 5. An inlet flow rate of 1400 m^3/hr was provided. The exhaust port inside the fire room (Line 1) was also active with a flow rate of 1700 m^3/hr. Recall that the combined volume of the fire room and the adjoining doorway alcove areas was approximately 100 m^3, so the equivalent ventilation rates were an inlet flow rate of approximately 14 room air changes per hour and an outlet flow rate of 17 room air changes per hour. (Note for comparison that USNRC control room habitability requirements specify a smoke purge ventilation rate of no less than 10 room air changes per hour [5.2.4].) The exhaust gas port located in the fire products collection hood (Line 2) was also active with an initial flow rate of 2500 m^3/hr. The burner was ignited for a period of 60 seconds. Temperatures in the fire room rose relatively quickly. Within 4 minutes, the fire room hot layer temperature had reached 400°C, however, the temperatures leveled off at this point, and remained fairly constant for approximately 4 additional minutes.

It was intended that when half of the cables in trays 1-5 had become involved in the fire (as indicated by thermocouple measurements) one of the two fire room doors would be opened. This was intended to simulate the effects of fire fighters arriving on the scene after a limited period of fire development. This, in fact, occurred about 8-9 minutes after ignition. At this point, one of the two fire room doors was opened. This allowed a significant supply of fresh air to enter the fire compartment, and a significant surge in fire intensity was observed. Fire room hot layer temperatures jumped to approximately 700-800°C within 2 minutes of the door opening. In hindsight, it is apparent that the fire had already become ventilation (oxygen) limited, and that opening the door resulted in a sudden burning of unburned pyrolysis products which had accumulated within the fire room. Consistent with this type of behavior, fire room temperatures and fire intensity both increased sharply. In effect, the fire room experienced a flashover transition.

At 11 minutes after ignition, the fire area collection hood exhaust (Line 2) ventilation rate was increased from its initial value of 2500 m^3/hr to its maximum capacity (approximately 8500 m^3/hr). Instrumentation in adjoining spaces indicated that some smoke might be escaping from the confined fire area space. The increased collection hood exhaust rate was expected to compensate for this leakage. Temperatures measured within the fire room at 11 minutes were in excess of 700°C and continued to climb. By 13 minutes, temperatures of nearly 1000°C were being recorded directly above the cable trays, with general hot layer temperatures of approximately 850-900°C.

By 14 minutes temperatures measured in the fire room had stabilized and were relatively constant at approximately 850-900°C. Temperatures measured in the adjacent hallway area had reached peak values of about 350°C at a location near the ceiling just outside the fire room. At a location farther along the hallway, peak temperatures of 250-300°C were recorded.

At 14 minutes, smoke was observed to be building up in rooms adjacent to, but nominally segregated from, the main fire area. This was a significant concern as it indicated that the fire area confinement strategy was being compromised. By this time, the visibility within the fire area had been severely degraded, and the remote cameras installed in the area were providing only blacked-out images. This was a further indication that smoke had built up within the fire area to the point where some smoke was escaping from the opening at the bottom of the hallway wall opposite the fire doors. (Recall that this opening was intended to provide for a fresh air makeup return path. One camera was positioned so as to provide a view of the fire room doors through this opening.) This indicated that the smoke layer had descended to within 0.5m (18") of the floor, even in the outer hallway area.

Based on the observed smoke leakage, a decision was taken to terminate the fire test. This involved two actions. First, attempts were made to close the one open fire room door in the hopes of damping out the fire through oxygen starvation. These attempts were not successful and the fire room door could not be closed. This was attributed to the acute intensity of the fire and the pressure exerted on the door by the hot fire products leaving the room. Second, the fire sprinkler system located directly above the cable trays was activated, also at approximately 14 minutes after ignition.

Concurrent with actuation of the sprinklers, the temperatures in the fire area immediately began to drop. By 16 minutes hot layer temperatures had dropped to approximately 600°C, and by 18 minutes had dropped to approximately 450°C. By 24 minutes, the fire room hot layer temperature appeared to stabilize at about 250°C. This temperature indicated that despite actuation of the fire sprinkler system, the fire continued to burn.

At 22 minutes the forced ventilation system for the fire room was shut down, including both the fresh air supply and the (Line 1) exhaust streams. By this time the internally installed charcoal filter banks had become thoroughly clogged by the combined loading of smoke and moisture. All ventilation exhaust gases were now being routed to the main HDR exhaust ducts through the (Line 2) collection hood exhaust system. At 38 minutes, in a further attempt to suppress the fire, the rate of water delivery to the fire was increased from 6 l/m^2/hr to 10 l/m^2/hr.

It was determined during post-test examinations that many of the cables which had been protected by the insulating blanketing materials had also been ignited. Apparently, while the sprinklers were successful at suppressing the fire in the open unprotected trays, the "protected" cable trays continued to burn, and in fact, the protective blankets apparently prevented the water from reaching and suppressing the fire in these trays. Hence the fire continued to burn for at least an additional 16 minutes.

The total duration of the significant (intense) portions of the fire was 14 minutes, the time to actuation of the sprinklers. However, the fire continued to burn at a significant level for in excess of 30 minutes, and smoldering combustion was suspected to have continued for in excess of 3 hours. Post test inspection revealed that virtually all of the installed cables had been consumed by the fire, including all of the exposed cable trays, several of the "protected" horizontal cable trays, and both the exposed and protected vertical cable trays. The exact extent of fire spread remains somewhat unclear based on the currently available information.

3.4.6 Test E42.3

During the third test, Test E42.3, the fire ignition source was moved to the bottom of the central stack of cable trays (that is, below tray 19). However, the upper four trays in this stack had apparently been consumed by fire during Test E42.2. Effectively, the fire source was comprised of a stack of four horizontal cable trays (Trays 16-19).

Relatively little information on this particular test has been made available. Apparently, very little fire growth was observed. As in Test E42.1, only the fuel immediately above the fire source was apparently consumed. The test was terminated after a short time, and only minimal temperature deviations were recorded. It is likely that the relatively intense temperatures experienced by the cables during Test E42.2 may have caused out-gassing in these cables, even though the cables did not actually burn. Such out-gassing is analogous to accelerated aging, and would be expected to reduce the flammability of the cables, potentially significantly [5.2.5]. This may well have impacted the cable behavior in this final test.

3.4.7 Summary of Tests Results and Observations

One fundamental finding of this particular test series was confirmation of earlier test results reported by various researchers which indicated that cable tray fires display a threshold type of behavior. That is, in some configurations, a cable fire will remain quite small and will self extinguish, while in other nominally similar circumstances a quite intense fire can result. This type of behavior has been observed in other testing programs, including the efforts of Factory Mutual Research Corp. (FMRC) in its fire testing of cable trays [5.2.6,7], and by SNL in the fire testing of cable trays [5.2.8,9] and electrical control panels [5.2.10,11]. In the case of Test E41.1, the fire never reached this threshold, and hence, self-extinguished. In Test E42.2, the configuration was altered only in that the stack of exposed trays was increased from three to five trays, and was somewhat higher in elevation. Nonetheless, the fire crossed the threshold of self-sustained fire growth, and became quite large.

The heat of combustion of the PVC cable insulation was measured by various laboratories and ranged from 12-17 MJ/kg. The peak rate of mass loss measured during the E42.2 test was approximately 1.8 kg/s [Karwat, May93]. Hence, the peak fire intensity can be estimated as 22-31 MW, a very large fire. (This estimate presumably includes some consideration of the efficiency of the burning because the theoretical heating value of the cables was estimated as 18-26 MJ/kg.) This can be compared to the largest fire experienced in the SNL/NRC cabinet fire test program [5.2.11] which was a fully involved cable loaded bench-board control panel which experienced a peak fire intensity of less than 2 MW.

It was also quite surprising that the intensity of the fire was sufficient to cause ignition of those cables nominally protected by the insulating blankets. These materials had been expected to protect the cables from fire damage. The intense flashover conditions in the E42.2 test overcame this protection. Temperatures measured inside some of these protective blankets clearly indicate that ignition did occur concurrent with the surge in fire room temperatures at 9 minutes. As it turned out, the fire barrier materials actually prolonged the fire test by preventing the fire sprinkler water from accessing the cables.

With regards to the concerns over the potential generation of dioxin contaminants, extensive analysis of soot samples taken during the tests revealed only very minor levels of dioxin contamination. In no case did these contamination levels approach the established unprotected worker exposure limits for dioxin. This experience appears to indicate that the previous results indicating significant dioxin production in PVC cable fires were not realistic for large-scale fire behaviors. It is quite possible that the earlier results can be attributed to artifacts of the small scale testing upon which the results were based; that is, fundamental issues of scale, contamination of the original cable samples, or some other experimental artifact. In any case, the E42.2 test in particular clearly casts considerable doubt on the suposition that dioxin production will occur during a large scale PVC cable fire.

3.4.8 SNL E42 Component Exposures

As a part of efforts under the USNRC sponsored cooperative research program, SNL participated in the E42 test series directly. In particular, samples of two commonly used types of nuclear grade cables, and two samples of a common nuclear grade electro-mechanical relay were installed within the fire area and monitored for performance during the tests. Only one of these components, a relay located within the fire room itself, actually experienced significant levels of thermal exposure. The other components, located in the hallway area, experienced only minor increases in environment temperature. All of the components performed without apparent degradation throughout each test, and in particular, throughout test E42.2. Upon their return to SNL after completion of testing and the completion of the dioxin sampling tests, these components still maintained their ability to function, despite the fact that no attempts to clean the samples were employed. The results of these tests are described in detail in Appendix A.

4 SUMMARY OF EXPERIMENTAL RESULTS AND FINDINGS

As a part of a larger program of nuclear power plant operational safety investigations, the German government has sponsored the performance of several fire tests in the containment building of a decommissioned nuclear power plant (HDR). These tests are unique in that the test structure was a very large, very complex, multi-room, multi-level structure, and in most of the tests, full containment volume involvement in a macro-scale circulation of fire products was observed.

Test fires were set in three different locations in the containment structure. Fuel sources included gas burners, wood cribs, oil pools, nozzle released oil fires, and electrical cables in cable trays. A variety of ventilation conditions were utilized including natural convection through open doorways only, forced ventilation only, and combined natural and forced ventilation.

Each of the tests was extensively instrumented. In particular, the temperature and air circulation data gathered during each test is extensive. Information is also available on the concentration of major gas constituents including oxygen, carbon dioxide, and carbon monoxide in certain selected regions of the containment volume. No direct measurements of fire intensity were made, but for many of the tests the fuel source was controlled so that, to a large extent, fire intensity can be inferred.

Fire conditions which were generated ranged from small fuel surface controlled fires to very large ventilation-limited fires. Many of the fires involved full flashover conditions within the fire room. Many of these larger fires also resulted in the burning of excess pyrolysates away from the location of the fire source itself. This included cases of burning both in the fire room hot layer and in the fire room exit plume (the plume of hot gases and fire products leaving the fire room doorways).

The usefulness of the test results lies in two general areas. First, the tests provide many valuable insights into the general behavior of fires and the interaction of fires with a large complex volume. Specific topics addressed by the tests include:

- Fire growth and extinguishment behavior,
- Smoke production and control,
- Fuel surface area to ventilation limited fire transition,
- Flashover,
- Effects on and interactions with forced ventilation systems,
- Effectiveness of selective area pressurization strategies,
- Macro-scale fire products circulation effects, and
- Cable fire toxicity and PVC dioxin production.

Second, the tests provide a very challenging basis for the validation of computer fire models. In parallel with the experimental efforts, an international fire model validation effort was also conducted. (This aspect of the program is addressed in a separate document and has not been considered here.) The fire tests performed in HDR present a particularly challenging situation with regards to fire modeling. In part this is due to the very complex nature of the structure. In addition, the nature of the fires observed (full flashover and ventilation limited fires) also presents difficulty for many of the current fire models. Nonetheless, a wide range of fire modeling experts participated in the validation effort, and many interesting insights were gained.

5 REFERENCES

5.1 German Research Publications

The following provides a listing of the principal German publications associated with the performance and analysis of the HDR fire tests. The publication list is not exhaustive, and only minimal efforts have been undertaken to identify secondary publications such as conference papers and technical journal articles. The listing provides for identification of the principal technical reports generated by the German researchers in the course of their efforts. In addition to those cited here, there are innumerable minor publications associated with specific aspects of the test program, selected program results, and the parallel fire model validation efforts.

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5.1.2. K. Müller, *Status and Selected Results of Fire-Experiments in the HDR-Plant: Paper Prepared for Introduction of HDR-Fire Experiments to Cooperation Partners*, KfK, PHDR Report 5.094/86, October 1986 (available in English).

5.1.3. K. Müller, *Status and Selected Results of Fire-Experiments in the HDR-Plant: Paper Prepared for Introduction of HDR-Fire Experiments to Cooperation Partners*, KfK, PHDR Report 40.017/89, October 1989 (available in English).

5.1.4. K. Müller, R. Volk, *Brandvesuche am HDR Ölbrand im Geschlossenen System E41.5-10*, KfK, Report 40.024/90, August 1990, (English language version available as: *DESIGN BASIS REPORT: Fire Experiments in the HDR: Oil Fire in a Closed System*, KfK Report 40.028/90, November, 1990).

5.1.5. Dr. Rautenberg, Dr. Dobbernack, D.I. Heins, K. Müller, *Verhalten von Bränden bei Zwangsventilation und Naturzug im HDR*, (author's translation: *Investigation of Fire Scenarios Under Forced and Natural Ventilation Conditions in the HDR-Containment*), KfK, March 1991, (available in German only with a limited English summary).

5.1.6. D. Hosser, R. Dobbernack, *Brandexperimente am HDR zum Ablauf und den Auswirkungen von Bränden in Kernkraftwerken; Aussagefähigkeit von Brandcodes für die Beschreibung der Vorgänge*, (roughly translates as: "Fire Experiments at HDR on the Results and Consequences of Fire on Reactor Energy Exchange; Output Capability from Fire Codes for the Description of the Process"), Contribution No. VIII, Section 15 of *Statusbericht PHDR Dez. 1991 (Status Report on Project HDR, December 1991)*, (available in German only), (Note: this is one of several annual summary documents prepared for use primarily as internal status reports for project participants.).

5.1.7. H. Karwat, K. Müller, U. Max, *CEC STANDARD PROBLEM: Prediction of Effects Caused by a Cable Fire Experiment Within the HDR-Containment: Task Specification*, Technical University of Munich, February 1992, available in English.

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5.2 General References

5.2.1 Nicolette, V.F., *Fire Modeling of the Heiss Dampf Reaktor Containment*, NUREG/CR-6017, SAND93-0528, Sandia National Laboratories, September, 1995.

5.2.2 *Nuclear Power Plant Fire Protection-Ventilation (Subsystems Study Task 1)*, SAND79-0263, NUREG/CR-0636, Sandia National Laboratories, August 1979.

5.2.3 *IEEE Standard for Type Test of Class 1E Electric Cables, Field Splices, and Connections for Nuclear Power Generating Stations*, IEEE383-74, Nuclear Power Engineering Committee of the IEEE Power Engineering Society, 1974.

5.2.4 Jacobus, M.J., *A Review of Regulatory Requirements Governing Control Room Habitability Systems*, NUREG/CR-3786, Sandia National Laboratories, August 1984.

5.2.5 Nowlen, S.P., *The Impact of Thermal Aging on the Flammability of Electric Cables*, NUREG/CR-5619, Sandia National Laboratories, March 1991.

5.2.6 Hill, J.P., *Fire Tests in Ventilated Rooms: Extinguishment of Fire in Grouped Cable Trays*, NP-2600, Factory Mutual Research Corp., Dec. 1982.

5.2.7 Tewarson, A., Khan, M.M., *Electrical Cables - Evaluation of Fire Propagation Behavior and Development of Small-Scale Test Protocol*, FMRC J.I. 0M2E1.RC, Factory Mutual Research Corp., Jan. 1989.

5.2.8 Dube, D.A., *Fire Protection Research Program for The Nuclear Regulatory Commission, 1975-1981*, NUREG/CR-2607, Sandia National Laboratories, April 1983.

5.2.9 Nowlen, S.P., *A Summary of the USNRC Fire Protection Research Program at Sandia National Laboratories; 1975-1987*, NUREG/CR-5384, Sandia National Laboratories, December 1989.

5.2.10 Chavez, J.C., *An Experimental Investigation of Internally Ignited Fires in Nuclear Power Plant Control Cabinets, Part I - Cabinet Effects Tests*, NUREG/CR-4527/V1, Sandia National Laboratories, April 1987.

5.2.11 Chavez, J.C., Nowlen, S.P., *An Experimental Investigation of Internally Ignited Fires in Nuclear Power Plant Cabinets, Part II - Room Effects Tests*, NUREG/CR-4527/V2, Sandia National Laboratories, October 1988.

Appendix A:
SNL E42 Component Exposure Test Results

A.1 Introduction

A.1.1 Overview and Scope

As a part of a USNRC sponsored cooperative research agreement, Sandia National Laboratories (SNL) participated in the E42 test series through the performance of certain cable and relay component performance experiments. The E42 tests were performed during January and February, 1992. During these experiments samples of two types of electrical cables and one type of electrical relay, all provided by SNL, were installed in the general fire area. These components were monitored for performance during each of the fire tests using SNL provided equipment.

The objective of these tests was to assess the impact of the fires on the operability of two common nuclear power plant components, namely, cables and relays. Parallel efforts underway at SNL were also investigating the thermal vulnerability of these components under controlled exposure conditions [A.5.1,2]. This appendix provides the results of the experiments performed in conjunction with the E42 tests.

A.1.2 The E42 Test Series

As has been discussed in Section 3.4 above, the E42 tests did not proceed entirely as planned. In particular, the E42 test plan had called for 5-6 cable tray fire tests of varying intensity. However, in the end only three fire tests were actually performed, and of these tests, only one resulted in a significant fire. This difficultly arose as a direct result of the rather unpredictable nature of a cable fire. A description of each of the three E42 fire tests is provided in Section 3.4 above.

A.2 Overview of the Test Setup

A.2.1 Physical Configuration of the Fire Area

A detailed description of the fire area and fuel array has been provided in Section 3.4 above. Recall that the E42 tests were conducted in a limited area of the HDR containment building comprised of two adjacent rooms and an adjoining doorway alcove. The first room, referred to as the "fire room," contained all of the combustible materials, namely, PVC insulated electrical cables. This room was connected through an alcove equipped with a pair of fire doors to a second room or hallway. This second area will be referred to as the "outer room." Both of these rooms were highly irregular in shape. Figure 3.5 described above provides a schematic representation of the fire area associated with the E42 test series.

A.2.2 Placement of the Component Exposure Samples

The component exposure experiments conducted using SNL equipment were performed in each of the three E42 tests. In each of the test exposures two samples of a General Electric HGA electro-mechanical relay, one sample of a Dekoron Dekorad 2-conductor cable, and one sample of a Rockbestos 3-conductor cable were located in the fire area and monitored for performance. These sample components were placed in three separate locations. These locations are also identified in Figure 3.5 described above.

Each of the two relays was placed within separate electrical enclosure boxes (each approximately 30x25x10 cm (12"x10"x4")) mounted directly to the walls of the fire area at a height of approximately 1.5 m (5') above the floor. In each case three of the conduit "knockout" penetrations were removed from both the top and bottom of the electrical enclosure boxes so that they were not air-tight. These boxes did protect the relays from direct radiative exposure to the fire source. The first relay was mounted at a location in the doorway alcove area just inside the doors to the fire room itself. The second relay was placed in the outer room on the partition wall opposite the fire room doors. In the case of this second relay, this location was selected such that the nearest fuel array element (cable tray) was separated from the relay by twenty feet (or approximately 6.1 m) of horizontal space (as per the Appendix R separation guidelines). It should, however, be noted that this second location was also separated from the fire source by the doors to the fire room (the fire room itself was too small to achieve a twenty foot separation).

The two cable samples were placed side-by-side in a single cable tray mounted near the ceiling of the outer room. This cable tray was placed such that the nearest fuel array element (cable tray) was separated from the cables by approximately twenty feet of horizontal space. This location was also separated from the fire source by the doors to the fire room. This location was roughly located at the transition point from the relatively square region immediately outside the fire room doors to the elongated hallway section leading to the fire products collection hood located in the primary equipment hatch at the end of this hallway section. In this position, it was expected that the cables would be exposed to hot fire gases upon the opening of the fire room doors. That is, it was expected that while the fire room doors were open, the fire room exit plume would leave the doors, rise to the ceiling of the outer room, and flow along the ceiling past the cables to the fire products collection hood.

A.2.3 Monitoring of the Component Performance

The performance of each of the two relays was monitored continuously during each fire test. This included an assessment of both load carrying and load switching capability. Each relay was provided with a controllable coil power source, and simulated load currents. During the exposures, the relays were normally deenergized such that the contacts remained in the open position. Once each minute, the coil to each relay was energized closing the contact pairs for a period of about 15 seconds. Relay performance monitoring included measurement of (1) open contact load current (normally zero), (2) closed contact load current (normally about 0.16 amps), and (3) closed contact resistance.

For the cables, performance monitoring was comprised of a relatively simple leakage current measurement scheme. One conductor in each of the cables was energized to 120VAC. The second, and for the Rockbestos cable the third, conductor(s) were grounded. Cable performance monitoring consisted of measuring the energized conductor leakage current from the high voltage conductor to the grounded conductor(s). This was accomplished using high precision ballast/load resistors, and measuring the AC voltage drop across these resistors.

A.3 Test Results

A.3.1 Fire Test Behavior

As discussed in Section 3.4 above, it was initially intended that a limited sub-section of the cable tray array would be burned in any one test, while the balance of the cable tray array would be protected by insulating blankets. The original test plan had called for the performance of 5-6 fire tests, depending on the conditions noted in each test. However, because of the unexpectedly large fire encountered in Test E42.2, only three tests were ultimately conducted, and of these three tests only Test E42.2 resulted in a significant fire.

Section 3.4 above provides a detailed discussion of each of the three E42 fire tests. Because tests E42.1 and E42.3 produced no significant fire growth or spread, these tests resulted in no significant temperature deviations from ambient. Hence, these tests are of no interest with regards to the component exposure tests. Only Test E42.2 produced significant temperature deviations, and hence, only this test will be considered further here.

During Test E42.2, the fire spread rather quickly through the five trays immediately above the fire source. Recall that the test began with the doors to the fire room closed. Upon opening of the fire doors at 9 minutes an immediate increase in fire intensity and in fire room hot layer temperature was experienced. The fire was apparently able to jump across the open gap from the initially exposed stack to the adjacent stack of cable trays, and it is also suspected that the one exposed vertical cable tray also ignited at this time. This transition caused a significant jump in the fire intensity, and the fire room hot layer temperatures quickly rose to between 700°C and 800°C.

This second, more intense phase of the fire lasted for about 5 minutes, or until about 14 minutes after ignition. At this point, the fire suppression sprinklers were activated, and the fire intensity was markedly reduced. However, the fire apparently continued to burn at a significant rate for an additional 16 minutes, and reportedly continued to smolder for over 3 hours. In particular, many of the protected cable trays had been ignited, and the insulating blankets interfered with the fire suppression system, preventing effective suppression efforts.

A.3.2 Cable Performance During Test E42.2

Figure A.1 provides a plot of the temperature exposure history at the location of the exposure sample cable tray. Recall that this cable tray was located in the outer room of the fire area near the ceiling and at least 20 feet from the fire source. The peak measured temperature at this location was approximately 235°C. This exposure temperature would not be expected to cause damage to the subject cables.

One reason for the relatively mild nature of the thermal exposure was that the doors to the fire room were only opened for approximately 5 minutes through the mid-portion of the test (from 9 to 14 minutes into the test). This resulted in a mitigation of the outer room exposure temperatures. As shown in Figure A.1, the temperature at the location of the cable samples saw only modest increases (to about 35°C) prior to opening of the fire room doors. Once the doors were opened, the temperature rose sharply to the peak exposure temperature, and were still rising sharply when the sprinkler system was actuated. At this point, temperatures began to fall sharply. Had the fire test been allowed to continue, failure of the cables would likely have been experienced. The threshold for damage for these cables is estimated at approximately 350°C [A.5.1]. Based on the rate of temperature increase being observed just prior to the activation of the sprinkler system, this temperature would likely have been reached in an additional 2-3 minutes.

Figure A.2 provides the leakage current data for the two cable samples. As expected, no significant degradation in performance is noted. The measured leakage currents are well within the anticipated normal performance limits for these cable products. Post-test examination of the cables showed no obvious signs of damage, although the cables were slightly discolored by smoke deposits. Electrical integrity testing showed the cable to be intact upon return to SNL.

A.3.3 Outer Room Relay Performance During Test E42.2

The exposure temperatures for the relay which had been located in the outer room of the fire are shown in Figure A.3. Note that the peak exposure temperature was approximately 77°C. This exposure temperature would not be expected to cause damage to the subject relay. One reason for the relatively low values of peak temperature was that the doors to the fire room were only opened for approximately 5 minutes through the mid-portion of the test (from 9 to 14 minutes into the test). This resulted in a mitigation of the outer room exposure temperatures as discussed immediately above. Temperatures were also mitigated by the fact that the relay was mounted just 1.5 m (5') above the floor level

Figure A.4 provides the load carrying data for this relay. As expected, no significant degradation in performance is noted, that is, the closed contact load current remained constant, and the open contact current remained zero. Figure A.5 provides the contact resistance data gathered during the test. Note that some minor deviations were observed at the same time as the temperature peaked. It is assumed that this deviation resulted from smoke deposition. However, it also appears that the opening and closing of the relay cleared the fouling, and no significant performance degradation is indicated.

Post-test examination showed significant discoloration of the relay. Further, upon return to SNL, (approximately three months after the fire exposure) evidence of modest corrosive attack on the relay metallic components was observed. However, electrical functionality tests showed that the relay was still functional.

A.3.4 Doorway Alcove Relay Performance During Test E42.2

Figure A.6 shows the temperature history experienced by the relay which was located in the alcove area just inside the doorway to the fire room itself. The peak temperature measured within the electrical enclosure box was approximately 425°C. Figure A.7 shows the load switching performance data for this relay. Note that some degradation of the "relay open" leakage current is indicated. In particular, after one hour into the test, several "spikes" in open contact current were noted. It is unclear as to the cause of this behavior. However, because these "spikes" were in excess of the closed contact load currents, it is suspected that some shorting to ground was experienced. This shorting was most likely caused by degradation at the point where the lead wires were connection to the relay. In particular, to provide thermal protection, ceramic blanket insulation was "packed" around these connections. Prolonged exposure to fire suppression induced moisture likely resulted in the saturation of this insulation and the creation of a leakage path to ground for these lead wires. Hence, these measurements are not considered to represent an indication of degradation in the relay itself. This conclusion is further supported in that no significant degradation in the "relay closed" load carrying capacity is noted.

Post-test examination of the relay upon its return to SNL showed extensive discoloration and some warping and blistering of the outer case of the relay. Significant evidence of corrosion was also noted, although approximately three months had passed since the fire exposure before the relays were returned to SNL. Figure A.8 provides the contact resistance data for this relay. Shortly after the time of peak fire intensity, the contact resistance experienced a 3-fold increase for a short period of time. This degradation corresponds to the time of fire suppression system actuation and may have resulted from deposition of soot-laden moisture on the contact points. The observed outer case warpage may have allowed the penetration of such contaminants. Testing of the relay showed it to remain operational, although some permanent increase in contact resistance was noted due to the corrosive attack on the contact points.

Note also that a series of relay thermal exposure tests using the same type of relay have recently been completed at SNL [5.1.2]. In these tests, a longer duration exposure at a peak temperature of 450°C did result in some relay failures. Hence, the peak exposure temperature of 425°C experienced would be considered a marginal short-term operating state, and a more prolonged exposure to the 425°C temperature may have resulted in relay failure. This is also supported by the signs of visible damage noted in the relay.

A.4 Summary

The results of the component exposure tests were somewhat disappointing. Unexpected events resulted in only three fire tests being performed (rather than the originally planned series of 5-6 tests). Of these three tests, only one resulted in any significant thermal exposure to the tested components, and this significant exposure was limited in time to a period of less than five minutes. In particular, the relay and cable samples located in the outer room area experienced only very limited temperature excursions because the fire room doors were not opened until nine minutes into the test, and then the fire sprinklers were actuated just five minutes later. Hence, the exposure temperatures in the outer room were still increasing sharply at the time of sprinkler actuation and never reached stable values.

During testing, all of the components performed well. Only the relay located within the fire room during Test E42.2 evidenced any significant level of performance degradation, and even this degradation was relatively minor despite the exposure of the relay to a peak temperature of 425°C (albeit for a short period of time). Independent SNL test results indicate that during a longer duration exposure at this temperature, relay failure might be expected. All of the tested relays did show evidence of some discoloration, and the one relay located in the fire room during Test E42.2 showed blistering and warpage of the outer case. All of the tested components showed some accumulation of soot on the outer surfaces.

Evidence of longer term corrosive attack was noted in all of the relays upon their return to SNL. Nearly three months had passed between the actual fire tests and the time the relays were returned to SNL (the relays were held by the Germans pending the results of the dioxin measurements). All of the components were tested upon their return to Sandia and all were found to be operational. The one most severely exposed relay did show some permanent degradation in contact resistance, presumably due to this corrosive attack, but the resistance values measured were not severe enough to result in significant operational degradation.

A.5 References

A.5.1 Nowlen, S.P., *An Investigation of the Effects of Thermal Aging on the Fire Damageability of Electric Cables*, SAND90-0696, NUREG/CR-5546, Sandia National Laboratories, May 1991.

A.5.2 Vigil, R., Nowlen, S.P., *An Assessment of Fire Vulnerability for Aged Electrical Relays*, SAND94-0769, NUREG/CR-6220, Sandia National Laboratories, Report to be published.

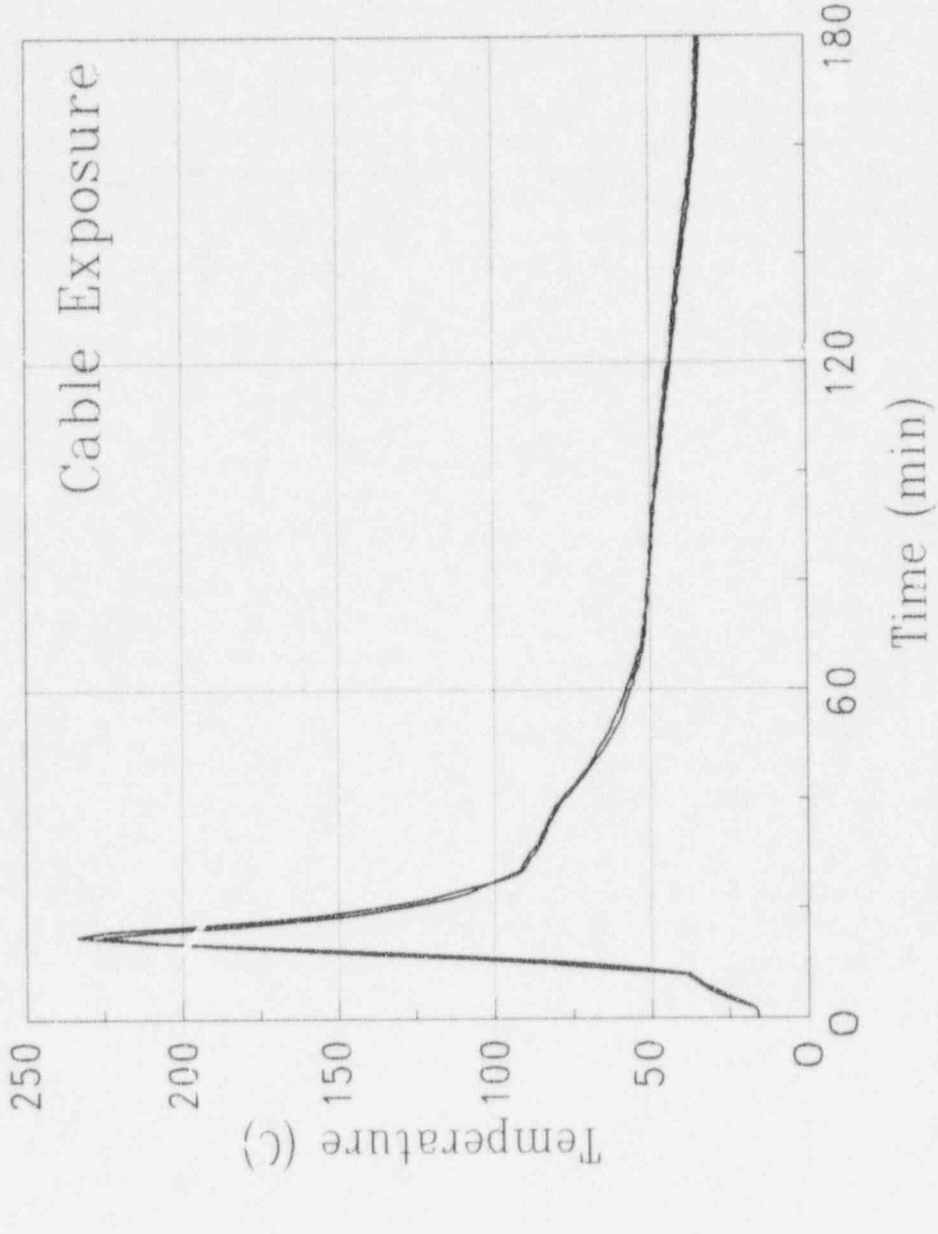

Figure A.1, Temperature Exposure History at the Location of the Sandia Cable Samples During Test E42.2

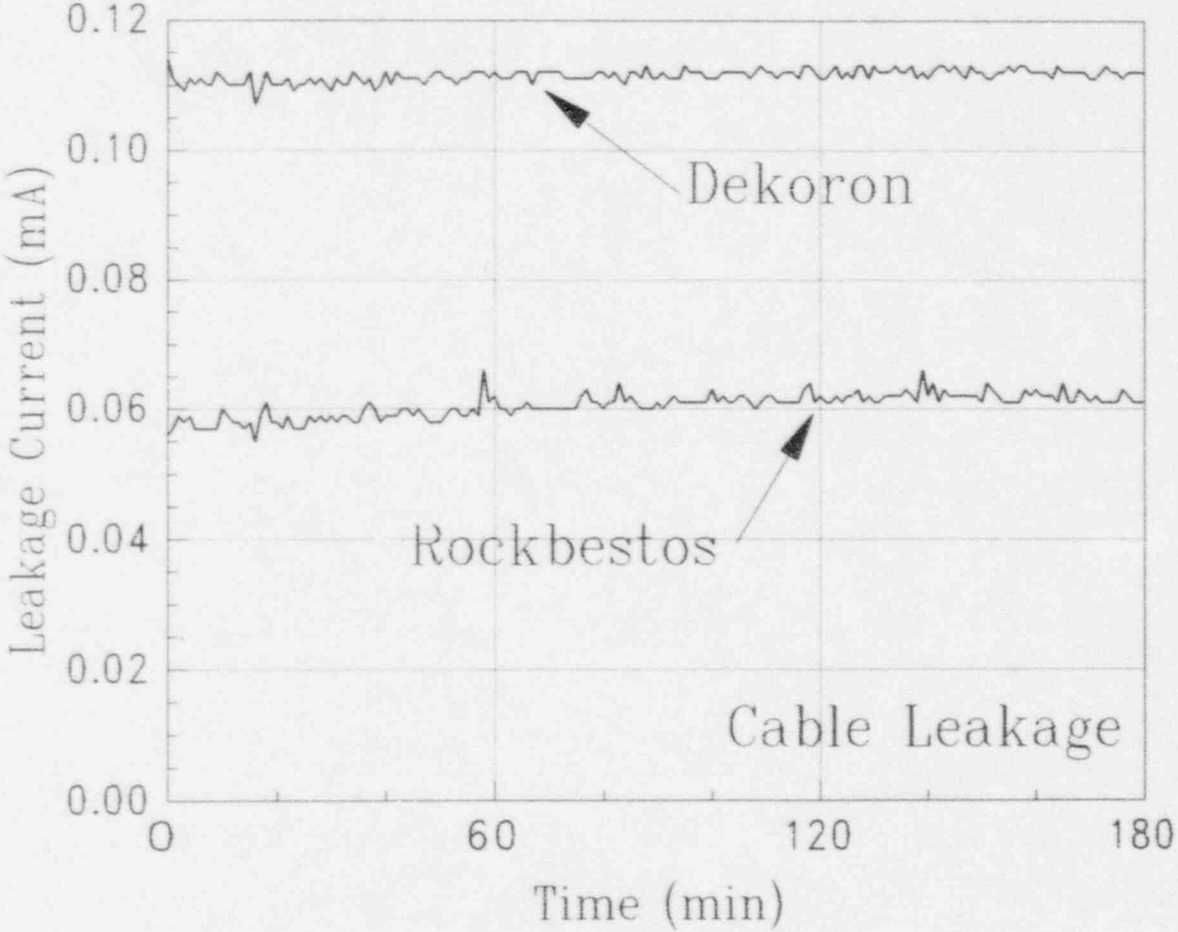

Figure A.2. Cable Performance Data, Leakage Current, for the Sandia Cable Samples During Test E42.2

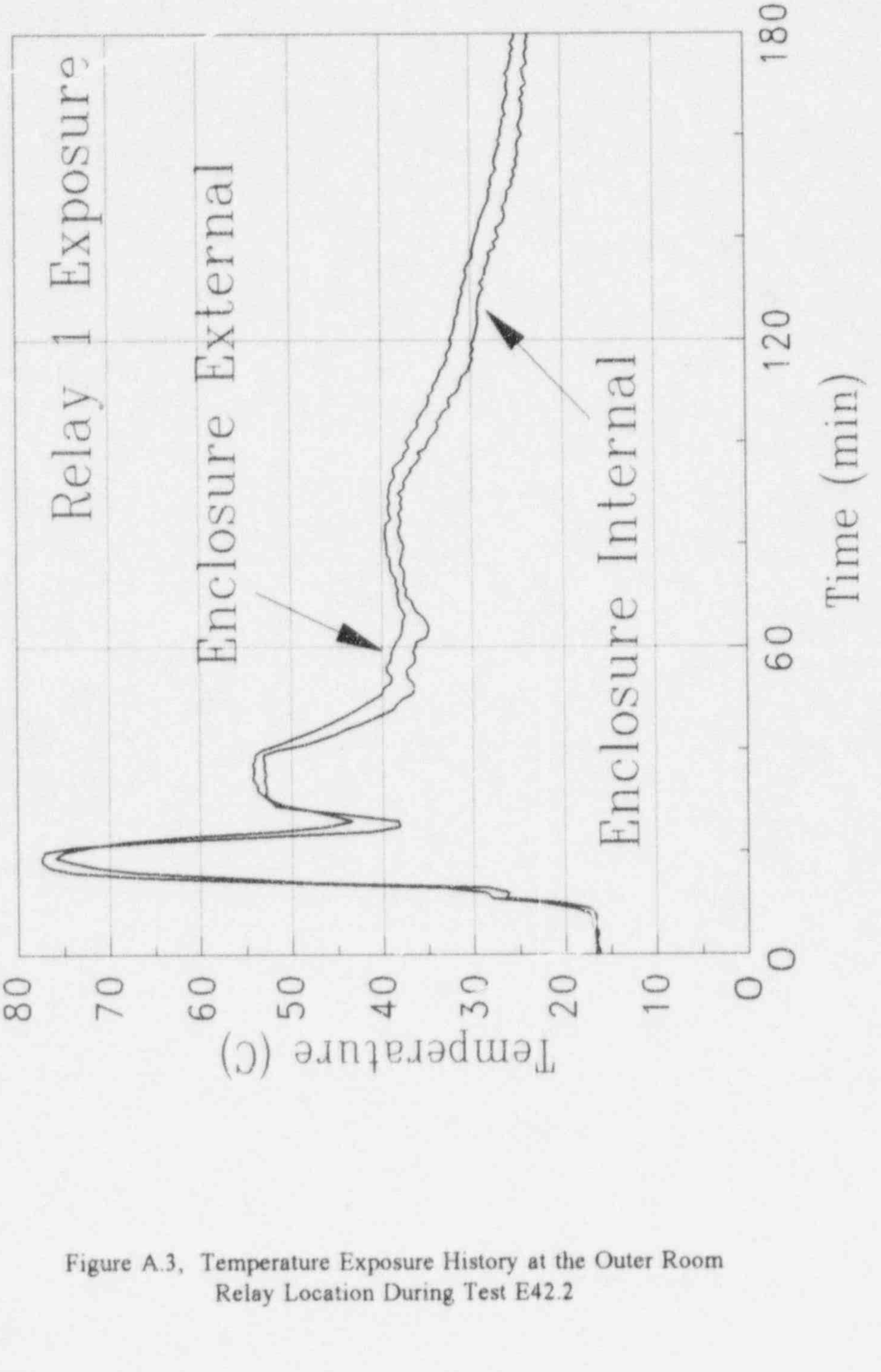

Figure A.3, Temperature Exposure History at the Outer Room Relay Location During Test E42.2

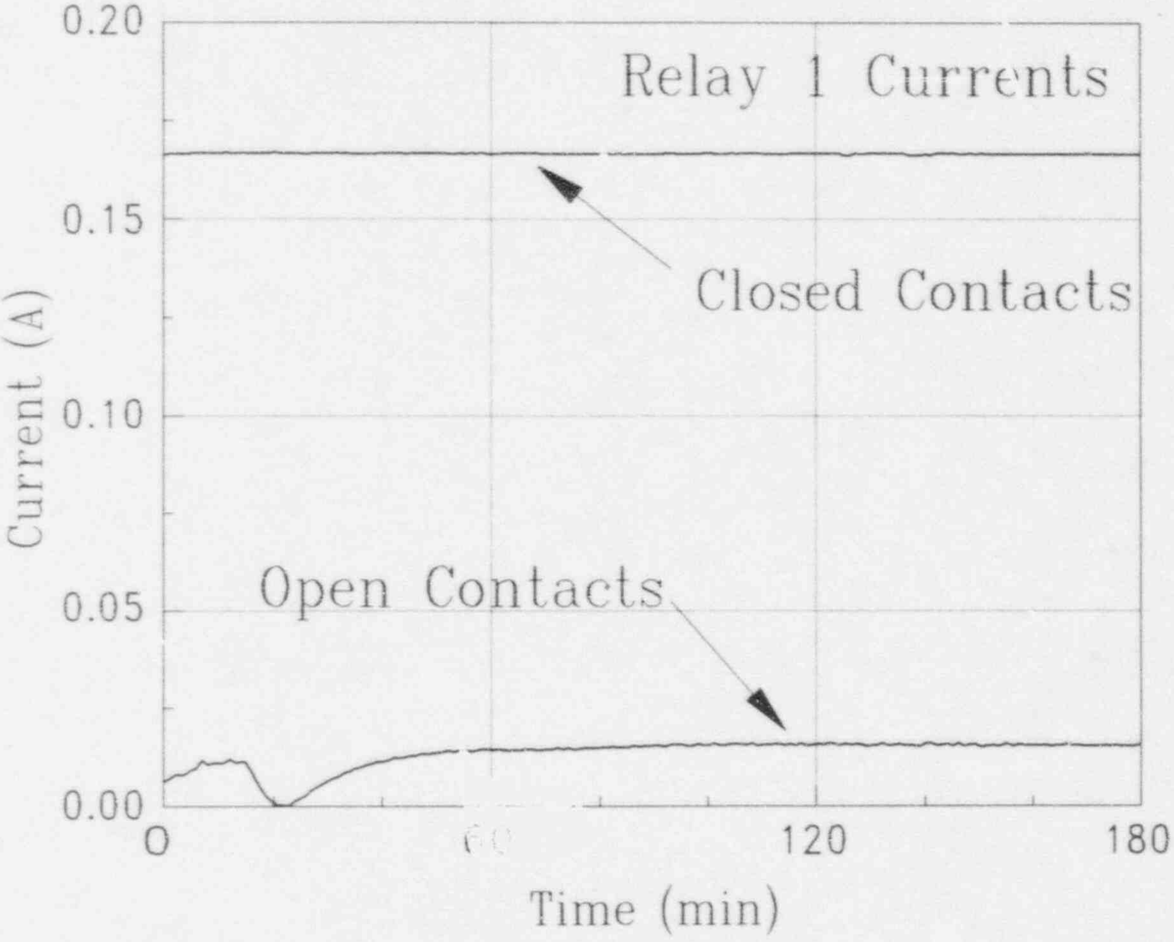

Figure A.4. Relay Switching Performance Data for the Outer Room Relay During Test E42.2

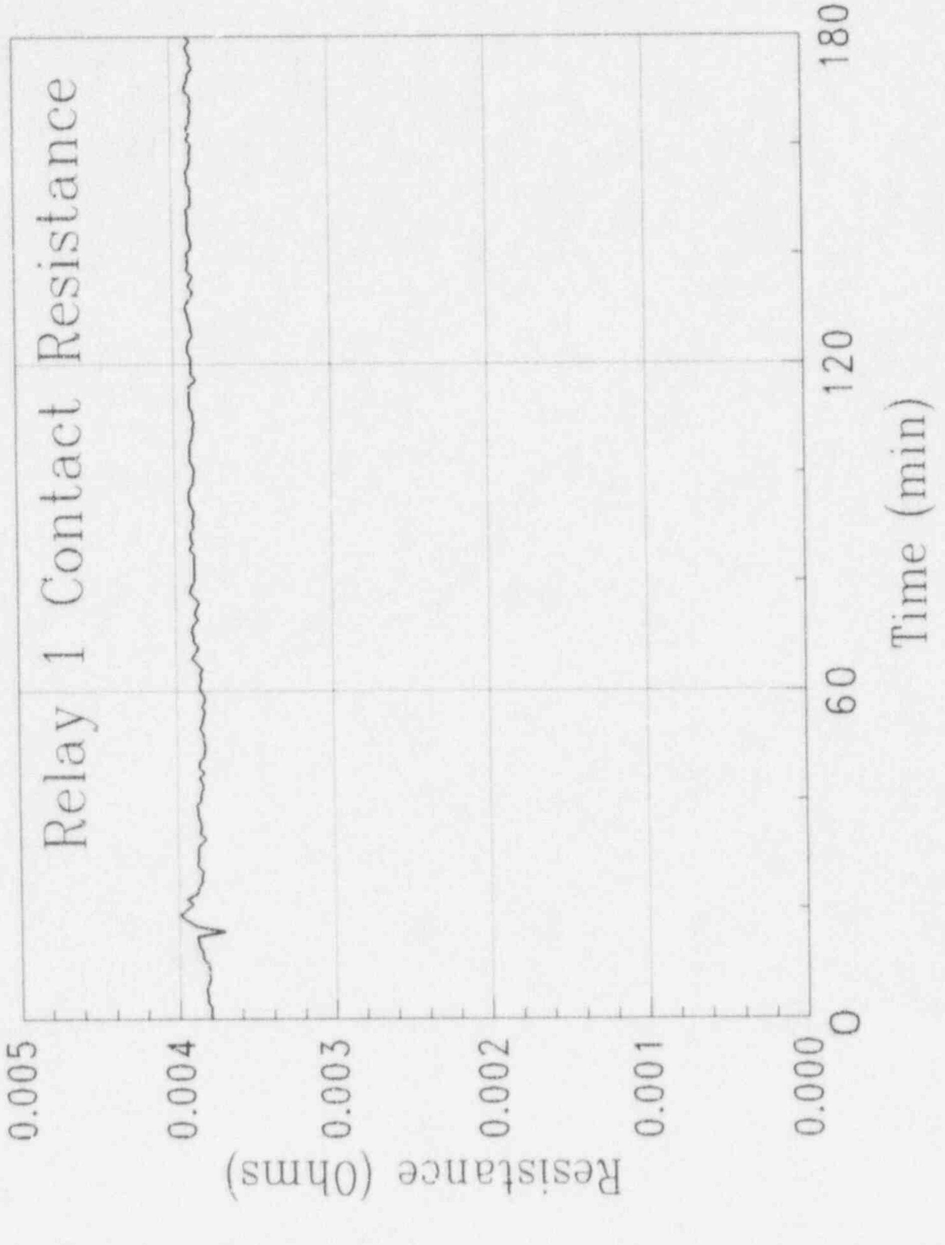

Figure A.5, Outer Room Relay Contact Resistance
Data Gathered During Test E42.2

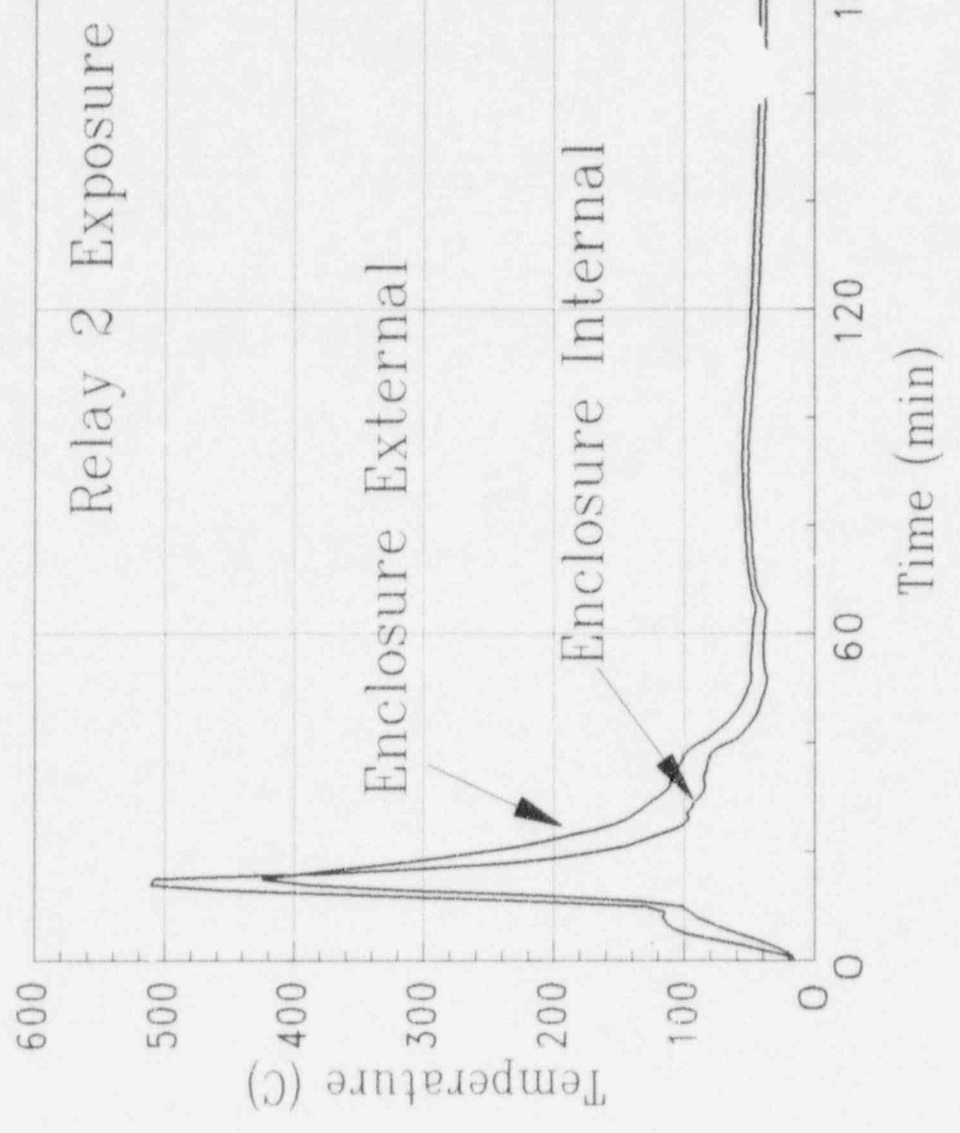

Figure A.6, Temperature Exposure History at the Fire Room Relay Location During Test E42.2

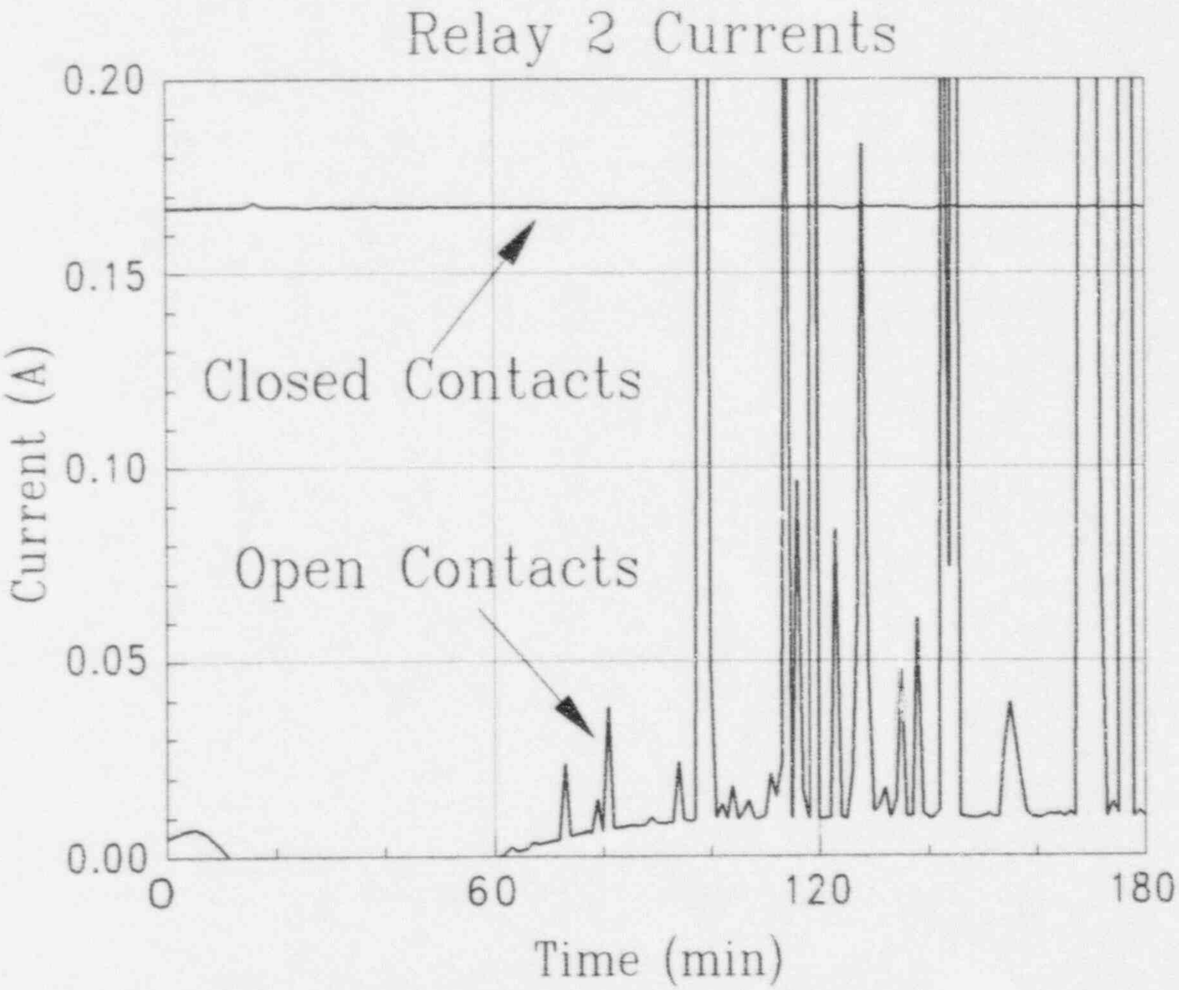

Figure A.7. Relay Switching Performance Data for the Fire Room Relay During Test E42.2

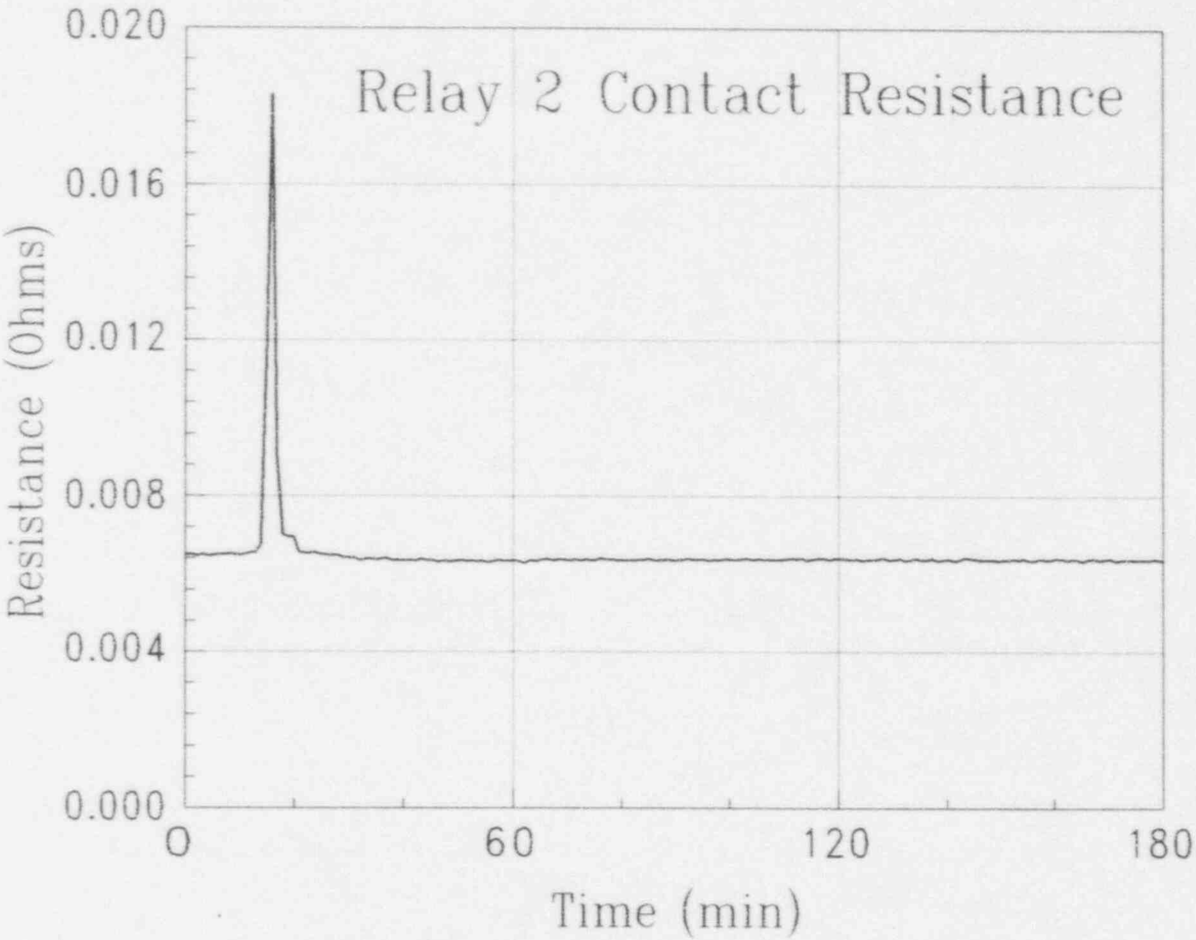

Figure A.8, Fire Room Relay Contact Resistance
Data Gathered During Test E42.2

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10. SUPPLEMENTARY NOTES

W. Gleaves, NRC Project Manager

11. ABSTRACT *(200 words or less)*

This report provides an overview of the fire safety experiments performed under the sponsorship of the German government in the containment building of the decommissioned pilot nuclear power plant known as HDR. This structure is a highly complex, multi-compartment, multi-level building which has been used as the test bed for a wide range of nuclear power plant operation safety experiments. These experiments have included numerous fire tests. Test fire fuel sources have included gas burners, wood cribs, oil pools, nozzle release oil fires, and cables in cable trays. A wide range of ventilation conditions including full natural ventilation, full forced ventilation, and combined natural and forced ventilation have been evaluated. During most of the tests, the fire products mixed freely with the full containment volume. Macro-scale building circulation patterns which were very sensitive to such factors as ventilation configuration were observed and characterized. Testing also included the evaluation of selective area pressurization schemes as a means of smoke control for emergency access and evacuation stairwells.

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