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EVALUATION OF THE HDR FIRE TEST DATA AND ACCOMPANYING COMPUTATIONAL ACTIVITIES WITH CONCLUSION FROM PRESENT CODE CAPABILITIES. VOLUME 1: TEST SERIES DESCRIPTION FOR T51 GAS FIRE TEST SERIES

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Notice

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Evaluation of the HDR Fire Test Data and Accompanying Computational Activities with Conclusions from Present Code Capabilities

NIST CONTRACT 60NANB6D0127

Volume 1:
Test Series Description for
T51 Gas Fire Test Series

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EXECUTIVE SUMMARY

Between 1984 and 1992 four major test series were performed in the HDR containment encompassing various fuels and three different axial positions in the high-rise, multi-level, multi-compartment facility. At that time, each HDR fire test series was accompanied by extensive efforts to evaluate the predictive capabilities of a variety of fire models and codes developed in different countries by both blind pre-test and open post-test computations. A quite large number of open issues remained in the area of fire computer code predictive qualities upon completion of the HDR program.

In the meantime, large progress has been made in improving and consolidate fire models and computer codes of all levels of simulations. This progress merits revisiting both experimental results and fire computer code validations. The results of the research efforts for this grant during FY 1996/97 are documented in two separate volumes:

Volume 1: Test Series Description for T51 Gas Fire Test Series
Volume 2: CFAST Validation for HDR T51 Gas Fire Test Series

Volume 1 by focusing on the T51 gas burner experiments covers the following aspects of the HDR fire experiments:

- Section 1 provides an overall introduction to the HDR test facility and especially the containment building layout. It provides an overview of all four major HDR fire test groups utilizing a range of fire sources including: propane gas burners, wood cribs, liquid fuel pools and nozzle releases, and protypical electrical cables. These fires have been set at three different axial elevations within the containment building under natural, forced, and combined ventilation conditions.
- Section 2 gives a detailed account for the compartment layouts for the propane gas burner and wood crib experiments. It also lists all fuel and thermophysical material properties involved in the experimental setup.
- Section 3 describes the objectives, requirements, and functional principles of the instrumentation applied during the test series and documents the positions of all sensors used in both tabular and graphical form. These layouts are separately displayed for test groups T51.11 - T51.15, T51.19, and T51.21 - T51.25 as the types and number of sensors evolved over time.
- Section 4 briefly summarizes the common test procedure used for executing every experiment.
- Section 5 provides an overview of major experimental results of the gas burner tests in three subsections. First, selected transient histories are shown for temperatures, gas concentrations, and velocities in the different connected compartments, including the dome, for the three experiments spanning the range of gas fire powers examined. The second set of experimental results involves the maximum values of the same quantities as a function of the applied fire power. Thirdly, the impact of an additional ventilation duct connecting the fire room to a higher-up compartment is documented for various damper openings.
- The concluding Section 6 addresses numerous aspects of potential contributions of the gas burner experiments towards the validation of zone model codes such as CFAST (see Volume 2), containment system codes such as GOTHIC, and CFD codes such as NIST-LES.

ACKNOWLEDGMENTS

The work performed in this grant was performed under the auspices of the Building and Fire Research Laboratory at the National Institute of Standards and Technology. It was funded by the Department of Commerce.

The program was monitored at NIST by Dr. Kevin McGrattan whose continued interest in and support of this work is greatly appreciated.

Also, we would like to thank Dr. Richard Peacock and Dr. Glenn Forney in support of the validation efforts documented in Volume 2 of this report.

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1 INTRODUCTION

1.1 HDR Test Facility and Containment Building

The HDR (Heiss-Dampf Reaktor) facility, shown in Figure 1.1, was the containment building for a decommissioned, experimental reactor in Germany. The building, while smaller in volume than a typical US containment building, contained many features which made it valuable for use in a containment research program. Many of these features also make it extremely valuable as a generic source of test data for industrial facilities. The building was a cylinder approximately 20 m in diameter by 50 m in height topped by a 10 m radius hemispherical dome for a total facility height of 60 m.. Internally the building was divided into eight levels with each level further subdivided into smaller compartments. For a typical HDR test approximately 60-70 compartments were available. Compartments were connected by a variety of flow paths which included doorways, pipe runs, cable trays, hatches, and staircases. Three fixed and two adjustable vertical channels were provided for in the form of an elevator shaft, two staircases, and two sets of equipment hatches running the axial length of the building which could be opened or closed to change the available vertical flow path at each level. Much of the original equipment from the nuclear steam supply system was still present in the facility including the reactor vessel, primary and secondary piping, pumps, electrical connections, and ventilation and exhaust systems. The total free volume of the facility was 11,000 m^3 of which the dome contained 4,800 m^3 above the operating deck. The HDR containment, its compartments, and internal structural materials, vent flow openings and other pertinent data are documented in [1].

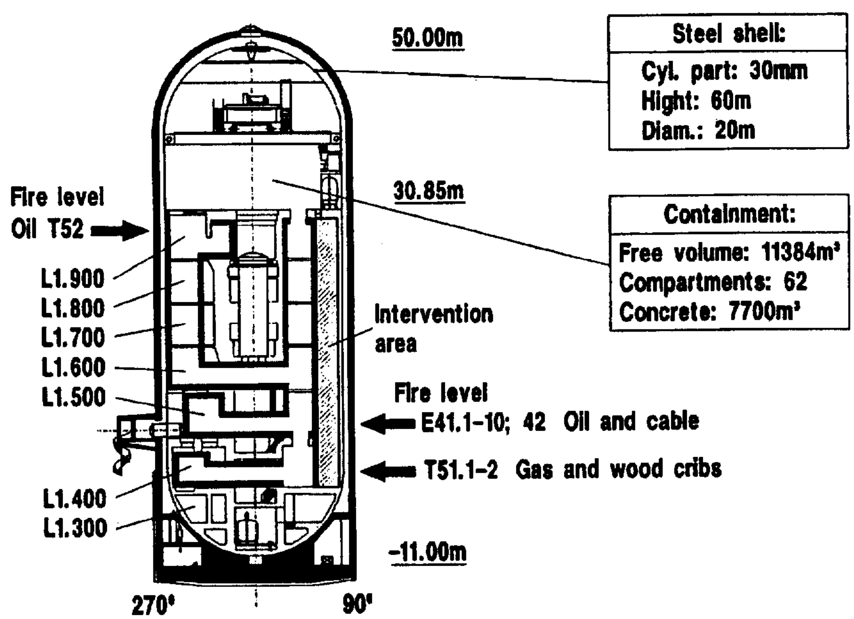

Figure 1.1: HDR Facility and Fire Test Group Locations

1.2 Summary of Fire Test Matrix

From 1984 to 1991 a total of four test series divided into seven fire test groups were performed inside the HDR facility. The fire tests consisted of the T51 series, six propane gas tests, three wood crib tests, and five more propane gas tests; the T52 series, four hydrocarbon oil pool tests; the E41 series, ten hydrocarbon oil pool tests; and the E42 series, three cable fire tests. Figure 1.2 shows the overall test matrix and range of fires powers tested and Figure 1.1 shows the location of the various test series inside the HDR facility. Each test series was performed at a different location inside the containment building as indicated.

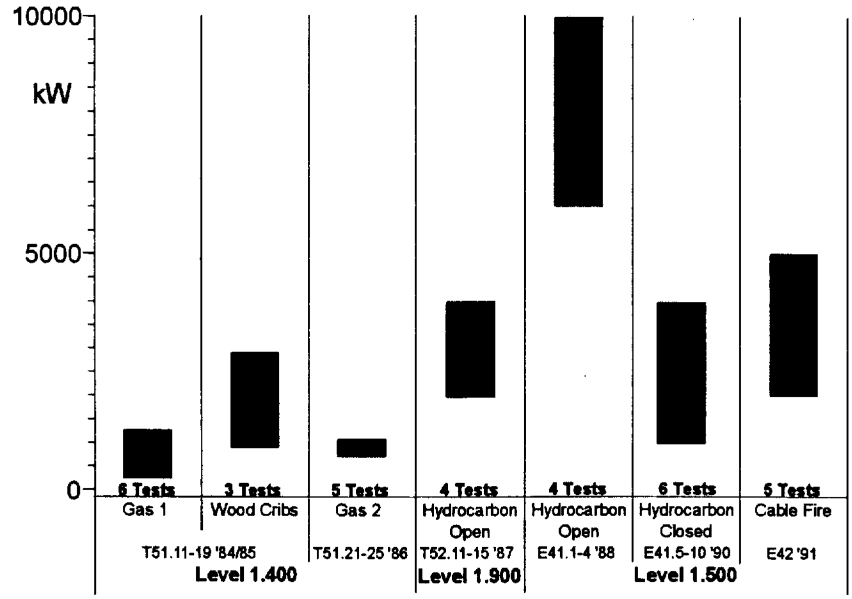

Figure 1.2: Fire Test Group Summary

The fire tests were performed with the following general objectives:

- An improvement in the general understanding of fire phenomena including smoke and aerosol production, distribution, and removal; temperature and pressure changes; and transient combustion in a large scale building.
- A better understanding of the effects of boundary conditions on fire phenomena.
- The creation of a large database for fire model and fire computer code validation.
- An increase in the ability to plan for successful fire fighting and rescue operations inside a burning high-rise structure.

The multi-level, multi-compartment structure of the HDR facility with its vertical shafts, large dome, and concrete and steel construction means that subsets of the fire test database have applications outside the nuclear industry. In general the fire test data can be used to gain insight on many industrial and commercial facilities as most share basic HDR features such as being a multilevel, steel and concrete structure with ventilation systems. More specifically, data from the large dome can be applied to hangars and atrium spaces. Data from the vertical shafts can be applied to any facility containing elevators, large vertical pipe channels, etc.

Each individual test series had its own specific objectives, which have been specified in the respective test series Design Report containing all pertinent geometric data, initial and boundary conditions, instrumentation plan, test procedures, and summary descriptions of the computer codes that participated in the pre-test and post-test computations. Data Reports were issued right after the experiments were performed and contained corrections/modifications of test procedures, qualification of the sensor operability and quality as well as all measured data in plots. All documented data have been stored on the PHDR data bank with the same format and sensor descriptions as used in all other HDR safety research experiments. Quick Look reports present and interpret the data according to the test series objectives and the associated physical phenomena. In addition to the presentation of the data of the individual experiments, results across the test series are documented. Moreover, Quick Look reports contain the comparisons between data and blind pre-test computational results by different models and codes used by the respective group of national and international participants. The Final Evaluation report documents all data assessments from the test series together with final conclusions and open issues. In addition, it contains the comparisons between data and open post-test predictions and identifies the learning effect, model and code improvements observed, lists remaining discrepancies, and open modeling issues. It is the final document for the test series. Section 7 lists all relevant documentation cited above for the respective HDR fire test series. The respective reports will be referenced where applicable in Section 1.3, which summarizes the fire tests.

The T51 test series, performed at the 1.400 level in the lower portion of the containment, was designed to be a relatively low power, exploratory test series in order to determine basic parameters of fire phenomena inside the facility [2-10]. The temperature changes inside of the fire room and the spread of smoke through the building and building ventilation systems was examined to determine safety margins for future, higher powered tests.

The T52 test series, performed just below the operating deck, was designed to simulate a large cable fire through an equivalent oil fire [11-13]. The effects of ventilation systems on smoke movement was examined to assess rescue and fire fighting techniques. One major objective was to measure the plume behavior from the fire into the dome.

The E41 test series, performed in the level above the one for the T51 test series, incorporated experiments that spanned the total range of fire powers examined in the HDR facility [14-20]. Additional parameters examined during this fire test series were the effects of opening and closing doors to the fire room, filter loading rates, and the effects of fire suppression systems.

The final test series, E42, was performed at the same level as the E41 tests. The tests, consisting of cable fires, were to collect data on the burning of prototypical cables in cable trays under natural conditions [21-25]. The fires took place in an completely isolated set of subcompartments to prevent the spread of toxic combustion products, namely dioxin, resulting from the burning of the PVC insulation. A primary objective of these tests was to monitor the propagation of the fire through racks of cable trays in various orientations and to closely examine the spread and impact of combustion products.

Initially, the HDR fire tests were designed, performed, and evaluated solely by the Nuclear Center Kalrsruhe, German universities, industry, and research labs. However, the international nuclear community quickly realized the value of these tests [10]. Which resulted in international support, cooperation, and participation throughout much of the fire testing program at the HDR. Reflecting this is the fact that one of the E42 tests was selected to be a European Commission Standard Problem for the evaluation of computer fire models [24,25].

1.3 Overview of Individual Fire Test Series

With the large variety of fire experiments performed in the HDR over many years, it is important to see where any one particular set of tests fits into the overall database of information. To this end a brief description of each of the fire test groups follows.

1.3.1 Gas Fire Tests (T51.11-T51.15, T51.19, and T51.21-T51.25)

The gas fire tests, the T51 test series [2-10], were the first set of fire experiments performed in the HDR facility, and they are the subject of the remainder of this volume as well as volume 2 [26]. A total of 14 tests were executed between 1984 and 1985. These tests consisted of three subgroups of five gas fires, a single gas fire performed at the end of the wood crib test series [5], and five additional gas fires [6-8,10]. The tests all took place in a specially constructed fire room on the 1.400 level, shown in Figure 1.3, of the HDR facility. This fire room was connected to a hallway which terminated under a vertical shaft formed by open maintenance hatches. Each experiment followed a similar test plan of a short period of pre-fire data collection to record initial conditions, followed by an hour long fire, and ending with approximately half an hour of cool down data collection. The fuel for each of the test was propane gas intended to be premixed with 10% excess air drawn from a vent in room 1.603. For the first group of gas tests no ventilation systems other than the air supply for the gas burners was employed. For the second group of gas tests a vent was constructed which connected the fire room to the 1.600 level. The vent had an adjustable damper which could be controlled during an experiment to change the size of the vent opening.

This first test series had a number of primary objectives. The foremost objective was to demonstrate that fire tests could be performed safely inside the HDR containment building as the integrity of the structure was still regulated as a nuclear facility. Another objective was to determine the extent to which the fire would involve the building in its entirety. A further objective was to examine the ability of the ventilation systems to remove smoke and other fire products. Lastly, data collected during the tests would serve as a initial data for computer code evaluation.

The gas fire tests contain a number of characteristics which pose different of challenges for fire code models. These are:

- The fire room is not a rectangular parallelepiped. The floor cross-section is L-shaped as can be seen in Figure 2.1 of Section 2. This geometric irregularity acts to impede some of the mixing that would otherwise occur in a symmetric compartment.
- The fire source is not a single location on the floor in the center of the room. Rather, there are six gas burners mounted on the wall 0.375 m off the floor along the L-side of the rooms length. Therefor the fire cannot be truly considered a point or local area source for the purpose of evaluating mixing and entrainment using common zone model approaches. Also the presence of the wall that the burners are mounted on prevents the formation of a typical, axi-symmetric plume that is assumed in many fire models.
- The number and selection of burners used varied depending on fire power.
- The doorway of the fire room is located at a corner, rather than at the center of one of the room's walls. As with the shape of the room this affects the mixing that takes place inside the fire compartment.
- The hallway from the fire room terminates in a subcompartment with a narrow vent, 0.5 m high, along the floor and a ceiling vent to a shaft leading to the hemispherical dome. Therefore, a fire model must be capable of handling a large ground level airflow as well as a separate, large buoyant plume in the same compartment.
- The hallway from the fire room is not a rectangular parallelepiped. It is a volume of revolution, a rectangle slowly increasing in width rotated at a fixed distance about an axis.

Table 1.1 on the next page contains a brief summary of the major characteristics of the gas fire tests. Figure 1.3 shows a top view of the fire floor.

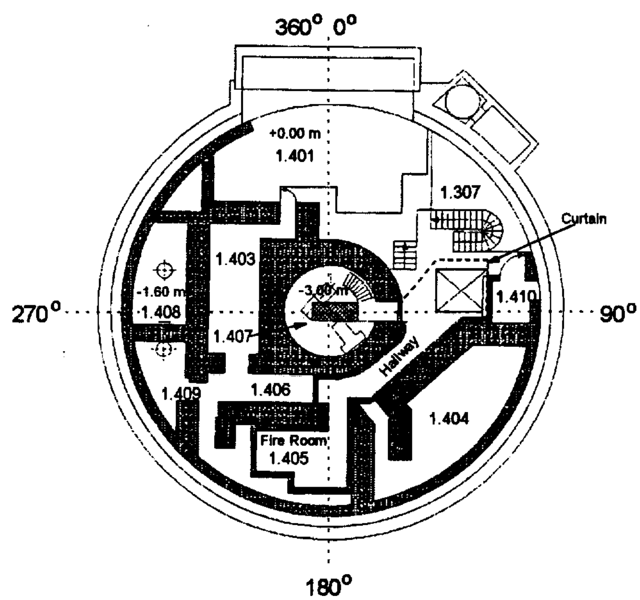

Figure 1.3: Level 1.400, Fire Floor for the T51 Tests

Table 1.1: Gas Fire Test Series Summary

Test	Fire Power (kW)	Gas Consumption (m^3)	Ventilation and Other Test Execution Comments	Burners Used
T51.11	229	8.82	All run with the same configuration with only fire power changing	Burner 3
T51.12	380	14.63		Burners 2,3
T51.13	692	26.62		Burners 2,3,4,5
T51.14	1,025	39.44		Burners 1,2,3,4,5
T51.15	380	14.62	T51.12 with closed vent between 1.600 and 1.700	Burners 2,3
T51.19	1,255	48.30	Increased number of sensors Uses Wood Crib sensor map	Burners 1,2,3,4,5
T51.21	716	27.55	Changes in sensor map Repeat of test T51.13 with vent to 1.600 closed	Burners 1,2,5,6
T51.22	715	27.55	30 minutes with vent 100% open 15 minutes with vent 75% open 15 minutes with vent 25% open	Burners 2,3,4,5
T51.23	1,011	38.98	Repeat of test T51.14 with vent to 1.600 closed	Burners 1,2,3,4,5
T51.24	951	36.58	30 minutes with vent 100% open 15 minutes with vent 75% open 15 minutes with vent 25% open	Burners 1,2,3,4,5
T51.25	985	37.91	30 minutes with vent 100% open 30 minutes with vent closed	Burners 1,2,3,4,5

1.3.2 Wood Crib Fire Tests (T51.16-T51.18)

The wood crib tests were part of the T51 series of experiments [5,8,9]. The wood crib tests, while not a fuel typically available in a nuclear power plant, were added for the benefit of the fire community which does use wood cribs as a standard fire load. Three separate tests of increasing fire power were executed. The tests took place in the same fire room as the gas fire tests. Each test consisted of burning one or more cribs made up of 30 cm x 4 cm x 4 cm beams of pine containing 8% humidity. The beams were nailed together into 15 layers of 4 beams each with adjacent layers having a 90° rotation of the beams, Figure 1.4 shows the construction of a wood crib. A 300 ml reservoir of mineral spirits was used to start the ignition of the wood cribs which were allowed to burn uncontrolled. Electronic scales underneath the wood cribs were used to determine the time-dependent burning rate for use as input functions for the computer code simulations. As compared to propane gas which burns relatively smokeless, these wood crib tests were performed with a main purpose of evaluating the response of the HDR facility and ventilation systems to heavy loadings of smoke in an effort to determine safety margins for future oil fires. The wood crib fires lasted on the order of 30 minutes. Table 1.2 gives some additional details on the wood crib tests.

The wood crib tests produced large quantities of smoke which were quickly distributed throughout the whole containment. This smoke overloaded the building ventilation system's HEPA filters and resulted in adjusting the testing schedule to accommodate the longer time required to clean the containment atmosphere between tests. The smoke was corrosive to the test equipment of other experiments, and some instrumentation was damaged. The smoke deposits of the HDR surfaces also proved difficult to remove, with success only occurring in cleaning of metal surfaces.

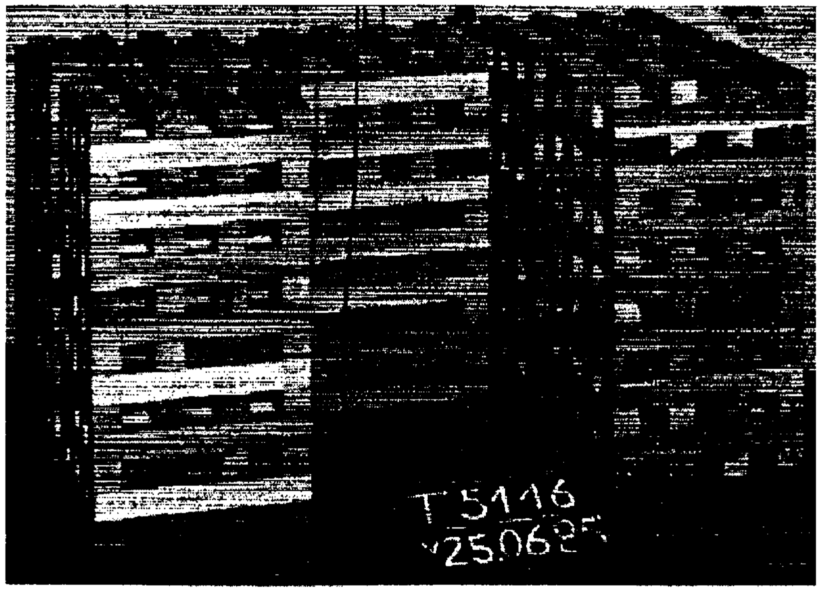

Figure 1.4: Wood Crib Construction

Table 1.2: Wood Crib Fire Test Series Summary

Test	Fire Power (kW)	Wood Consumption (kg)	Ventilation and Other Test Execution Comments
T51.16	1,000	79 (5 cribs)	Start of Wood Crib sensor map. Fires were naturally ventilated and natural convection conditions existed in the containment.
T51.17	1,500	109.8 (7 cribs)	Increase in fire load.
T51.18	2,300	169.1 (11 cribs)	Further increase in fire load.

1.3.3 Oil Fire Test Summary (T52)

The second test series of fire experiments was the T52 oil fire test series which consisted of four oil pool fire tests performed in 1986 [10-14]. The tests ranged in power from two to four megawatts with the fire lasting approximately 30 minutes. Whereas the previous test series, the gas and wood fires, were performed at a level low in the containment building it was decided to position this test series high up in the containment building as shown in Figure 1.1. Thus, the fires were positioned in a special fire compartment constructed on Level 1.900, the level just below the operating deck. It was anticipated that this would confine smoke and soot to the dome region. The fire compartment, shown in Figure 1.5, was located such that it vented directly into the dome through the maintenance hatch next to the spiral staircase. Fuel for the fires consisted of an initial volume of oil in a pool with a surface area ranging from 1 m^2 to 3 m^2 in size.

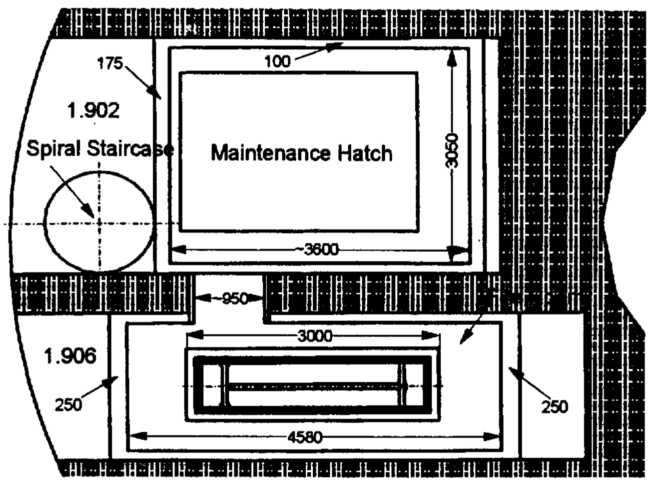

Figure 1.5: T52 Oil Fire Compartment

The initial amount of fuel was augmented by a nozzle feeding a continuous supply of oil once the initial pool was consumed. Each fire lasted approximately 30 minutes. Oxygen for the fires was supplied either by natural convection alone or a combination of forced and natural convection.

For this test series special attention was paid to the buoyant fire plume entering the upper dome. Two-dimensional grids of thermocouples and other sensors were placed at two axial levels within the plume to aid in determining the plume's evolution in the dome.

In addition to the generic purposes of improvements in knowledge about fire dynamics in a complex structure this test series introduced the concept of selective pressurization of test compartments for the prevention of smoke entry in rescue/intervetion areas. For this test series the elevator shaft next to the main staircase, see Figure 1.1, was pressurized and monitored to determine if selective pressurization was indeed capable of maintaining the entire shaft as a relatively smoke free area for the purpose of evacuation or for the staging of emergency personnel.

Some of the significant results are noted on the next page:

- The fires quickly reached flashover conditions, turning the fire room into a large fire ball with heavy soot production.
- As the fire vented directly into the upper dome a large buoyant plume formed whose basic characteristics were measured.
- The large buoyancy forces of the plume rising through the maintenance hatch behaved like a jet pump; that is large quantities of air were entrained into the plume which resulted in a large global circulation inside of the entire facility which widely spread the soot throughout the whole building.
- Provided a sufficient air flow rate was used, the selective pressurization strategy was successful in keeping the elevator shaft free of smoke.
- Due to the high entrainment, fire plume temperatures impinging on the containment steel shell were rather low.

Table 1.3 below summarizes some details on the T52 tests.

Table 1.3: T52 Oil Fire Test Series Summary

Test	Peak Fire Power (kW)	Pool Size (m^2)	Initial Fuel Volume (liters)	Fuel Delivery Rate (liter/min)
T52.11	2,000	1	25	3.72
T52.12	3,000	1	50	5.57
T52.13	4,000	3	75	7.43
T52.14	3,500	3	50	5.57

1.3.4 Oil Fire Test Summary (E41)

The T52 test group indicated that both higher power and longer duration tests could be withstood by the HDR facility. A further set of oil fires, the E41 test group [14-20], was performed to take advantage of this. This test group, which consisted of ten tests ranging in power from six to ten megawatts, took place on the 1.500 level of the containment building. As with the other test groups a specially prepared fire compartment was used for this series. This compartment, shown in Figure 1.6, was significantly larger than compartments for the other tests and included sprinkler systems, ventilation systems, and a remotely operated doorway. For this test series the building ventilation systems were equipped with different types of filter setups. Furthermore, autonomous, aerosol measurement devices were added to the sensor equipment.

The addition of extra features to the fire room and ventilation system allowed the examination of some additional fire phenomena. Filter loading and clogging was examined through the use of the different filter systems. The effects of steam release into the fire room was examined. The interrelationships of doorway openings and mechanical ventilation were explored. The selective pressurization strategy was examined further. Tables 1.4 and 1.5 provide details on this test group. Note that each test in the latter portion of this test series actually consists of a series of individual subtests.

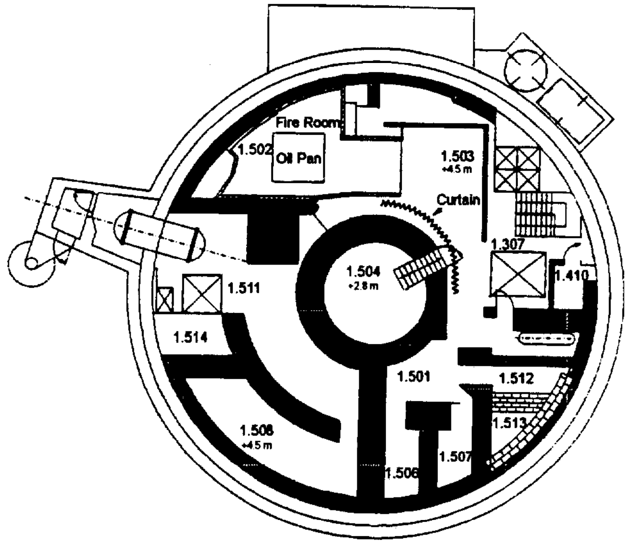

Figure 1.6: E41 Oil Fire Compartment

Some of the significant results of this test group are given below:

- Fire extinguishing systems were tested under extreme conditions of fire power and temperature due to the high fire powers, as high as 10 MW, in the fire compartment.
- Spatial and temporal distributions of aerosols were measured at different locations.
- Depending on the ventilation system settings a variety of flow circulation modes were observed inside the containment building.
- Selective pressurization of the elevator shaft was again successful in preventing smoke from entering this rescue shaft.
- Filters continued to become overloaded with soot even when a prefiltered bank consisting of coarse filters was added to the filtration system.

Table 1.4: E41.1-10 Oil Fire Test Series Summary

Test	Pool Size (m^2) and Pool Wall Material	Fuel Volume* (l)	Max Power (kW)	Fire Duration (min)
E41.1	3 (steel)	224	7,055	17
E41.2	2 (steel)	150	4,016	20
E41.3	2 (steel)	224	4,798	25
E41.4	2 (steel)	224	5,452	22
E41.5	2 (steel)	20	850	78
E41.6	2 (steel)	60	4,250	68
E41.7	2 (steel)	40	5,100	65
E41.8	2 (steel)	40	3,400	74
E41.9	1.7 (concrete)	48	4,250	43
E41.10	1.7 (concrete)	40	2,550	50

*For tests E41.5-10 the fuel volume represents the initial pool volume.

Table 1.5: E41.5-10 Oil Fire Test Subsection Summary

Test	Subsection	End Time (min)	Fuel Addition (kg/s)	Door
E41.5	E41.51a	5	Initial Volume	Closed
	E41.51b	20	0.01	Closed
	E41.52	35	0.01	Closed
	E41.53	50	0.02	Closed
	E41.54	65	0.05-0.07	Closed
	E41.55	90	0.07	Door 1,45°
E41.6	E41.61	15	Initial Volume	Closed
	E41.62	30	0.01	Door 1,45°
	E41.63	45	0.02	Door 1,45°
	E41.64	60	0.02	Door 1 Open
	E41.65	75	0.01	Both Open
	E41.66	80	None	Both Open
E41.7	E41.71	15	Initial Volume	Closed
	E41.72	30	0.1	Door 1 Open
	E41.73	45	0.02	Closed
	E41.74	60	0.1	Both Open
	E41.75	75	.03-.05	Door 1 Open
	E41.76	90	.03-.05	Door 1, 45°
E41.8	E41.81	15	Initial Volume	Both Open
	E41.82	30	0.1	Both Open
	E41.84	45	0.1	Door 1 Open
	E41.84	60	0.03-0.05	Door 1 Open
	E41.85	75	0.03-0.05	Door 1 Open
	E41.86	90	None	Closed
E41.9	E41.91	15	Initial Volume	Both Open
	E41.92	30	0.1	Both Open
	E41.93	45	0.1	Door 1 Open
	E41.94	60	0.05-0.07	Closed
	E41.95	75	0.01	Closed
	E41.96	90	None	Closed
E41.10	E41.101	15	Initial Volume	Closed
	E41.102	30	0.05	Door 1 Open
	E41.103	45	0.03	Closed
	E41.104	60	0.05	Door 1, 90°
	E41.105	75	0.05	Closed

1.3.5 Cable Fire Test Summary (E42)

The cable fire test group was the last set of fire experiments performed in the HDR and had the primary purpose of evaluating the effects of a prototypical fire using real fuel sources, e.g. the electric power and instrumentation cables used in power plants [21-25]. Due to concerns of dioxin production from the PVC cable insulation, this test group was performed in an isolated subset of compartments on the 1.500 level which is shown in Figure 1.7. Additional partitions and ventilation and fire extinguishing systems were constructed on this level to prevent the spread of toxic combustion products through the rest of the facility and into the local environment. Three tests involving different amounts and types of cables were performed. It is important to note that the fire compartments were completely sealed for the duration of this test series which created problems in determining the exact fuel source available or consumed during any given test. As shown in Figure 1.8, before the first test, E42.1, many of the cable trays were wrapped in Alsiflex mats in an attempt to prevent the combustion of those cables during the first test. Attempts were made to isolate specific cable trays from burning by covering some of the cable trays in Alsiflex blankets which could be removed for other tests. The blankets did not completely prevent combustion of the protected cables; that plus a lack of information on the fraction of exposed cables which completely burned results in an uncertainty in specifying the exact fuel source available and consumed during each test.

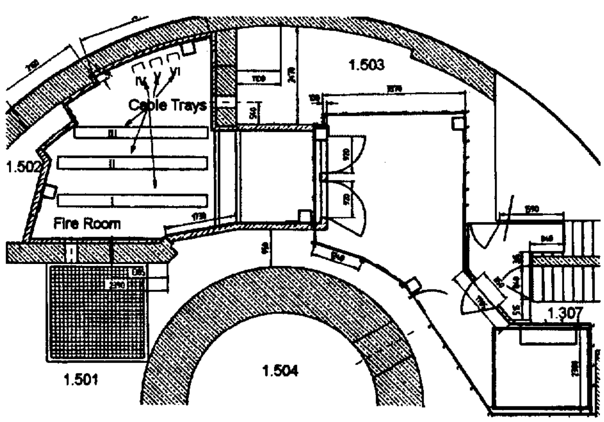

Figure 1.7: E42 Cable Fire Room

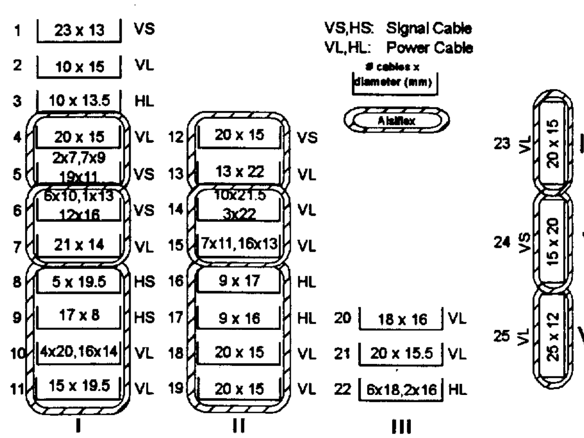

Figure 1.8: Cable Tray Layout

Some of the important results from the E42 test series are given below:

- Depending on the particular configuration of available cables the cables fires were either self sustaining to the point of flashover or burned out after a short period of time.
- Dioxin production from the PVC insulation was not detectable/measureable.
- The fires were capable of becoming intense enough to burn the cables underneath the Alsiflex blankets.
- The presence of the blankets actually acted to prolong fires as they prevented water from the sprinklers from reaching the cables under the blankets.

2 FACILITY DESCRIPTION

2.1 Compartment Layouts for the T51 Gas Fire Tests

2.1.1 Fire Floor (Level 1.400)

To avoid damaging the structure of the HDR facility, as the building was still considered a nuclear facility, a special set of fire test rooms was prepared at the 1.400 level of the containment building, see Figure 1.1 for the location of the 1.400 level. These rooms also served to control the flow of gases in and out of the fire room. Figure 2.1 shows a cross section view of the 1.400 level and indicates the location of these rooms which consisted of the fire room with a narrow doorway, a long hallway wrapping around the reactor vessel shield wall, and a curtained area centered beneath the maintenance hatch next to the main staircase. For the remainder of the facility no special precautions were undertaken with respect to insulation as gas temperatures outside the fire floor were anticipated to be below damage causing levels. Table 2.1 below gives the geometric data of the prepared compartments [2].

Table 2.1: Fire Compartment Dimensions

Compartment	Height (m)	Area (m2)	Volume (m3)	Doorway (m wide x m tall)	Hatch (m x m)
Fire Room	2.750	9.66	26.58	1.01x1.975	N/A
Doorway	1.975	1.51	2.99	1.01x1.975	N/A
Hallway	2.485	11.16	22.15	1.80x2.485	N/A
Curtained	5.350	11.83	63.29	7.40x0.50	2.3x2.0

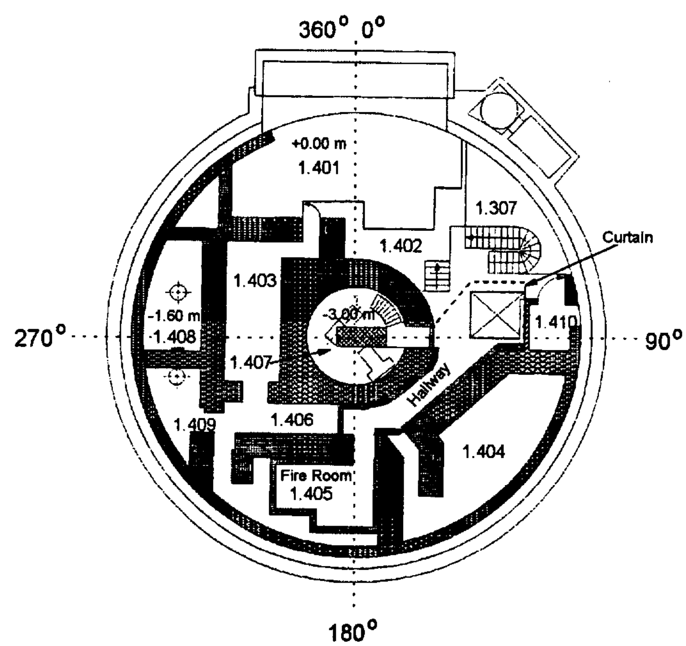

Figure 2.1: Fire Floor at Level 1.400 for T51 Gas Fire Tests

The fire room, vertical cross section through the 0-180° line and horizontal cross section at the +0.0 m elevation are shown in Figure 2.2, was constructed inside of room 1.405. The floor, walls, and ceiling of the fire room were lined with 25 cm of Ytong fire brick. The ceiling, which would be exposed directly to the fire plume, had additional protection in the form of a 3 cm thick layer of Alsiflex fireproof matting. Alsiflex is a ceramic fabric. The floor of room 1.405 below the Ytong fire bricks consisted of a 1 m thick layer of concrete coated with a 1.5 mm thick coating of paint. Along the wall of the fire room opposite the doorway were the six gas burners used for the gas fire tests, as shown in Figure 2.2. The gas burners were mounted 0.675 m above the floor of room 1.405 or 0.425 m above the brick lining of the fire room. In addition to the gas burners the fire room also contained a viewport for a video camera as shown as item 8 in Figure 2.5 and for the T51.2 group of tests a 400 mm diameter ventilation duct leading to the 1.600 level was installed above the video port, shown as item 7 in Figure 2.5.

The doorway to the fire room had the same construction as the fire room itself. The doorway's height was less than both that of the fire room and the hallway.

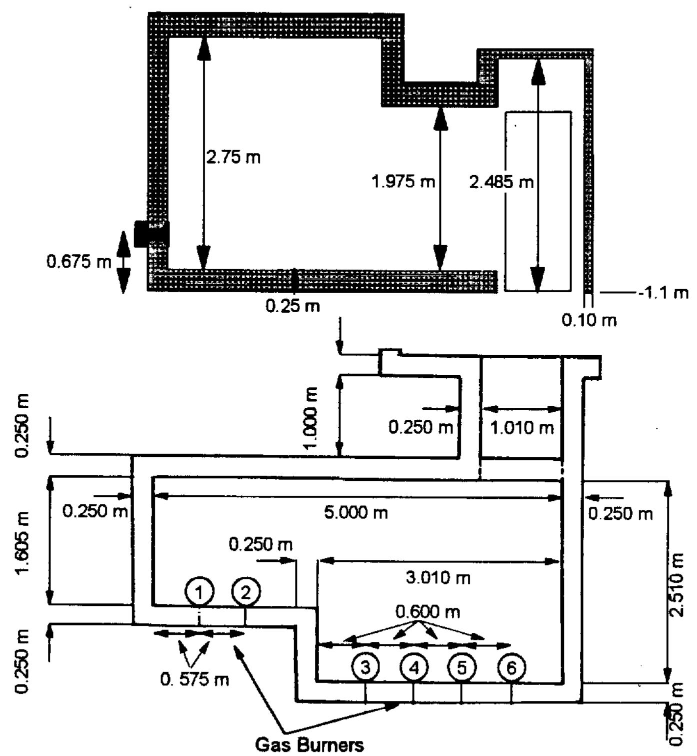

Figure 2.2: Fire Room and Doorway

The hallway, its top view shown in Figure 2.3, was constructed inside of room 1.406. This compartment wrapped around the reactor vessel shield wall, thus, the walls along the length are not parallel planes, but instead are concentric arcs. The doorway from the fire room enters the hallway slightly off set from the end of the hall. The walls and ceiling of the hallway were constructed of a 10 cm thick layer of Ytong fire brick. The floor of the hallway was not insulated and was of the same concrete and paint as in the fire room. This results in the floor of the hallway being 25 cm below the floor of the fire room and doorway. The hallway had a constant ceiling height, and its width varied from 1.14 m at the door to the fire room to 1.8 m at the entrance to the curtained area. This variation results from the curvature of the hallway and the general layout of neighboring compartments.

The curtained area, shown in Figure 2.4, was constructed next to the main staircase under an open maintenance hatch and was created primarily to force flue gasses from the fire away from the inside steel shell and up through the vertical shaft of the open maintenance hatches. This area was created by draping Alsiflex mats from the ceiling down to 0.5 m above the floor. This 0.5 m gap served to enhance the cold air return flow to the fire room and to force a better separation of the hot and cold gas streams. It is important to note that the gap below the curtain opened up towards both the main staircase and towards compartment 1.403 which had a floor elevation that was 1.1 m above the floor of the fire hallway or 0.6 m above the top edge of the gap beneath the curtain. The floor of the compartment below the hatch consisted of a 0.6 m thick layer of concrete protected by a 1.5 mm thick paint coating. The ceiling around the open maintenance hatch consisted of a 0.25 m thick layer of concrete protected with a 1.5 mm thick paint coating.

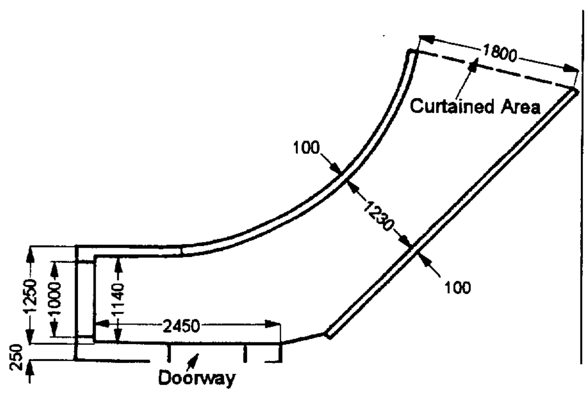

Figure 2.3: Fire Level Hallway

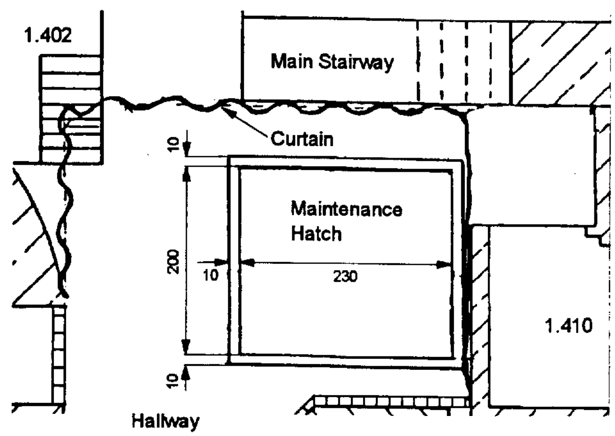

Figure 2.4: Curtained Area

Figure 2.5 shows a perspective view of all the added enclosures indicating (1) the fire room, (2) the doorway, (3) the hallway, (4) the area inside the curtain, (5), the curtain, (6) the maintenance hatch, (7) the 400 mm vent pipe for the T51.2 tests, and (8) a window for viewing the fire with a video camera.

2.1.2 Vent Floor (Level 1.600) and Vent Pipe

As mentioned previously all of the gas fire tests fed the burners propane gas premixed with air drawn from compartment 1.603 as shown in Figure 2.6. The T51.2 tests added some additional complexity to the fire room in the form of a ventilation duct which connected the fire room to compartment 1.611, the compartment containing the spiral staircase on the 1.600 level. This is also shown in Figure 2.6. The exit of the duct on the 1.600 level was centered beneath the open maintenance hatch located in the ceiling of compartment 1.611. The maintenance hatch leading down towards the 1.500 level from compartment 1.611 was closed for all test in the T51 series;

however, all hatches above level 1.600 were open all the way up to the dome and served as another vertical shaft.

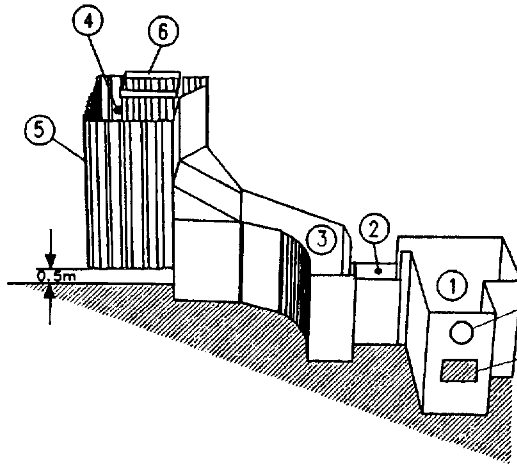

Figure 2.5: Perspective View of Level 1.400 Fire Compartments

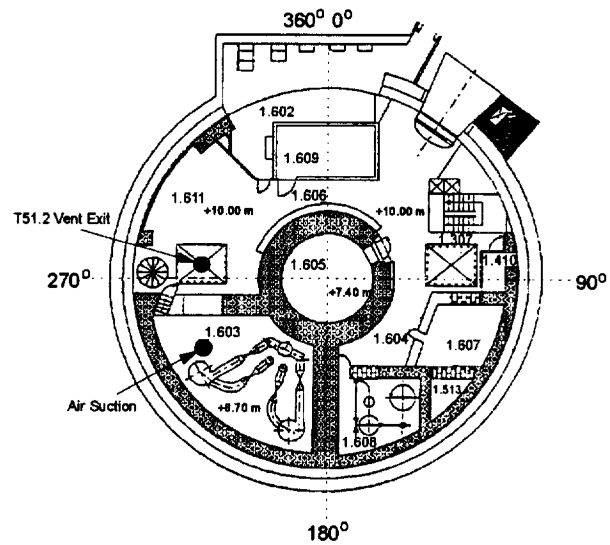

Figure 2.6: Fresh Air Suction and T51.2 Fire Room Vent Exit on Level 1.600

The additional ventilation duct was an insulated, circular pipe 400 mm in diameter. The duct contains two valves. The first valve either opened or closed the duct. The second valve, located at the duct exit into 1.611, was a louvered, regulating valve which was used to change the vent opening during the tests. The 2 m of the duct connecting to the fire room was insulated with a 3 cm layer of Alsiflex on both the inner and outer surfaces of the duct. The remainder of the duct is insulated with a 3 cm layer of Alsiflex on the outer surface only. Figure 2.7 shows the duct layout in relation to the rest of the facility.

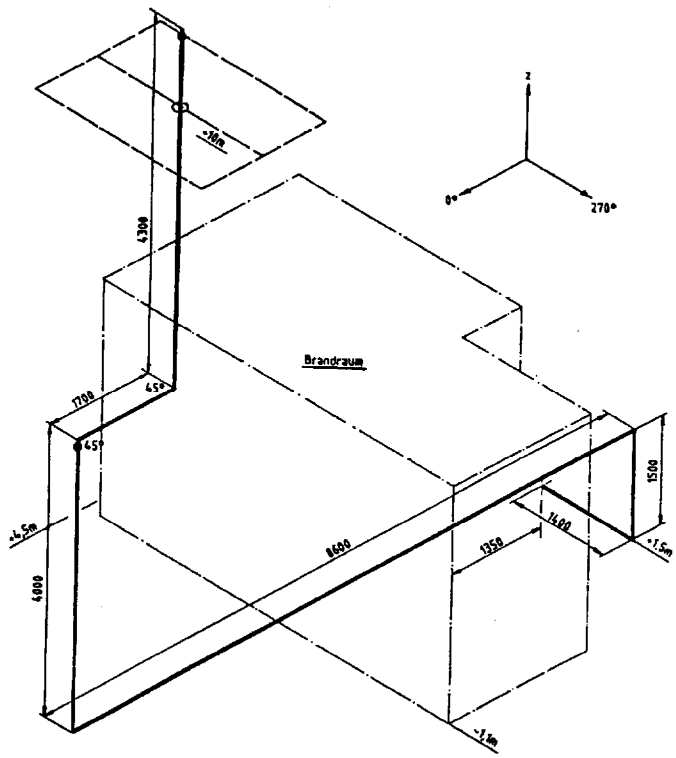

Figure 2.7: T51.2 Additional Ventilation Duct

2.1.3 Facility Remainder

The following two tables, Tables 2.2 [1,26-28] and 2.3 [1,26-28], give volumes for the different compartments in the HDR facility as well as the sizes of the major room interconnections available during the gas fire tests. Details on the layout of the HDR compartments can be located on the instrumentation maps shown in section 3.

Table 2.2: HDR Compartment Volumes

Compartment Number	Volume (m^3)	Elevation (m)	Height (m)	Comments
1.201	152	-8.50	1.80	
1.202 1.203 1.303	78	-9.20	5.80	Separate volume information not given for these compartments.
1.301	206	-5.80	5.30	
1.302	93	-5.80	3.60	
1.304	39	-5.80	3.60	
1.305 1.311	63	-4.80	4.60	Separate volume information not given for these compartments.
1.307	58	-5.80	4.10	Main staircase level 1.300
1.308	102	-5.80	3.60	

Compartment Number	Volume (m^3)	Elevation (m)	Height (m)	Comments
1.317	63	-1.10	5.45	Main staircase level 1.400
1.327	61	4.50	5.25	Main staircase level 1.500
1.337	40	10.00	4.80	Main staircase level 1.600
1.347	83	15.05	4.70	Main staircase level 1.700
1.357	40	20.60	4.65	Main staircase level 1.800
1.367	82	25.30	5.30	Main staircase level 1.900
1.401	296	0.00	4.10	Not open during gas fire tests.
1.402	40	0.00	3.50	No volume found, estimated from floor area.
1.403	76	-1.10	4.60	
1.404	116	-1.10	4.60	.
1.405	95	-1.10	4.60	Includes volume of fire room
1.406	266	-1.10	4.60	Includes volume of fire hallway and curtained area.
1.407	84	-3.00	5.00	
1.408	59	-1.60	4.60	
1.409	37	-1.10	4.60	
1.410	113	-2.60	39.90	Elevator shaft. Not open for T51
1.501 1.506 1.507 1.512	158	4.50	4.50	Separate volume information not given for these compartments.
1.502	107	4.50	4.50	
1.503	304	4.50	5.25	
1.504	57	2.80	3.40	
1.505	10	4.50	4.50	
1.508	57	4.50	4.50	
1.511	222	4.50	5.00	
1.513	8	3.50	8.80	Not open during gas fire tests.
1.514	13	4.50	5.00	
1.602	61	10.00	4.75	Not open during gas fire tests.
1.603	280	8.70	7.70	
1.604	25	10.00	3.25	
1.605	78	7.40	4.70	
1.606	183	10.00	4.60	
1.607 1.608	87	10.00	3.40	Separate volume information not given for these compartments.
1.609	59	10.00	4.75	Not open during gas fire tests.
1.611	192	10.00	4.75	
1.701u	64	13.85	3.90	
1.701o	44	20.60	2.50	
1.702	54	15.05	4.20	Not open during gas fire tests.

Compartment Number	Volume (m^3)	Elevation (m)	Height (m)	Comments
1.703	83	15.05	4.20	
1.704 1.901	805	14.25	15.60	Separate volume information not given for these compartments.
1.706	19	15.05	4.20	Not open during gas fire tests.
1.707	119	15.05	4.20	
1.708	90	15.05	5.35	
1.801	343	21.05	9.80	
1.802	125	20.60	7.10	
1.804	79	20.60	5.00	
1.805	58	20.60	5.00	
1.902	90	25.30	4.50	
1.903	71	25.30	4.50	
1.904 1.905 1.803	164	20.60	4.60	Separate volume information not given for these compartments.
1.906	62	25.30	4.50	
Lower Dome	2,153	30.85	9.15	Cylindrical portion of dome
Upper Dome	2,660	40.00	10.00	Hemispherical portion of dome

Table 2.3: HDR Room Interconnections for the T51 Gas Fire Tests

Connects		Type	Width (m)	Height (m)	Depth (m)	Comment	Connects		Type	Width (m)	Height (m)	Depth (m)	Comment
Room 1	Room 2						Room 1	Room 2					
1.201	1.202	C	0.2	0.2	1		1.201	1.203	C	0.2	0.2	1	
1.201	1.308	P	1	0.5	0.82	2 of these	1.201	1.301	P	0.45		0.7	Width is diam.
1.201	1.301	P	0.35		0.8	Width is diam.	1.201	1.301	W	0.1	0.9	0.1	
1.202	1.302	P	0.28	0.51	4	Min. opening	1.203	1.305	P	0.28	0.56	4	Min. opening
1.301	1.302	W	0.1	0.15	0.5		1.301	1.302	P	0.3	1	11.9	Min. opening
1.301	1.302	P	0.1	0.4	5.2		1.301	1.303	P	0.5	0.5	1.2	2 of these
1.301	1.308	W	1.27	1.77	1.15		1.301	1.408	W	1.2	1	0.35	
1.302	1.308	B	0.1		0.5	Width is diam. 22 of these	1.302	1.308	D	0.66	1.97	0.6	Min. opening
1.302	1.408	P	1.1	0.6	0.54	2 of these	1.302	1.408	P	0.7	0.6	0.54	
1.302	1.408	P	1.3	0.6	0.54		1.302	1.409	B	0.13		0.6	Width is diam. 2 of these
1.302	1.502	P	0.93		5	Width is area (m^2)	1.303	1.308	B	0.1		1.29	Width is diam. 22 of these
1.303	1.308	D	1.9	0.96	1.02	Min. opening	1.303	1.407	P	0.9	0.55	0.81	Min. opening
1.303	1.407	P	0.3	1.45	0.8		1.304	1.305	P	0.32	0.54	0.4	
1.304	1.305	W	2.5	3.73	0.43		1.304	1.308	D	0.56	1.9	1	Min. opening
1.304	1.308	O	1.2	2	0.4	Min. opening	1.305	1.308	W	1.52	2	0.4	Min. opening
1.305	1.308	D	0.55	1.98	0.48	Min. opening	1.308	1.404	P	2.1	0.7	1.05	
1.307	1.317	S	1.8			Width is area (m^2)	1.402	1.403	D	0.54	1.82	2.8	Min. opening
1.403	1.406	W	0.5	1.21	1.05	1.4	1.403	1.406	P	1	1.2	2.18	
1.403	1.511	W	2.3	2.3	1	1.4	1.403	1.406	C	0.4	0.25	0.8	
1.404	1.507	0.07			1.05	Width is area (m^2)	1.405	1.406	W	2.72	1.9	1.05	
1.406	1.409	D	0.56	1.9	1		1.406	1.501	P	3.35			Width is area (m^2)
1.407	1.504	C	0.19		1.89	Width is diam. 6 of these	1.408	1.502	P	0.4	0.84	1	
1.317	1.327	S	3.61			Width is area (m^2)	Fire Room	Hallway	D	1.01	1.98	1.5	Fire room doorway
Hallway	Curtained Area	D	1.8	2.485			Curtained Area	1.501	M	4.54		0.57	Width is area (m^2)

Connects		Type	Width (m)	Height (m)	Depth (m)	Comment
Room 1	Room 2					
Curtained Area	Main Staircase	O	4.3	0.5		Gap under curtain
1.501	1.511	B	0.06		1.2	Width is diam.
1.502	1.503	B	0.08		0.5	Width is diam. 4 of these
1.502	1.511	B	0.08		0.5	Width is diam. 7 of these
1.502	1.511	C	0.66	0.15	0.5	
1.502	1.611	P	0.7	2.2	0.5	
1.503	1.511	W	1.08	3.67		
1.503	1.605	C	0.27		2.9	Width is diam.
1.504	1.605	W	0.08		1.2	Width is area (m^2)
1.506	1.508	W	0.95	1.5	1.22	
1.508	1.511	D	0.55	1.92	0.1	
1.511	1.611	C	0.14		0.57	Width is area (m^2) 2 of these
1.327	1.337	S	3.2			
1.603	1.606	W	5.5		1.2	Width is area (m^2)
1.603	1.608	W	1	1	1.2	
1.603	1.704	C	1.7	0.5	1.4	
1.603	1.704	W	1.8	2	4	
1.603	1.708	O	2	1.64	1.2	Min. opening
1.606	1.704	P	0.5	0.5	3	Width is diam. 5 of these
Curtained Area	1.402	O	2	0.5		Gap under curtain
1.501	1.606	P	2.55			Width is area (m^2)
1.502	1.503	D	0.5	1.95	1.58	Min. opening
1.502	1.511	C	0.47	0.42	0.5	
1.502	1.603	P	0.8	0.7	5	Min. opening
1.503	1.504	D	0.96	2	1.15	Min. opening
1.503	1.603	C	0.27		2.9	Width is diam.
1.503	1.605	C	0.16			Width is area (m^2)
1.505	1.607	W	0.12		1.06	Width is area (m^2)
1.507	1.608	P	0.41	1	1.05	
1.501	1.606	M	4.54		0.57	Width is area (m^2)
1.603	1.605	W	0.3	0.67	1.3	
1.603	1.606	D/S	1.6	0.69	2.8	Min. opening
1.603	1.608	W	0.6	0.47	1.2	
1.603	1.704	W	1.64		0.15	Width is area (m^2)
1.603	1.704	C	0.39	0.4	1.9	Min. opening 3 of these
1.605	1.606	C	0.3		2.3	Width is diam. 5 of these
1.605	1.701u	B	1.37		2	Width is area (m^2) 2 of these
1.606	1.707	P	3.58			Width is area (m^2)

Connects		Type	Width (m)	Height (m)	Depth (m)	Comment	Connects		Type	Width (m)	Height (m)	Depth (m)	Comment
Room 1	Room 2						Room 1	Room 2					
1.606	1.707	M	4.54		0.5	Width is area (m^2)	1.606	1.708	M	4.81		0.6	Width is area (m^2) Spiral stair
1.606	1.708	S	0.74		0.42	Width is area (m^2) Spiral stair	1.607	1.704	P	0.5	0.5	1.06	
1.608	1.704	W	0.3	0.14	1.3		1.608	1.704	C	0.4	0.4	1.9	
1.611	1.703	C	0.25	1.74	0.56		1.337	1.347	S	3.39			Width is area (m^2)
1.701u	1.701o	W	1.7		3	Width is area (m^2)	1.701o	1.704	P	0.7	0.48	1.75	Min. opening 2 of these
1.701o	1.704	W	1.3	1.8	1.6	Min. opening	1.701o	1.704	B	0.52		1.75	Width is diam.
1.701o	1.704	C	0.6	0.6	1.6	2 of these	1.701o	1.707	B	0.3		3	Width is diam.
1.701o	1.804	C	0.4	0.6		Min. opening	1.701o	1.805	B	0.08		2	Width is area (m^2) 3 of these
1.703	1.707	D	0.84	2.01	0.28	Min. opening	1.704	1.707	D	2.09	0.62	2.37	Min. opening
1.704	1.804	P	0.79	0.6	2.27		1.704	1.805	B	0.25		1.24	Width is diam. 2 of these
1.704	1.901	W	0.8	0.6	0.8		1.704	1.903	W	1.64		0.15	Width is area (m^2)
1.704	1.904	B	0.55		1.25	Width is diam.	1.704	1.906	W	1.6		1.3	Width is area (m^2)
1.707	1.805	P	2.32			Width is area (m^2)	1.707	1.805	M	4.54		0.5	Width is area (m^2)
1.708	1.804	M	4.81		0.6	Width is area (m^2) Spiral stair	1.708	1.804	S	0.74		0.42	Width is area (m^2) Spiral stair
1.347	1.357	S	3.24			Width is area (m^2)	1.801	1.905	W	4.5			Width is area (m^2)
1.802	1.804	D	0.63	0.2	0.4		1.802	1.902	D	0.94	1.87	0.4	
1.802	1.902	W	0.4	0.23	0.4		1.802	Dome	W	0.4	1.2	1.52	
1.804	1.902	M	4.81		0.6	Width is area (m^2) Spiral stair	1.804	1.902	S	0.74		0.42	Width is area (m^2) Spiral stair

Connects		Type	Width (m)	Height (m)	Depth (m)	Comment	Connects		Type	Width (m)	Height (m)	Depth (m)	Comment
Room 1	Room 2						Room 1	Room 2					
1.805	1.903	P	2.32			Width is area (m^2)	1.805	1.903	M	4.54		0.5	Width is area (m^2)
1.357	1.367	S	3.24			Width is area (m^2)	1.902	1.906	P	0.3	0.5	0.5	2 of these
1.902	Dome	W	0.4	0.2	0.4	2 of these	1.902	Dome	W	0.45	2.65	0.4	
1.902	Dome	M	4.81		0.6	Width is area (m^2) Spiral stair	1.902	Dome	S	2.06		0.42	Width is area (m^2) Spiral stair
1.903	Dome	P	2.32			Width is area (m^2)	1.903	Dome	M	4.54		0.5	Width is area (m^2)
1.906	Dome	C	0.2	1.3		Width is diam.	1.367	Dome	S	3.25			Width is area (m^2)

2.2 Thermophysical Material Properties

2.2.1 Thermophysical Wall Surfaces Properties

There were five different materials which were used as compartment surfaces within the HDR facility. Alsiflex mats and Ytong firebrick were used to create the fire room and hallway on the 1.400 level. In general, rooms in the HDR facility had painted concrete for the room surfaces with a different paint used for the floor than was used on the other room surfaces. Tables 2.4 and 2.5 gives the known thermophysical properties for these materials [16].

Table 2.4 :Material Properties for Room Surfaces

Material	Density (kg/m^3)	Specific Heat (kJ/kg K)	Thermal Conductivity (W/m K)
Alsiflex Mats	130	1,000	See Table 2.5
HDR Concrete	2,225	879	2.10
HDR Floor Paint	1,540	1,280	0.29
HDR Wall Paint	1,250	1,550	0.20
Ytong Fire Brick	340	950	See Table 2.5

Table 2.5 :Thermal Conductivities for Room Surfaces

Material	Thermal Conductivity (W/m K)				
	100 °C	300 °C	500 °C	800 °C	1000 °C
Alsiflex Mats	0.05	0.05	0.10	0.18	0.25
Ytong Fire Brick	0.09	0.15	0.19	0.23	0.24

2.2.2 Thermophysical Fuel Properties

Propane gas was used as the fuel for the T51 test series. The gas was intended to be premixed with 10% excess air before being injected into the fire room through the gas burners. Some basic data on propane is given below [9]:

Chemical Formula:	C_3H_8
Molecular Weight:	44 g/mol
Heat of Combustion:	2044 kJ/mol C_3H_8
	4.65×10^4 kJ/kg C_3H_8
Oxygen Required:	5 mol O_2 /mol C_3H_8
	3.64 kg O_2 /kg C_3H_8
Oxygen Supplied:	5.5 mol O_2 /mol C_3H_8
	4.00 kg O_2 /kg C_3H_8

3 INSTRUMENTATION LAYOUT

3.1 Introduction

Because the fire research experiments were added to the HDR Safety Program about midway in the course ist of execution, the development of an instrumentation plan and the selection of the sensor types rested upon tested and proven measurement technologies. These technologies were successfully applied during the previous HDR containment experiments. This proved to hold for the majority of typical pressure and temperature sensors. However, it was apparent from the outset that the fire experiments had somewhat different instrumentation criteria owing to the high temperature, low flow, and corrosive environment that the sensors would be exposed to.

Therefore, the T51.1 experiments opened up new challenges for the instrumentation, especially because all previous expertise resulted from high-momentum driven flows only. On the other hand, the fire experiments required reliable instrumentation for buoyancy driven flows with much lower velocities and much higher temperatures.

Given all these circumstances, test series T51.1 served as an exploratory test bed for advanced instrumentation such as velocity sensors, gas concentration sensors, smoke detection sensors, and other fire related sensors. The outcome of these qualification tests served as input for a qualified and expanded instrumentation plan for T51.2.

In addition to the sensor qualification issues, numerous questions arose regarding:

- safety procedures (injecting explosive gases in the building and the effects of high temperature loads on the structure)
- the optimal placement of a limited number of sensors and sensor types.

Answers and resolution guidance for both issues for all previous HDR experiments commonly rested on so-called design computations representing a broad spectrum of different approaches and models plus compliance with industrial codes and regulatory standards.

In the case of the T51 fire experiments, all analytical and computational methods at that time were limited to treat only single compartment, single burning object and single vent flow opening. The resultant predictions were naturally overly conservative because they did not account for multi-compartment geometry, counter-current flows of hot and cold gas streams and associated mixing as well as heat transfer to structures.

Therefore, safety measures and experimental procedures were extremely stringent and conservative, such as the installation of the curtain at the end of the hallway in order to keep the hot flue gas layer away from the inside surface of the containment steel shell.

Equally, the instrumentation plan for T51.1 was primarily geared towards safety rather than towards physical phenomena. This concept was changed for test series T51.2 once the experimental results for T51.1 clearly indicated the immense importance of mixing processes and much reduced thermal loads on the structures. These details should be kept in mind when reading the subjects about sensor types and instrumentation maps described Tables 3.1 through 3.3 along with their accompanying figures of facility cross-sections and instrument positions..

3.2 Objectives and Requirements

With the background knowledge from the previous section, the instrumentation for T51.1 was designed to encompass the following elements:

1. Instrumentation in the Fire Room:
   - 20 thermocouples in the fire room and door vent opening
   - 10 thermocouples at/in the structures
   - pressure sensor in the fire room
   - heat transfer instrumentation in the fire room and neighboring compartments

2. Instrumentation in the Containment:
   - thermocouples and pressure sensor from previous containment blowdown experiments
   - several flue gas analysis sensors
   - heat transfer blocks from previous containment blowdown experiments
   - pitot tube sensors
   - determination of smoke density
   - miscellaneous special sensors as describe in Section 3.3

3. Instrumentation of Exhaust
   - thermocouples and velocity sensors

4. Safety Instrumentation for Protection of the Containment's Steel Shell Integrity
   - thermocouples along the height of the vertical staircase/maintenance shafts
   - thermocouples in the reactor dome above the operating deck
   - thermocouples at inside and outside steel surfaces
   - gas concentration sensors in the dome and lower containment regions

Whereas the instrumentation in the fire room and the ventilation system needs to satisfy the special fire requirements, the rest of the containment instrumentation relied upon the available, proven containment measurement sensors. All data acquisition needs were accomplished by the central HDR computer and data storage system. All subsequent expansions in sensor numbers and types (Sections 3.4.2 and 3.4.3) evolved from the aforementioned "reduced" measurement plan for T51.1 as a baseline.

3.3 Instrumentation Descriptions

3.3.1 Temperature Measurement

NiCr-Ni, sheathed thermocouples were used for temperature measurements in accordance with German DIN 43710. The thermocouple sheath had a 3 mm diameter and an insulated tip. The signal wires did not require special treatment as long as they remained outside of the hot flue gasses. Depending on the thermocouples physical location in the facility, the signal wires were up to 20 m in length. As high frequency temperature changes were not anticipated, thermocouples with standard response characteristics were chosen; e.g. for temperature an error of ±1% of the measured value and for strong thermal radiation conditions an error of ±5%.

3.3.2 Pressure Measurement

Figure 3.1 shows schematically the major elements of determining the pressure difference with the TELEPERM measurement converter. The difference between containment inside and outside pressures acts on the bellow and is transmitted through a lever to the flexible beam tube which in turn transmits to a differential capacitor providing an analog signal. The TELEPERM converter works for a pressure difference of up to 5 mbar with a response time of 0.3 s and a measurement accuracy of ±1%. This device had to be protected from high temperatures; hence, its placement on Level 1.6 of the facility.

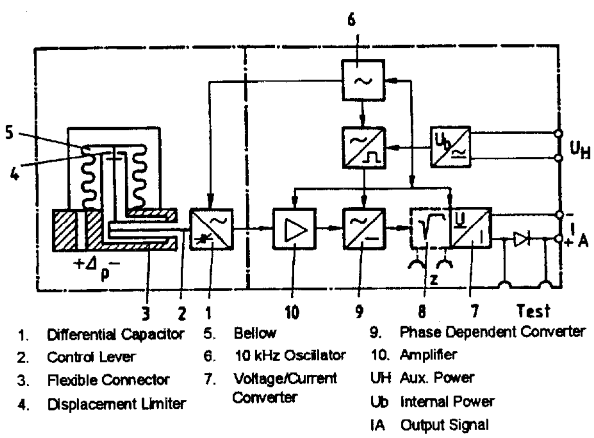

Figure 3.1: TELEPERM Transmitter

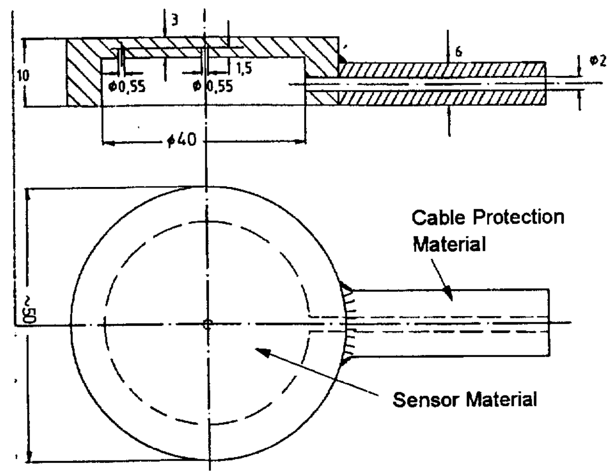

Figure 3.2: Local Heat Transfer Measurement

3.3.3 Heat Transfer Measurement

The local heat transfer at the containment steel shell was determined using the sensor depicted in Figure 3.2. The sensor used a 40 mm diameter annular control volume with a thin disk bottom of known material properties. Two NiCr-Ni sheathed thermocouples with a 0.5 diameter measured the disk temperature.

Additionally, large concrete blocks were devised and equipped with thermocouples as schematically shown in Figure 3.3. The type of concrete chosen was the same as used for the construction of the HDR containment Except for the front surface of the block all other surfaces were insulated. These massive concrete blocks were positioned at location where high convective flows, such as in the staircases, could be anticipated.

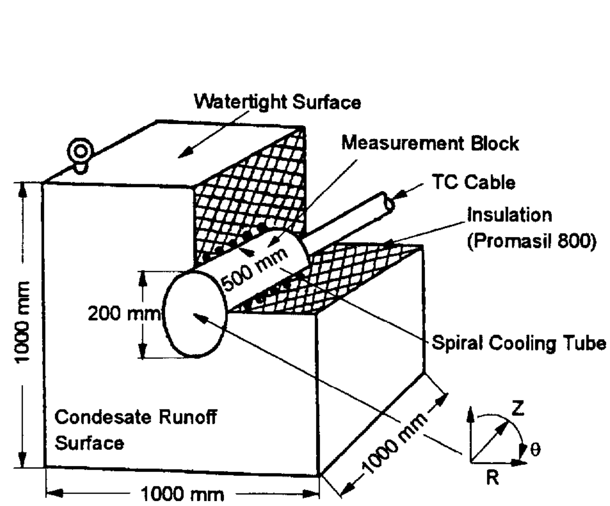

Figure 3.3: Heat Transfer Block

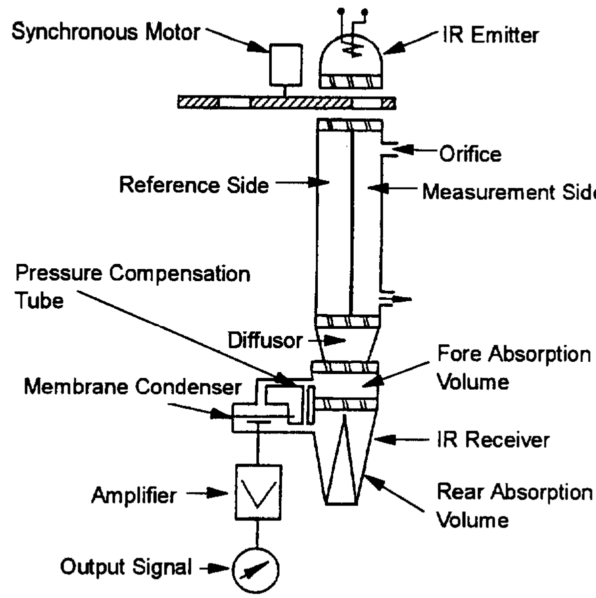

Figure 3.4: Gas Volume Analyzer

As the determination of the heat flux and subsequently the heat transfer coefficient at the measurement block's front surface rests on the solution of the inverse heat conduction problem, errors in these quantities became larger when temperature differences between thermocouples became smaller. Therefore, the expected accuracy of these blocks was only ±20%.

3.3.4 Smoke/Flue Gas Analysis

One of the major overall objectives of the HDR fire test series was the evaluation of the hazard potential to personnel, fire fighting, and rescue teams dependent on the type of burning substance, ventilating conditions, and fire location within the high-rise, containment building. Aside from direct exposure to heat, it is the smoke and flue gas mixture (O_2, CO, CO_2, NO_x, SO_x) as well as the production of HCl and potentially dioxin in the case of burning PVC cables which determines the hazard level. Therefore, instrumentation measuring the concentrations of these individual components had to be in place. Fortunately, as the majority of the experiments of the T51 test series used non-sooting gas flames, the requirements for smoke and gas analysis largely reduced to measuring O_2, CO, and CO_2 concentrations.

Figure 3.4 shows a schematic of the non-dispersive infrared photometer which worked with a modulated, single beam. This instrument allowed for continuos operation using a suction pump in the range of 10-100 l/h volumetric flow. The device outputted a 0-10 VDC signal proportional to the volumetric concentration in terms of vol. % or ppm.

Prior to the start of each experiment, these sensors were calibrated with a calibration gas. The measurement accuracy of these sensors was expected to be ±2%.

3.3.5 Optical Smoke Density

In order to follow the distribution and propagation of the flue gases inside the containment, an optical smoke densitometer, type ME82 made by Maurer, was positioned throughout the containment. A schematic of this sensor is shown in Figure 3.5, This sensor was used to determine the optical gas density in the rescue paths as well as the smoke density according to German Standard DIN 4102 Pt. 1.

As shown in Figure 3.5, a standardized light source in accordance with DIN 5033 emits a beam of light which passes through a control volume containing the gas to be analyzed. The control volume size can be modified. The amount of light passing through the volume is converted to an analog signal from 0-10 VDC corresponding to 100-0% transmittance. The measured values had an accuracy of ±2%.

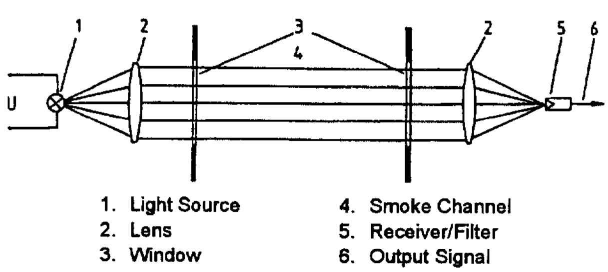

Figure 3.5: Smoke/Gas Density Sensor

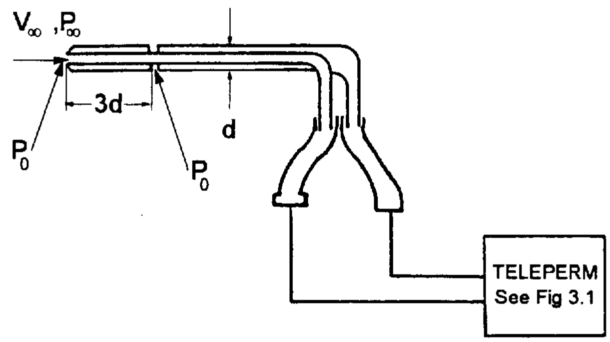

Figure 3.6: Pitot Tube Velocity Sensor

3.3.6 Velocity Measurement

In order to measure the flow velocities in different regions inside the containment, pitot tube type sensors, shown in Figure 3.6, were used. These sensors determine the pressure difference relative to stagnation pressure and use that to calculate the velocity. Hence, they used to same TELEPERM transmitter as discussed in Section 3.3.1, Figure 3.1. To obtain the velocity, the gas density must be measured simultaneously. For this purpose a thermocouple close to the pitot tube was used to determine density by application of the real gas law. The pitot tubes were capable of operating in temperatures as high as 800 °C. As before, the TELEPERM transmitter was shielded to protect it from high temperatures.

3.3.7 Video System

3.3.7.1 Introduction

The HDR facility was equipped with a color video system consisting of cameras, monitors, and tape machines. This system was used for monitoring the fire behavior in the fire compartments. The camera position for the T51 test series is shown in Figure 2.5.

In addition, a black and white video network consisting of 20 cameras with a switching board was installed. This system was developed by the Technical University of Karlsruhe, Germany, for use in monitoring the evacuation of personnel from high-rise buildings during fire exercises.

3.3.7.2 B&W Video System Network

Figure 3.7 shows the black and white video network which was used to monitor smoke movement at up to 20 locations under low lighting conditions, 20 lux. The cameras are connected with 50 m long cables to a video switching board. This device switches to next camera after three half pictures are taken. With a camera frequency of 50 frames per second, the switching board could rotate through the cameras in 1.2 s. This results in a nearly simultaneous observation of the smoke throughout the building. The other elements shown in the Figure are self-explanatory.

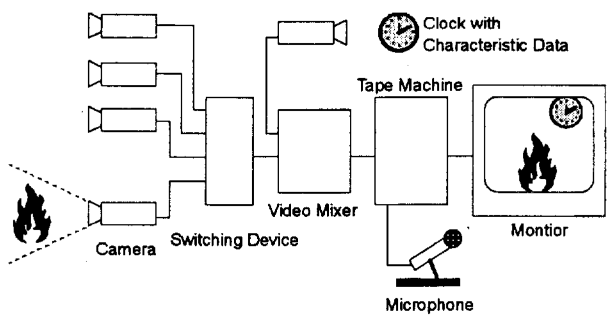

Figure 3.7: B&W Video System

3.3.7.3 Fog Generators

In order to enhance the video observations and monitoring of the smoke movement, a fog generator was positioned at Level 1.6 with the fog droplets blown in the direction of the maintenance hatch to enhance the visibility of the ascending plume from the fire. The operation of this generator was remotely controlled. The material used for the fog generators was non-corrosive to the HDR's walls and internal structures. However, the fog that was generated was only stable for temperatures below 80 °C, so the generators were only useful for visualizing cold air flows (descending).

Because this system did not live up to expectations, it was decided to remotely ignite an additional smoke cartridge in the fire compartment by a glow plug. This cartridge generated smoke that was stable up to 800 °C.

3.3.8 Safety Measures

In addition to the thermal insulations listed in Section 3.1, the measures described in the following were implemented for safety purposes:

- Gas and fresh air supply lines to the gas burners were positioned behind the fire-resistant wall along the containment. The temperature of this region together with the inlet temperature at the blower were continuously monitored from the control room.
- The color video system monitoring the fire compartment was continuously operated.
- Every gas burner had an associated thermocouple positioned above the exit flame to measure temperature anomalies.
- The amount of unburned propane was monitored at the doorway to the fire compartment, and the gas supply was set to be turned off if the propane concentration reached 1%, half the value of the lower ignition limit.
- A number of gas detectors were positioned at Levels 1.4 and 1.6 for safety reasons.
- All other containment regions including the steel shell were monitored with thermocouples.
- Each gas burner was equipped with its own ignition electrode and ionization flame suppression system which guaranteed an automatic stop of the total gas supply in case of non-ignition or fluctuating irregularities in the flame cone.

3.4 Instrumentation Layouts

As the first fire test series performed in the HDR facility the T51 series had an evolving instrumentation mapping primarily designed for the needs of zone models. Thus, the first test group, T51.1, had a fairly sparse instrumentation mapping. Some additional sensors were added to this mapping for the wood crib tests and the T51.19 gas fire test. The remaining experiments, the T51.2 test group, added numerous measurement devices to the fire floor and removed some of the sensors located at higher elevations inside the HDR facility.

The following two sections describe respectively the instrumentation mapping for T51.1 gas fire tests [2], the T51.19 gas fire test [5], and the T51.2 test group [6]. A complete listing of all instruments as well as diagrams showing their locations within the facility are documented in the tables following. To aid in reading the tables and diagrams the following nomenclature, standard for all HDR tests, is used for the instrumentation:

CF:	Velocity Sensor
CG:	Gas Concentration Sensor
CP:	Pressure
CQ:	Heat Transfer Measurement Block Sensor
CS:	Temperature Sensor
CT:	Temperature Sensor
CV:	Velocity Sensor
OA:	Steel Shell Expansion

In addition to the directly measured quantities, post processing was performed for some of the tests to yield indirectly measured parameters such as density and mass flow rate. These indirect measurements were not performed consistently throughout the test series. These measurements used the following nomenclature:

CD:	Calculated Density
CM:	Calculated Mass Flow Rate
CQ:	Calculated Heat Flux or Heat Transfer Coefficient

In the tables that follow sensor location refers to one of two coordinate systems. For heat transfer measurement blocks the location uses the front, center of the measurement block for the reference location with the position given in Cartesian coordinates [9]. All other sensors use the HDR center line at the +0.0 m elevation, see Figure 1.1, for the reference location with the position given in cylindrical coordinates [1].

3.4.1 Instrumentation Layout for T51.11 - T51.15

Table 3.1 lists all sensors in place for tests T51.11 through T51.15. The table shows the quantity/parameter measured, the sampling frequency, and the location for each sensor relative to the appropriate coordinate system. Any special comments about the sensor's performance is also given. Figures 3.8 through 3.20 schematically depict the sensors' locations level by level in the HDR facility for Table 3.1.

Table 3.1: T51.11-T51.15 Instrument Network

Sensor	Parameter	Frequency (Hz)	Location			Comments
			R (cm)	θ (deg)	Z (cm)	
CD1045	kg/m^3	0.17	540	168	96	Calculated density*
CF7701	m/s	0.17	730	85	1700	
CG4641	CO v/o	0.17	445	175	100	Failed
CG4642	O_2 v/o	0.17	445	175	100	
CG4643	CO_2 v/o	0.17	445	175	100	
CG4644	C_nH_m ppm	0.17	445	175	100	
CG6601	CO_2 v/o	0.17			1000	Failed
CG6602	CO v/o	0.17			1000	Failed
CG6603	O_2 v/o	0.17			1000	Failed
CG6611	CO_2 v/o	0.17	760	80	1000	Failed
CM1045	m^3/s	0.17	540	168	96	Calculated mass flow rate*
CP4640	ΔP mbar	0.17	500	170	100	
CP6201	ΔP mbar	0.17	1,005	0	1100	Staircase stepping in data but follows overall transient
CQ2353	W/m^2	0.17				Calculated heat flux*
CQ5310	°C	0.17	0	0	5	Steel measurement block
CQ5311	°C	0.17	20	180	5	Steel measurement block
CQ5312	°C	0.17	0	0	30	Steel measurement block
CQ5313	°C	0.17	90	180	355	Steel measurement block
CQ5314	°C	0.17	0	0	395	Steel measurement block
CQ5320	°C	0.17	0	0	10	Concrete measurement block
CQ5321	°C	0.17	0	0	20	Concrete measurement block
CQ5322	°C	0.17	0	0	30	Concrete measurement block
CQ5323	°C	0.17	0	0	40	Concrete measurement block
CQ5324	°C	0.17	0	0	50	Concrete measurement block
CQ5325	°C	0.17	0	0	200	Concrete measurement block
CQ5326	°C	0.17	0	0	300	Concrete measurement block
CQ5327	°C	0.17	75	180	400	Concrete measurement block
CS3301	°C	0.17	220	90	-650	
CS3705	°C	0.17	1000	60	600	

Sensor	Parameter	Frequency (Hz)	Location			Comments
			R (cm)	θ (deg)	Z (cm)	
CS3710	°C	0.17	1000	65	550	
CS3720	°C	0.17	1000	65	800	
CS4531	°C	0.17	605	185	110	
CS6601	°C	0.17	924	265	1200	
CT 403	°C	0.17	0	270	5000	
CT 404	°C	0.17	195	50	4000	
CT 405	°C	0.17	900	160	4000	
CT 406	°C	0.17	110	50	4500	
CT 410	°C	0.17	310	50	3400	
CT 411	°C	0.17	900	45	3400	
CT 412	°C	0.17	900	270	3400	
CT 413	°C	0.17	635	270	3900	
CT 414	°C	0.17	310	270	4600	
CT 420	°C	0.17	600	90	3900	
CT 421	°C	0.17	600	270	3900	
CT 422	°C	0.17	950	55	3400	
CT 423	°C	0.17	570	80	3400	
CT 424	°C	0.17	550	275	3100	
CT 425	°C	0.17	550	275	3500	
CT3702	°C	0.17	950	70	550	
CT3706	°C	0.17	950	70	1700	
CT4511	°C	0.17	530	175	-70	
CT4512	°C	0.17	685	175	-70	
CT4513	°C	0.17	690	187	-70	
CT4514	°C	0.17	750	205	-70	
CT4521	°C	0.17	530	175	20	Failed in T51.15
CT4522	°C	0.17	685	175	20	
CT4523	°C	0.17	750	205	20	
CT4531	°C	0.17	530	175	110	
CT4532	°C	0.17	645	172	110	
CT4533	°C	0.17	730	185	110	
CT4534	°C	0.17	810	205	110	
CT4541	°C	0.17	690	187	200	
CT4542	°C	0.17	685	175	200	
CT4543	°C	0.17	750	205	200	Failed in T51.15
CT4551	°C	0.17	590	175	70	Failed
CT4552	°C	0.17	750	190	300	Failed
CT4653	°C	0.17	500	215	0	
CT4654	°C	0.17	410	65	0	Failed in T51.11 and 12

Sensor	Parameter	Frequency (Hz)	Location			Comments
			R (cm)	θ (deg)	Z (cm)	
CT4655	°C	0.17	680	60	0	
CT4660	°C	0.17	610	82	-50	
CT4661	°C	0.17	430	105	-50	
CT4662	°C	0.17	390	125	-50	
CT4663	°C	0.17	400	145	-50	
CT4664	°C	0.17	400	165	-50	
CT4670	°C	0.17	610	82	100	
CT4671	°C	0.17	430	105	100	
CT4672	°C	0.17	390	125	100	
CT4673	°C	0.17	400	145	100	
CT4674	°C	0.17	400	165	100	
CT5101	°C	0.17	410	110	600	
CT5301	°C	0.17	417	25	650	
CT5302	°C	0.17	980	55	600	
CT5303	°C	0.17	740	85	600	
CT6309	°C	0.17	820	235	800	
CT6402	°C	0.17	450	110	1200	
CT6606	°C	0.17	510	20	1200	
CT6607	°C	0.17	640	280	1200	
CT6609	°C	0.17	720	75	1200	
CT7702	°C	0.17	950	55	1700	
CT7703	°C	0.17	670	80	1700	
CT7802	°C	0.17	500	270	1900	
CT8402	°C	0.17	457	270	2257	
CT8502	°C	0.17	700	80	2300	
CT8503	°C	0.17	600	65	2300	
CV4640	m/s	0.17	540	168	96	
CV7701	m/s	0.17	650	85	1700	Failed
CV7702	m/s	0.17	650	85	1700	Failed
CV7704	m/s	0.17	730	85	1700	Failed in T51.15
OA2010	Shell Expansion	0.17	1003	270	4000	
OA2015	Shell Expansion	0.17	1003	270	0	
OA3010	Shell Expansion	0.17	1003	270	4000	
OA3015	Shell Expansion	0.17	1003	270	0	
OA3016	Shell Expansion	0.17	1003	270	-100	

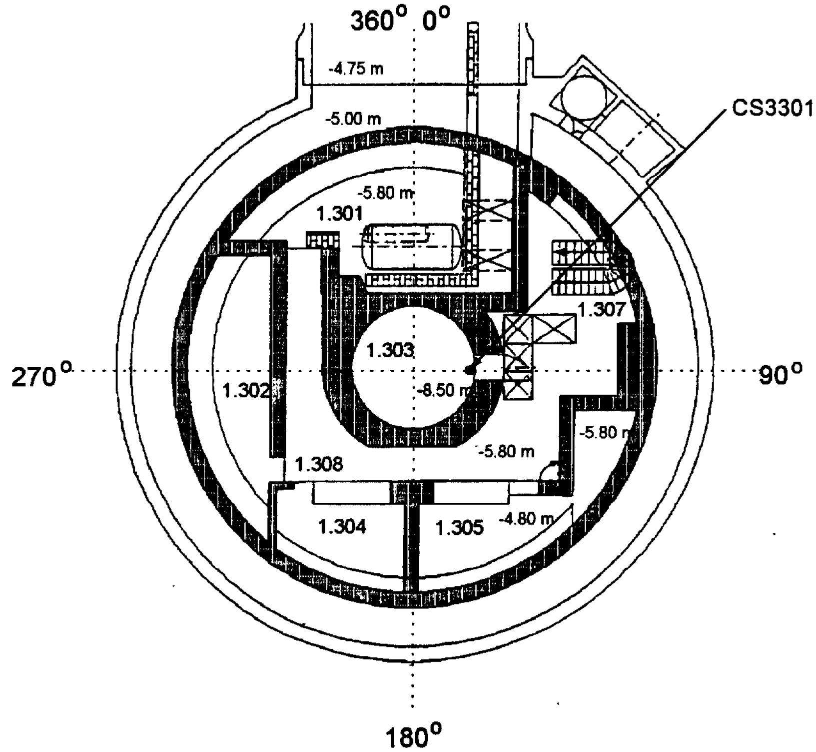

Figure 3.8: Level 1.200 and 1.300 at the -6.5 m Elevation for T51.1

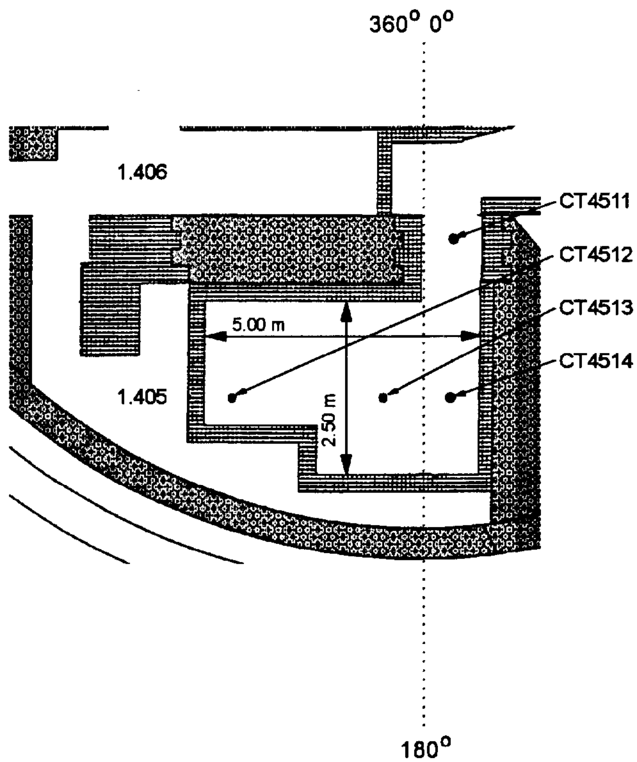

Figure 3.9: Fire Room at the -0.7 m Elevation for T51.1

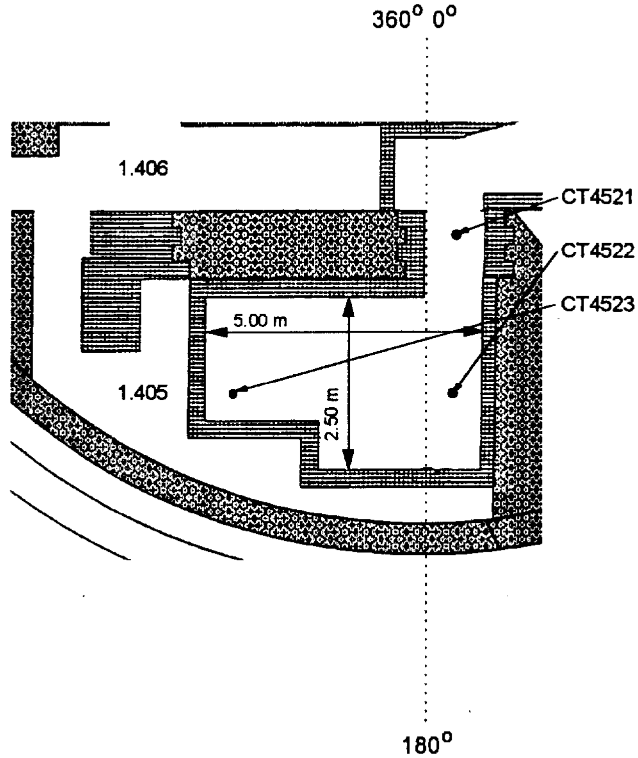

Figure 3.10: Fire Room at the +0.2 m Elevation for T51.1

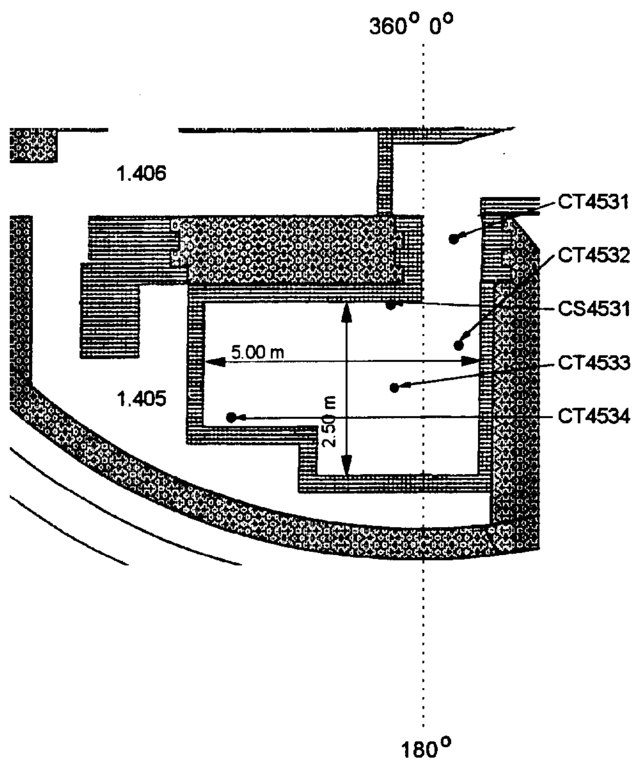

Figure 3.11: Fire Room at the +1.1 m Elevation for T51.1

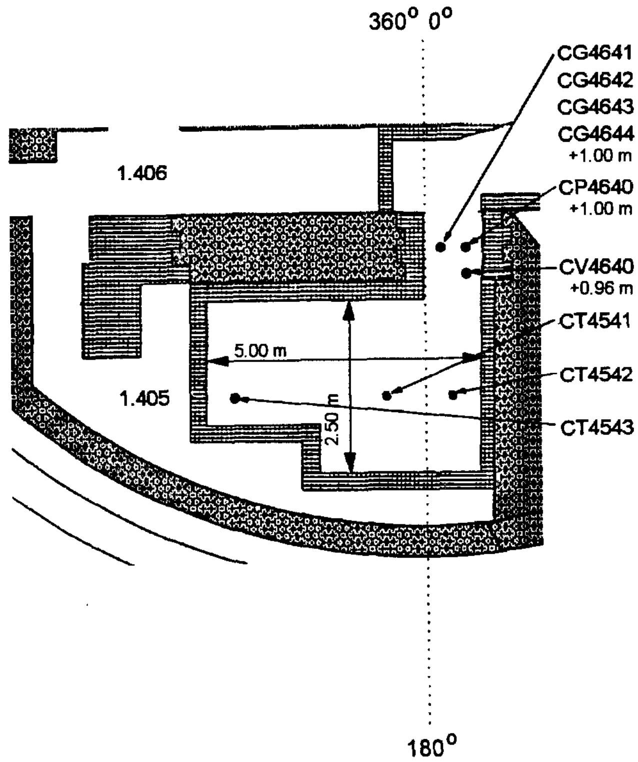

Figure 3.12: Fire Room at the +1.7 m Elevation for T51.1

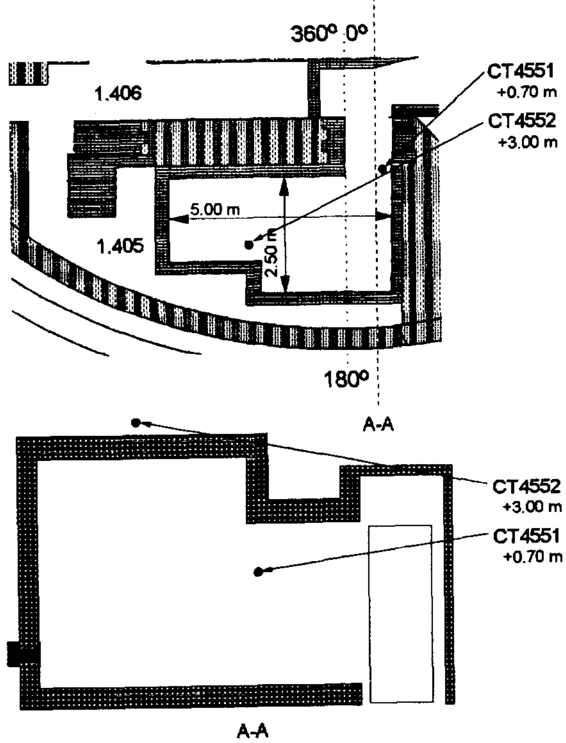

Figure 3.13: Fire Room Vertical Cross Section for T51.1

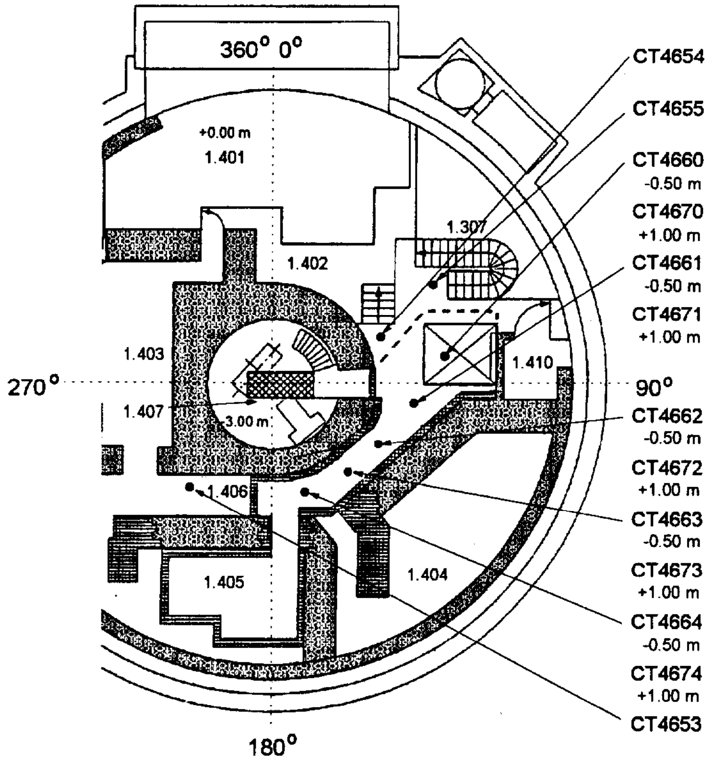

Figure 3.14: Fire Hallway at the +0.0 m Elevation for T51.1

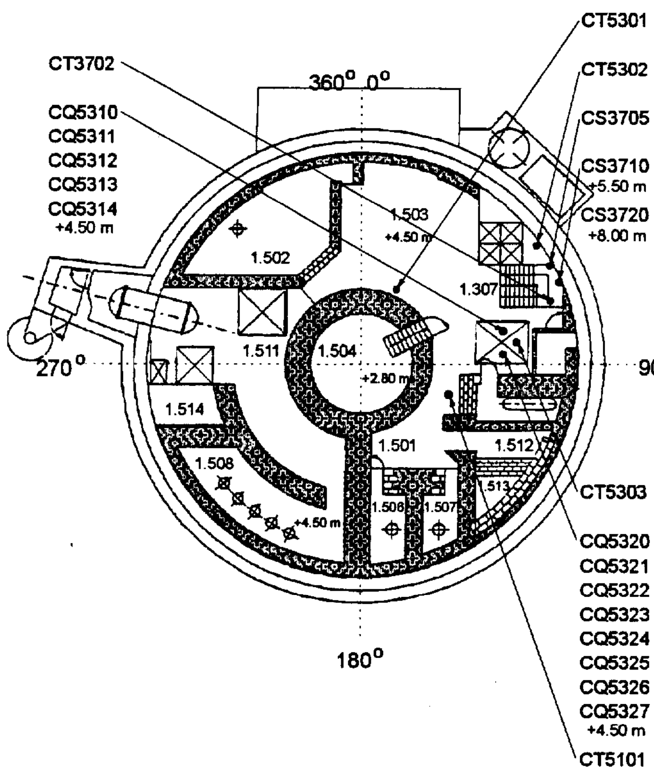

Figure 3.15: Level 1.500 at the +6.0 m Elevation for T51.1

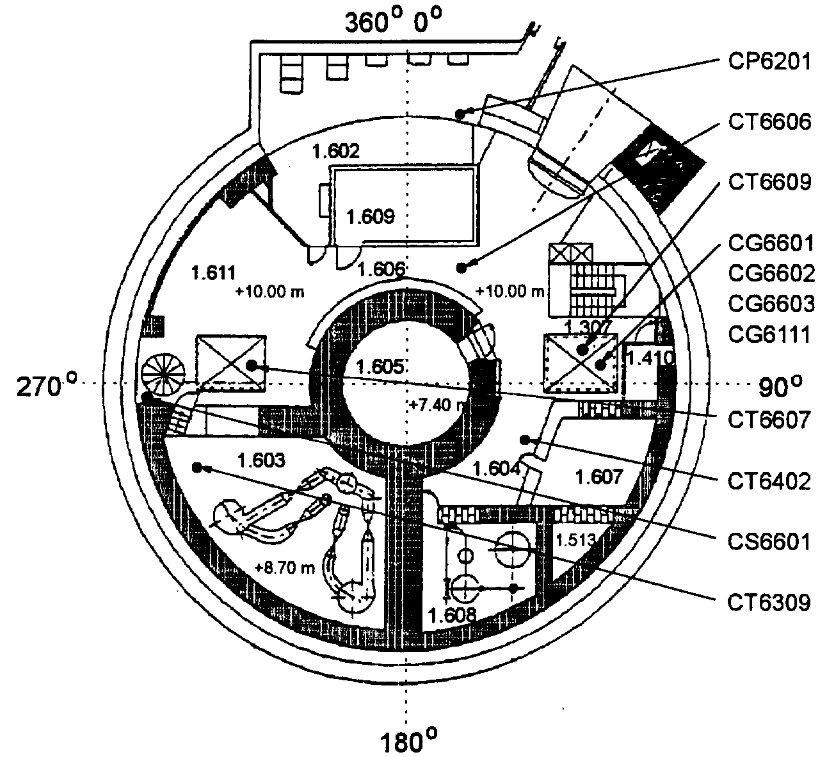

Figure 3.16: Level 1.600 at the +12.0 m Elevation for T51.1

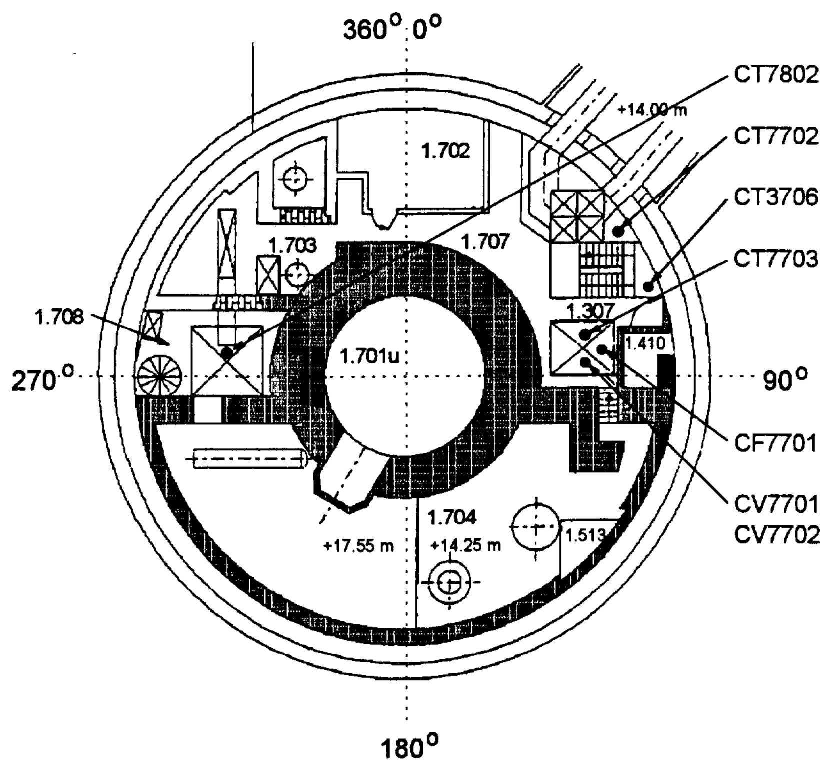

Figure 3.17: Level 1.700 at the +17.0 m Elevation for T51.1

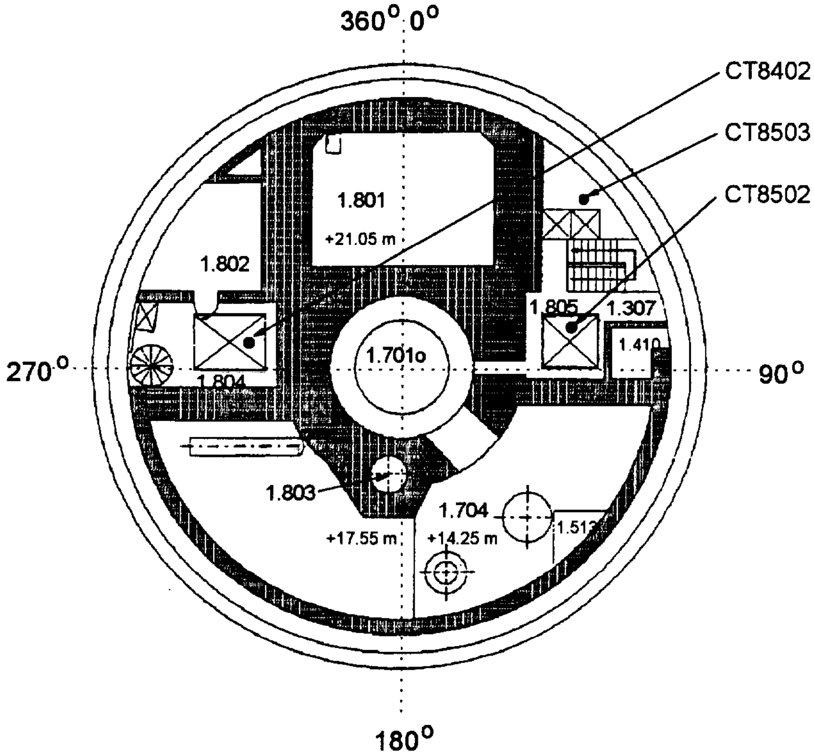

Figure 3.18: Level 1.800 at the +23.0 m Elevation for T51.1

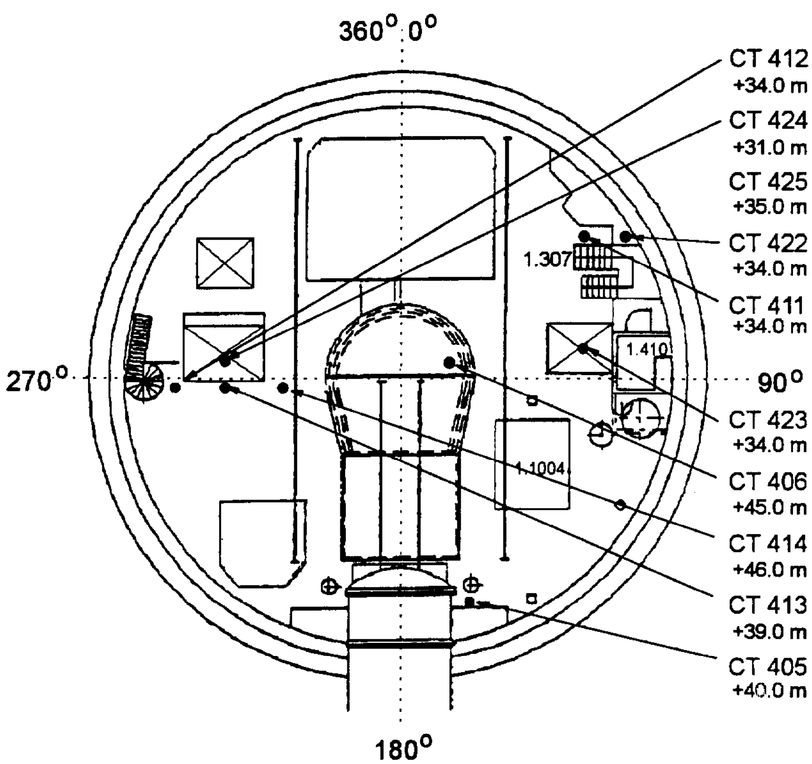

Figure 3.19: Dome Level at the +31.0 m Elevation for T51.1

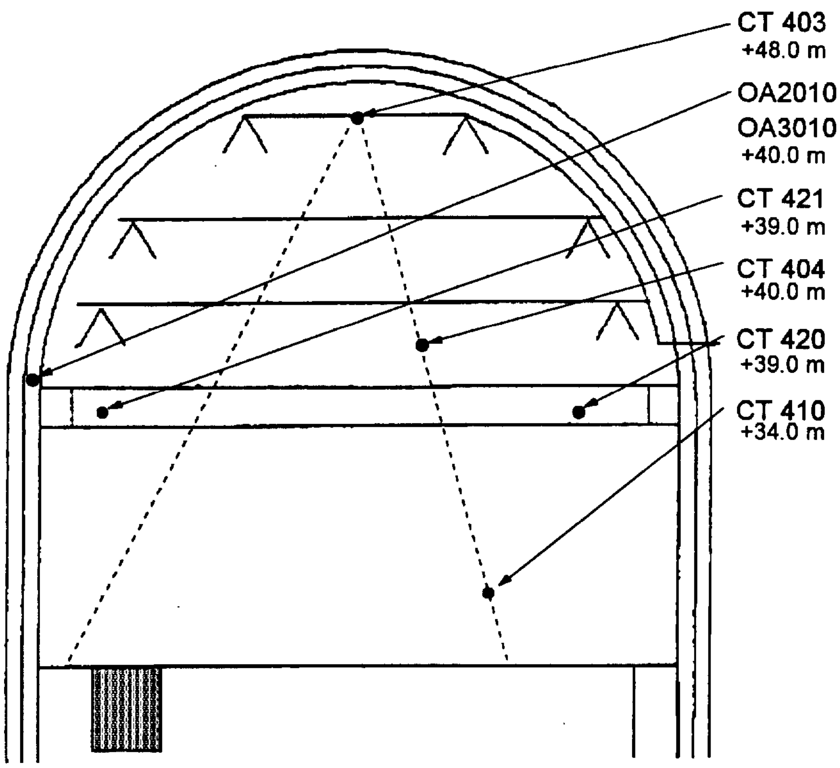

Figure 3.13: Dome Vertical Cross Section for T51.1

3.4.2 Instrumentation Layout for T51.19

Table 3.2 lists all sensors in place for test T51.19. The table shows the quantity/parameter measured, the sampling frequency, and the location for each sensor relative to the appropriate coordinate system. Any special comments about the sensor's performance is also given. Figures 3.21 through 3.34 schematically depict the sensors' locations level by level in the HDR facility for Table 3.2.

Table 3.2: T51.19 Instrument Network

Sensor	Parameter	Frequency (Hz)	Location			Comments
			R (cm)	θ (deg)	Z (cm)	
CD1045	kg/m^3	0.17	540	168	96	Calcualted density
CF3712	m/s	0.17	540	62	-90	
CF3721	m/s	0.17	840	48	100	Possible failure
CF3723	m/s	0.17	925	52	1200	
CF3724	m/s	0.17	910	45	2300	Possible failure
CF4311	m/s	0.17	500	321	100	
CF4612	m/s	0.17	460	124	-90	
CF5324	m/s	0.17	600	76	500	
CF6611	m/s	0.17	490	0	1200	
CF7701	m/s	0.17	730	85	1700	
CF7821	m/s	0.17	650	273	1700	
CF8521	m/s	0.17	630	83	2300	
CG 401	CO_2 v/o	0.17	0	0	0	Failed
CG1104	CO_2 v/o	0.01	670	85	3100	
CG1145	CO_2 v/o	0.01	590	177	-80	
CG1146	CO_2 v/o	0.01	610	90	-80	
CG1153	CO_2 v/o	0.01	670	85	600	
CG1166	CO_2 v/o	0.01	670	85	1020	
CG1177	CO_2 v/o	0.01	670	85	1700	
CG1178	CO_2 v/o	0.01	670	275	1900	
CG1185	CO_2 v/o	0.01	670	85	2300	
CG1204	CO_2 v/o	0.01	195	50	4000	
CG1266	CO_2 v/o	0.01	670	275	1200	
CG1304	CO_2 v/o	0.01	670	275	3100	
CG1366	CO_2 v/o	0.01	480	20	1270	
CG2104	1/m	0.17	670	85	3100	Extinction coefficient
CG2166	1/m	0.17	670	85	1020	Extinction coefficient
CG2266	1/m	0.17	450	20	1450	Extinction coefficient
CG2366	1/m	0.17	450	20	1360	Extinction coefficient
CG2466	1/m	0.17	450	20	1270	Extinction coefficient
CG2566	1/m	0.17	450	20	1180	Extinction coefficient

Sensor	Parameter	Frequency (Hz)	Location			Comments
			R (cm)	θ (deg)	Z (cm)	
CG2666	1/m	0.17	450	20	1090	Extinction coefficient
CG4641	CO v/o	0.17	445	175	100	Failed
CG4642	O_2 v/o	0.17	445	175	100	
CG4643	CO_2 v/o	0.17	445	175	100	
CG4644	C_nH_m ppm	0.17	445	175	100	Failed
CG5301	kg/m^3	0.17	630	88	470	
CG5302	kg/m^3	0.17	630	88	470	
CG6601	CO_2 v/o	0.17	0	0	0	Failed
CG6604	CO_2 v/o	0.17	0	0	0	Failed
CG6611	CO_2 v/o	0.17	760	80	1000	Failed
CG6621	CO_2 v/o	0.17	0	0	0	Failed
CG6622	CO_2 v/o	0.17	0	0	0	Failed
CG6623	CO_2 v/o	0.17	0	0	0	Failed
CG6624	CO_2 v/o	0.17	0	0	0	Failed
CG6625	CO_2 v/o	0.17	0	0	0	Failed
CM1045	kg/s	0.17	540	168	96	Calculated mass flow rate
CP4640	ΔP mbar	0.17	500	170	100	
CP6201	ΔP mbar	0.17	1005	0	1100	Staircase stepping in data but follows overall transient
CQ1153	W/m^2 K	0.17	0	0	0	Calculated heat transfer coef.
CQ1185	W/m^2 K	0.17	0	0	0	Calculated heat transfer coef.
CQ2153	W/m^2	0.17	0	0	0	Calculated heat flux
CQ2185	W/m^2	0.17	0	0	0	Calculated heat flux
CQ2353	W/m^2	0.17	0	0	0	Calculated heat flux
CQ3153	°C	0.17	0	0	0	
CQ3185	°C	0.17	0	0	0	
CQ5310	°C	0.17	0	0	5	Steel measurement block
CQ5311	°C	0.17	20	180	5	Steel measurement block
CQ5312	°C	0.17	0	0	30	Steel measurement block
CQ5313	°C	0.17	90	180	355	Steel measurement block
CQ5314	°C	0.17	0	0	395	Steel measurement block
CQ5320	°C	0.17	0	0	10	Concrete measurement block
CQ5321	°C	0.17	0	0	20	Concrete measurement block
CQ5322	°C	0.17	0	0	30	Concrete measurement block
CQ5323	°C	0.17	0	0	40	Concrete measurement block
CQ5324	°C	0.17	0	0	50	Concrete measurement block
CQ5325	°C	0.17	0	0	200	Concrete measurement block
CQ5326	°C	0.17	0	0	300	Concrete measurement block
CQ5327	°C	0.17	75	180	400	Concrete measurement block
CQ8510	°C	0.17	0	0	2	Steel measurement block

Sensor	Parameter	Frequency (Hz)	Location R (cm)	Location θ (deg)	Location Z (cm)	Comments
CQ8511	°C	0.17	20	180	2	Steel measurement block
CQ8512	°C	0.17	0	0	30	Steel measurement block
CQ8513	°C	0.17	90	180	355	Steel measurement block
CQ8514	°C	0.17	0	0	395	Steel measurement block
CS3301	°C	0.17	220	90	-650	
CS3705	°C	0.17	1000	60	600	
CS3710	°C	0.17	1000	65	550	
CS3720	°C	0.17	1000	65	800	
CS4531	°C	0.17	605	185	110	
CS6601	°C	0.17	924	265	1200	Failed
CT 403	°C	0.17	0	270	5000	
CT 404	°C	0.17	195	50	4000	
CT 405	°C	0.17	900	160	4000	
CT 406	°C	0.17	110	50	4500	
CT 410	°C	0.17	310	50	3400	
CT 411	°C	0.17	900	45	3400	
CT 412	°C	0.17	900	270	3400	
CT 413	°C	0.17	635	270	3900	
CT 414	°C	0.17	310	270	4600	
CT 420	°C	0.17	600	90	3900	
CT 421	°C	0.17	600	270	3900	
CT 422	°C	0.17	950	55	3400	
CT 423	°C	0.17	570	80	3400	
CT 424	°C	0.17	550	275	3100	
CT 425	°C	0.17	550	275	3500	
CT3702	°C	0.17	950	70	550	
CT3706	°C	0.17	950	70	1700	
CT4511	°C	0.17	530	175	-70	
CT4512	°C	0.17	685	175	-70	
CT4513	°C	0.17	690	187	-70	
CT4514	°C	0.17	750	205	-70	
CT4521	°C	0.17	530	175	20	
CT4522	°C	0.17	685	175	20	
CT4523	°C	0.17	750	205	20	
CT4531	°C	0.17	530	175	110	
CT4532	°C	0.17	645	172	110	
CT4533	°C	0.17	730	185	110	
CT4534	°C	0.17	810	205	110	
CT4541	°C	0.17	690	187	170	Failed

Sensor	Parameter	Frequency (Hz)	Location			Comments
			R (cm)	θ (deg)	Z (cm)	
CT4542	°C	0.17	685	175	170	
CT4543	°C	0.17	750	205	170	
CT4544	°C	0.17	815	181	170	
CT4545	°C	0.17	815	181	170	
CT4551	°C	0.17	590	177	80	Failed
CT4552	°C	0.17	750	190	300	
CT4553	°C	0.17	590	177	50	
CT4554	°C	0.17	590	177	-10	
CT4555	°C	0.17	590	177	-80	
CT4556	°C	0.17	590	177	100	
CT4653	°C	0.17	500	215	0	
CT4654	°C	0.17	410	65	0	Failed
CT4655	°C	0.17	680	60	0	
CT4660	°C	0.17	610	82	-50	
CT4661	°C	0.17	430	105	-50	
CT4662	°C	0.17	390	125	-50	
CT4663	°C	0.17	400	145	-50	
CT4664	°C	0.17	400	165	-50	
CT4671	°C	0.17	430	105	100	
CT4672	°C	0.17	390	125	100	
CT4673	°C	0.17	400	145	100	
CT4674	°C	0.17	400	165	100	
CT4682	°C	0.17	390	125	130	
CT4684	°C	0.17	400	165	130	
CT5101	°C	0.17	410	110	600	
CT5301	°C	0.17	417	25	650	
CT5302	°C	0.17	980	55	600	
CT5303	°C	0.17	740	85	600	
CT5310	°C	0.17	600	75	470	
CT6309	°C	0.17	820	235	800	
CT6402	°C	0.17	450	110	1200	
CT6606	°C	0.17	510	20	1200	
CT6607	°C	0.17	640	280	1200	
CT6609	°C	0.17	720	75	1200	
CT7702	°C	0.17	950	55	1700	
CT7703	°C	0.17	670	80	1700	
CT7802	°C	0.17	500	270	1900	
CT8402	°C	0.17	457	270	2257	
CT8502	°C	0.17	700	80	2300	

Sensor	Parameter	Frequency (Hz)	Location			Comments
			R (cm)	θ (deg)	Z (cm)	
CT8503	°C	0.17	600	65	2300	
CT8510	°C	0.17	600	73	1520	
CV4640	m/s	0.17	540	168	96	
CV6601	m/s	0.17	490	0	1180	Failed
CV6602	m/s	0.17	490	0	1180	Failed
CV7701	m/s	0.17	650	85	1700	Failed
CV7702	m/s	0.17	650	85	1700	Failed
CV7704	m/s	0.17	730	85	1700	
OA2010	Shell Expansion	0.17	1003	270	4000	
OA2015	Shell Expansion	0.17	1003	270	0	
OA3010	Shell Expansion	0.17	1003	270	4000	
OA3015	Shell Expansion	0.17	1003	270	0	
OA3016	Shell Expansion	0.17	1003	270	-100	

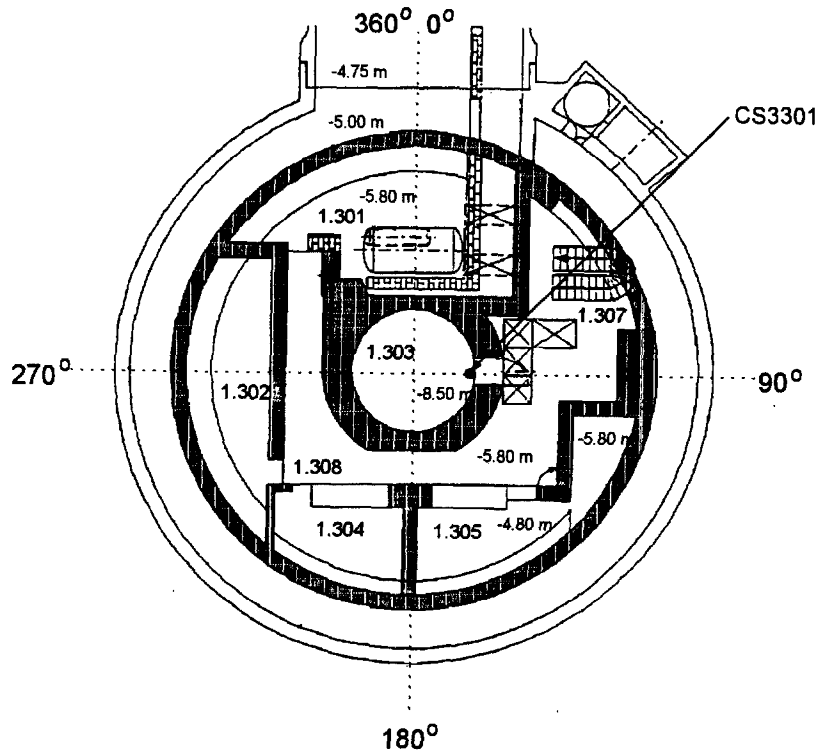

Figure 3.21: Level 1.200 and 1.300 at the -6.5 m Elevation for T51.19

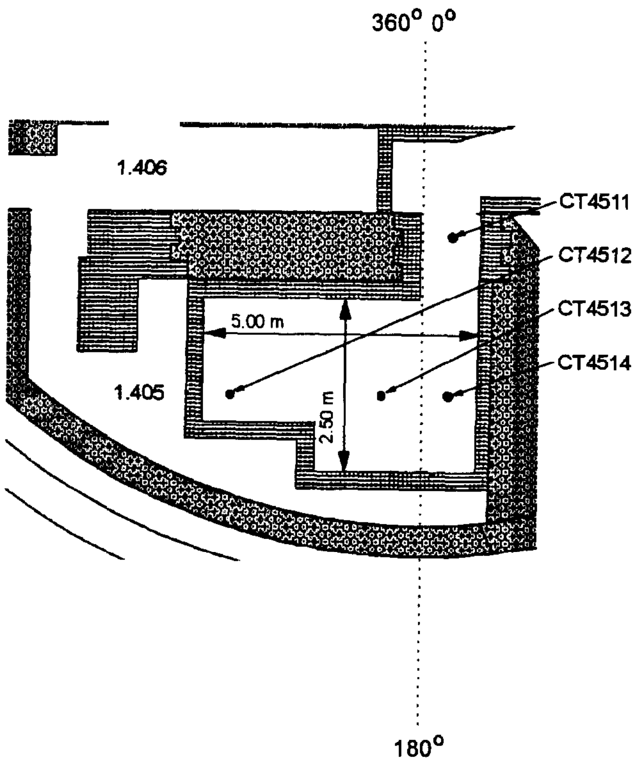

Figure 3.22: Fire Room at the -0.7 m Elevation for T51.19

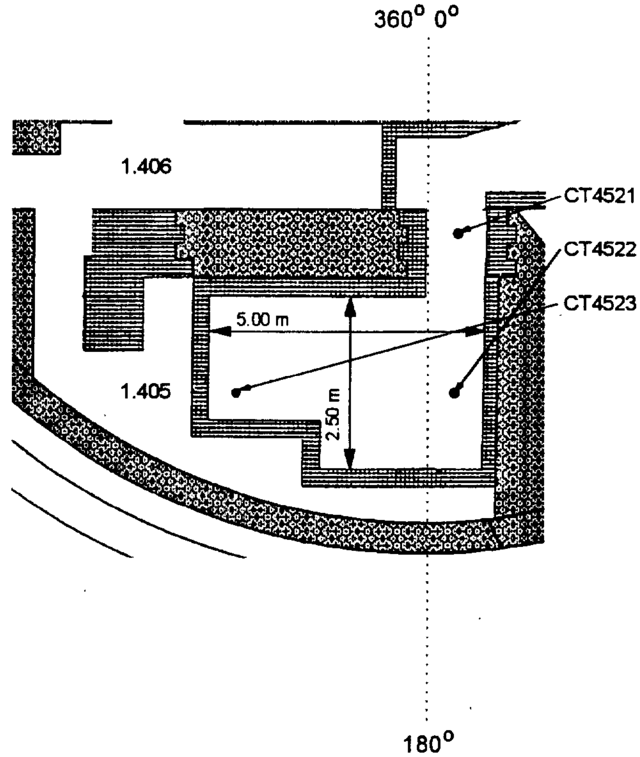

Figure 3.23: Fire Room at the +0.2 m Elevation for T51.19

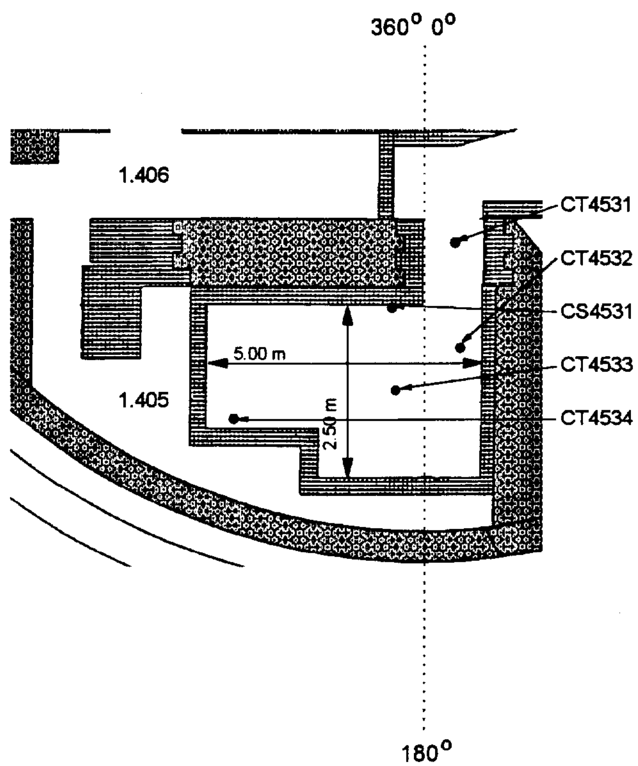

Figure 3.24: Fire Room at the +1.1 m Elevation for T51.19

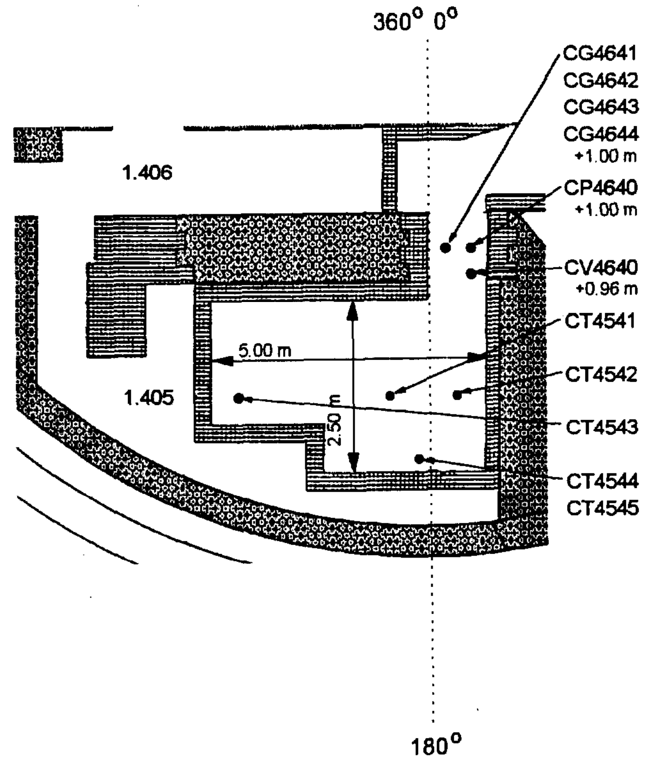

Figure 3.25: Fire Room at the +1.7 m Elevation for T51.19

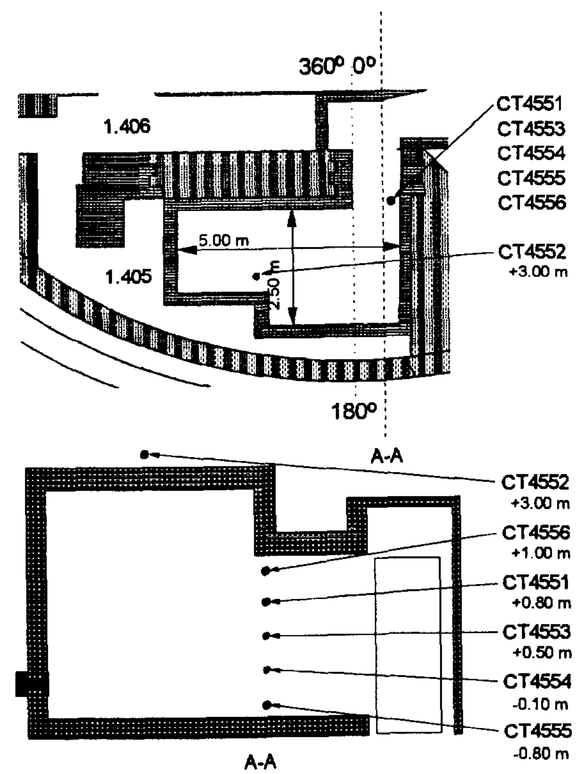

Figure 3.26: Fire Room Vertical Cross-Section for T51.19

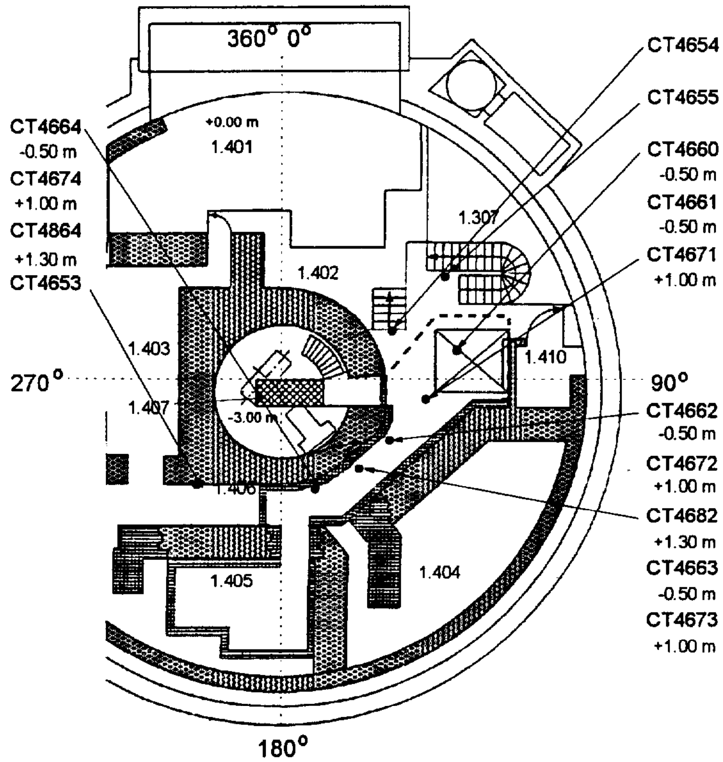

Figure 3.27: Level 1.400 TC's at the +0.0 m Elevation for T51.19

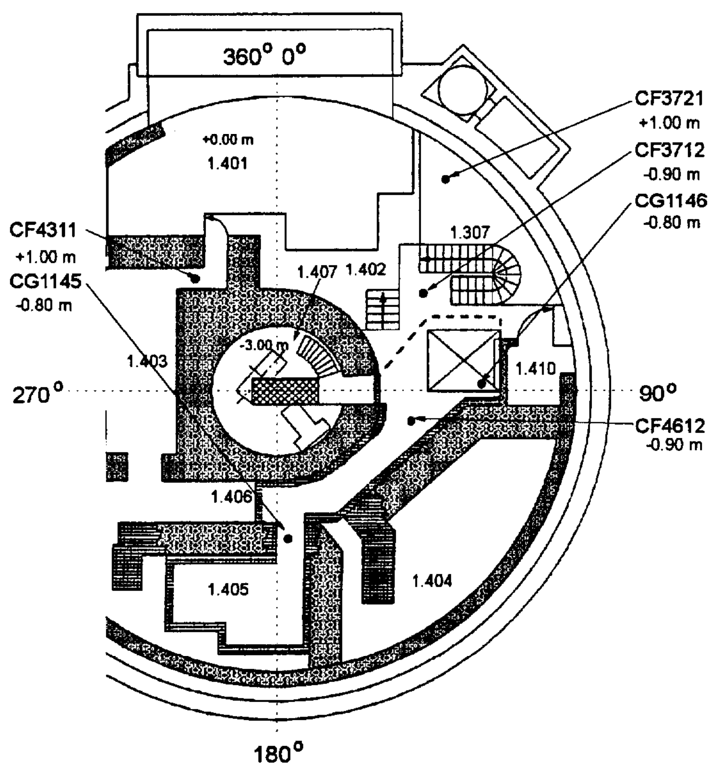

Figure 3.28: Level 1.400 Velocity Sensors and Gas Sensors at the +0.0 m Elevation for T51.19

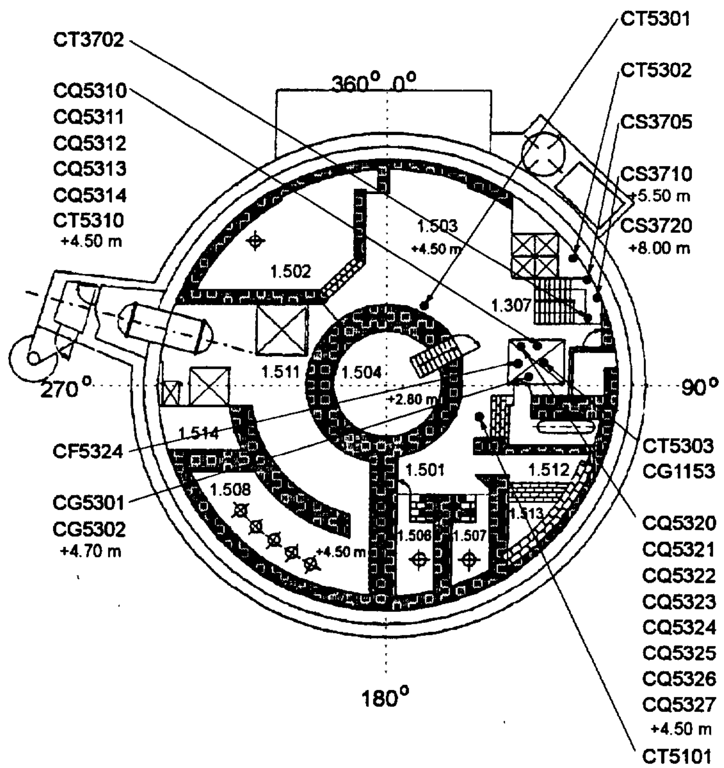

Figure 3.29: Level 1.500 at the +6.0 m Elevation for T51.19

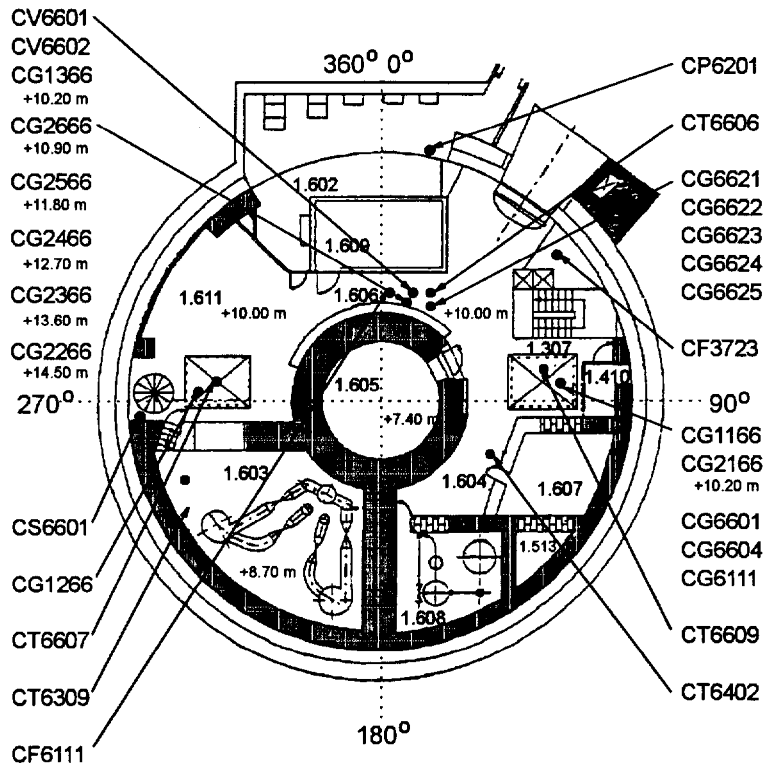

Figure 3.23: Level 1.600 at the +12.0 m Elevation for T51.19

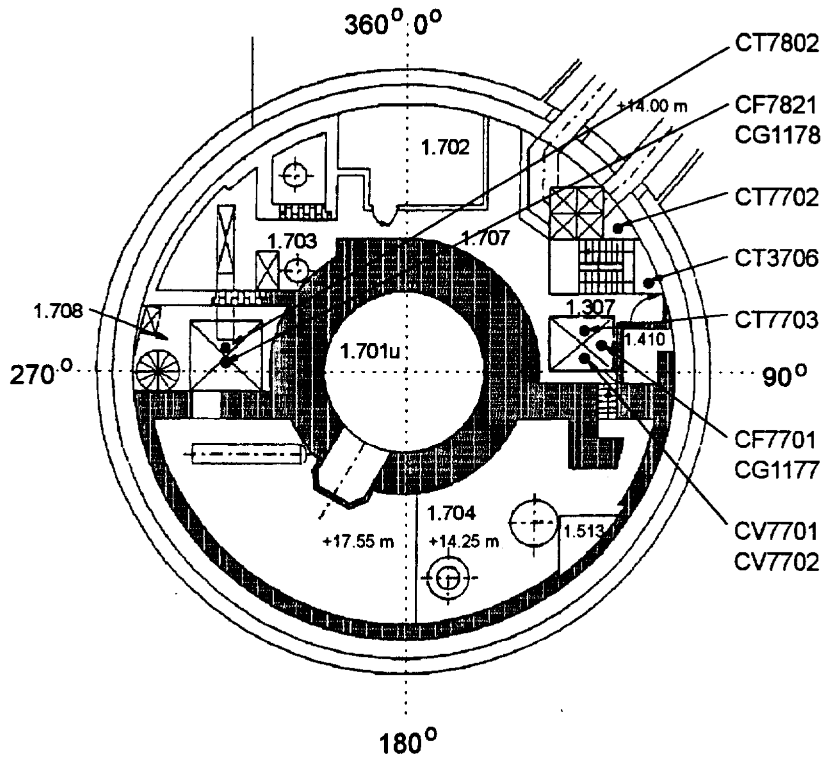

Figure 3.31: Level 1.700 at the +17.0 m Elevtaion for T51.19

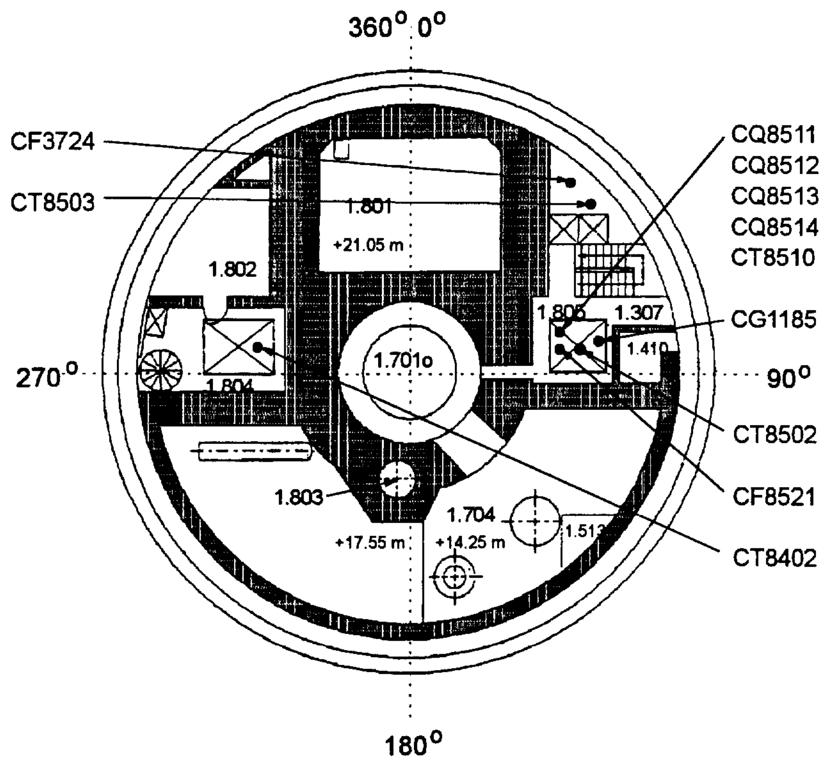

Figure 3.32: Level 1.800 at the +23.0 m Elevation for T51.19

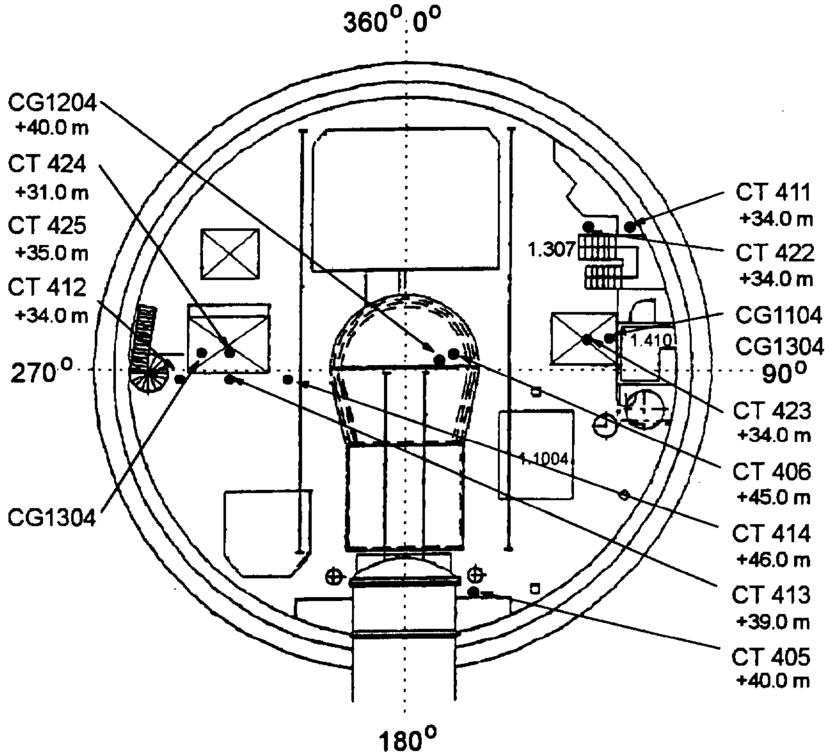

Figure 3.33: Dome Level at the +31.0 m Elevation for T51.19

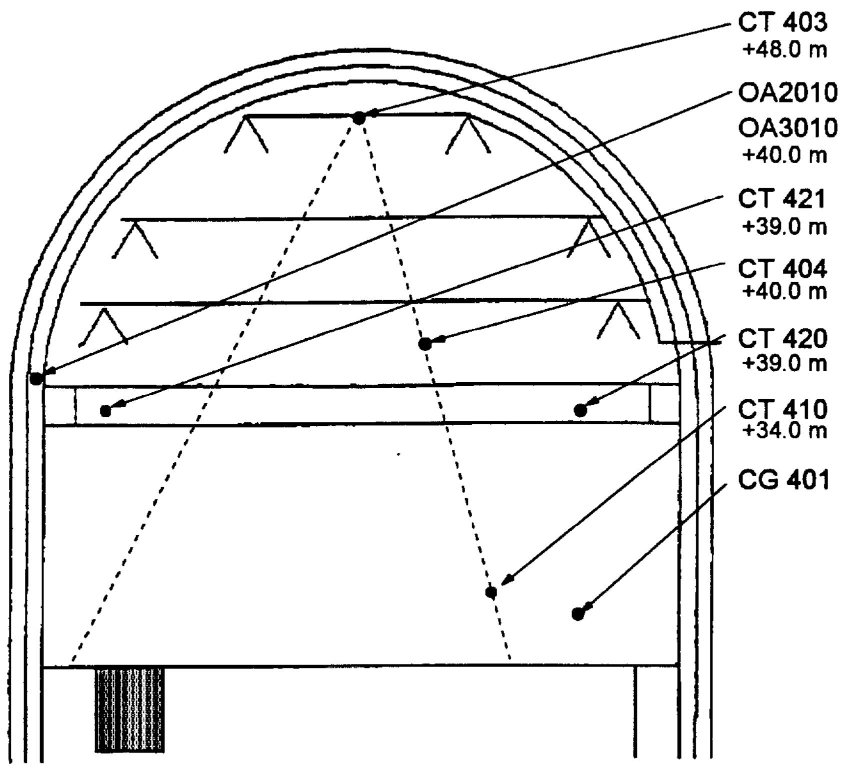

Figure 3.34: Dome Vertical Cross-Section for T51.19

3.4.3 Instrumentation Layout for T51.21 - T51.25

Table 3.3 lists all sensors in place for the T51.2 test group. The table shows the quantity/parameter measured, the sampling frequency, and the location for each sensor relative to the appropriate coordinate system. Any special comments about the sensor's performance is also given. Figures 3.28 through 3.46 schematically depict the sensors' locations level by level in the HDR facility for Table 3.3. It is worth mentioning that the additional instrumentation was applied for test series T51.2 in order to obtain more local information about physical phenomena such as layer height, plume spread, and the like.

Table 3.3: T51.2 Instrument Network

Sensor	Parameter	Frequency (Hz)	Location			Comments
			R (cm)	θ (deg)	Z (cm)	
CF 401	m/s	1.00	640	280	3080	
CF3712	m/s	1.00	540	62	-90	
CF3721	m/s	1.00	840	48	100	
CF3723	m/s	1.00	925	52	1200	
CF3724	m/s	1.00	910	45	2300	
CF4612	m/s	1.00	460	124	-90	
CF5324	m/s	1.00	600	76	500	Failed T51.21, 22, and 23
CF6611	m/s	1.00	490	0	1200	
CF7701	m/s	1.00	730	85	1700	
CF7821	m/s	1.00	650	273	1700	
CF8521	m/s	1.00	630	83	2300	
CG4600	CO_2 v/o	0.05	393	125	-85	
CG4641	CO v/o	0.05	445	175	100	Failed
CG4642	O_2 v/o	0.05	445	175	100	
CG4643	CO_2 v/o	0.05	445	175	100	
CG4644	C_nH_m ppm	0.05	445	175	100	Failed
CG4651	CO_2 v/o	0.05	393	125	-85	
CG4652	CO_2 v/o	0.05	393	125	-60	
CG4653	CO_2 v/o	0.05	393	125	15	
CG4654	CO_2 v/o	0.05	393	125	115	
CG4661	CO_2 v/o	0.05	400	145	-85	
CG4662	CO_2 v/o	0.05	400	145	-60	
CG4663	CO_2 v/o	0.05	400	145	15	
CG4664	CO_2 v/o	0.05	400	145	115	
CG4665	CO_2 v/o	0.05	471	171	-85	
CG4666	CO_2 v/o	0.05	471	171	-60	
CG4667	CO_2 v/o	0.05	471	171	15	
CG5301	CO_2 v/o	1.00	630	88	470	Failed
CG5302	CO_2 v/o	1.00	630	88	470	Failed

Sensor	Parameter	Frequency (Hz)	Location R (cm)	θ (deg)	Z (cm)	Comments
CG6605	CO_2 v/o	0.05	640	282	1040	
CM1040	kg/s	1.00	0	0	0	Calculated mass flow rate
CM1045	kg/s	1.00	0	0	0	Calculated mass flow rate
CM2045	kg/s	1.00	0	0	0	Calculated mass flow rate
CP4640	ΔP mbar	1.00	500	170	100	
CP4651	PDPA	1.00	393	125	-60	Failed - Used for CV4651
CP4652	PDPA	1.00	393	125	52	Failed - Used for CV4652
CP4653	PDPA	1.00	400	145	-60	Used for CV4653
CP4654	PDPA	1.00	0	145	65	Used for CV4654
CP4655	PDPA	1.00	369	144	-85	Failed T51.21, 22, and 25 - Used for CV4655
CP4656	PDPA	1.00	369	144	-60	Failed T51.21, 22, and 25 - Used for CV4656
CP4657	PDPA	1.00	369	144	15	Used for CV4657
CP4661	PDPA	1.00	369	144	65	Used for CV4661
CP4662	PDPA	1.00	369	144	115	Used for CV4662
CP4663	PDPA	1.00	418	145	-85	Used for CV4663
CP4664	PDPA	1.00	418	145	-60	Used for CV4664
CP4665	PDPA	1.00	418	145	15	Failed
CP4666	PDPA	1.00	418	145	65	Used for CV4667
CP4667	PDPA	1.00	418	145	115	
CP6201	ΔP mbar	1.00	1005	0	1100	
CS3301	°C	1.00	220	90	-650	
CS3710	°C	1.00	1000	65	550	
CS3720	°C	1.00	1000	65	800	
CS4531	°C	1.00	605	185	110	
CS6601	°C	1.00	924	265	1200	
CT 405	°C	1.00	900	160	4000	
CT 411	°C	1.00	900	45	3400	
CT 412	°C	1.00	900	270	3400	
CT 413	°C	1.00	635	270	3900	
CT 414	°C	1.00	310	270	4600	
CT 420	°C	1.00	600	90	3900	
CT 421	°C	1.00	600	270	3900	
CT 422	°C	1.00	950	55	3400	
CT 423	°C	1.00	570	80	3400	
CT 424	°C	1.00	640	280	1200	
CT3702	°C	1.00	950	70	550	
CT3707	°C	1.00	740	44	-490	
CT4511	°C	1.00	530	175	-70	

Sensor	Parameter	Frequency (Hz)	Location R (cm)	Location θ (deg)	Location Z (cm)	Comments
CT4512	°C	1.00	685	175	-70	
CT4513	°C	1.00	690	187	-70	
CT4514	°C	1.00	750	205	-70	
CT4521	°C	1.00	530	175	20	
CT4522	°C	1.00	685	175	20	
CT4523	°C	1.00	750	205	20	
CT4531	°C	1.00	530	175	110	
CT4532	°C	1.00	645	172	110	
CT4533	°C	1.00	730	185	110	
CT4534	°C	1.00	810	205	110	
CT4541	°C	1.00	690	187	170	
CT4542	°C	1.00	685	175	170	
CT4543	°C	1.00	750	205	170	
CT4544	°C	1.00	815	181	170	
CT4545	°C	1.00	815	181	170	
CT4551	°C	1.00	590	177	100	
CT4552	°C	1.00	750	190	300	
CT4553	°C	1.00	590	177	50	
CT4554	°C	1.00	590	177	-10	
CT4555	°C	1.00	590	177	-80	
CT4556	°C	1.00	590	177	80	
CT4600	°C	1.00	706	235	310	Failed T51.21 and 23
CT4610	°C	1.00	466	177	-60	
CT4611	°C	1.00	466	177	15	
CT4612	°C	1.00	466	177	40	
CT4613	°C	1.00	466	177	65	
CT4614	°C	1.00	466	177	90	
CT4615	°C	1.00	466	177	102	
CT4616	°C	1.00	471	171	-60	
CT4617	°C	1.00	471	171	15	
CT4618	°C	1.00	471	171	40	
CT4619	°C	1.00	471	171	65	
CT4620	°C	1.00	471	171	90	
CT4621	°C	1.00	471	171	102	
CT4622	°C	1.00	373	172	75	
CT4623	°C	1.00	373	172	95	
CT4624	°C	1.00	373	172	115	
CT4628	°C	1.00	400	145	-85	
CT4629	°C	1.00	400	145	-60	

Sensor	Parameter	Frequency (Hz)	Location			Comments
			R (cm)	θ (deg)	Z (cm)	
CT4630	°C	1.00	369	144	15	
CT4631	°C	1.00	369	144	40	
CT4632	°C	1.00	369	144	65	
CT4633	°C	1.00	369	144	90	
CT4634	°C	1.00	369	144	115	
CT4635	°C	1.00	418	145	15	
CT4636	°C	1.00	418	145	40	
CT4637	°C	1.00	418	145	65	
CT4638	°C	1.00	418	145	90	
CT4639	°C	1.00	418	145	115	
CT4640	°C	1.00	370	125	15	
CT4641	°C	1.00	370	125	40	
CT4642	°C	1.00	370	125	65	
CT4643	°C	1.00	370	125	90	
CT4644	°C	1.00	370	125	115	
CT4645	°C	1.00	416	125	15	
CT4646	°C	1.00	416	125	40	
CT4647	°C	1.00	416	125	65	
CT4648	°C	1.00	416	125	90	
CT4649	°C	1.00	416	125	115	
CT4653	°C	1.00	500	215	0	
CT4654	°C	1.00	410	65	0	Failed
CT4655	°C	1.00	680	60	0	
CT4660	°C	1.00	610	82	-50	
CT4661	°C	1.00	430	105	-50	
CT4662	°C	1.00	390	125	-50	
CT4663	°C	1.00	400	145	-50	
CT4664	°C	1.00	400	165	-50	
CT4671	°C	1.00	430	105	100	
CT4672	°C	1.00	390	125	100	
CT4673	°C	1.00	400	145	100	
CT4674	°C	1.00	400	165	100	
CT4682	°C	1.00	390	125	130	
CT4684	°C	1.00	400	165	130	
CT4691	°C	1.00	404	91	215	
CT4692	°C	1.00	472	93	215	
CT5302	°C	1.00	980	55	600	
CT5303	°C	1.00	740	85	600	
CT5310	°C	1.00	600	75	470	

Sensor	Parameter	Frequency (Hz)	Location			Comments
			R (cm)	θ (deg)	Z (cm)	
CT5320	°C	1.00	558	71	440	
CT5321	°C	1.00	744	76	440	
CT5322	°C	1.00	722	99	440	
CT5323	°C	1.00	530	88	440	
CT6309	°C	1.00	820	235	800	
CT6606	°C	1.00	510	20	1200	
CT6607	°C	1.00	457	270	2257	
CT6609	°C	1.00	720	75	1200	
CT6610	°C	1.00	640	282	1040	
CT7702	°C	1.00	950	55	1700	
CT7703	°C	1.00	670	80	1700	
CT7802	°C	1.00	550	275	3100	
CT8402	°C	1.00	500	270	1900	
CT8502	°C	1.00	700	80	2300	
CT8503	°C	1.00	600	65	2300	
CV4640	m/s		540	168	96	
CV4641	m/s		590	177	-80	
CV4642	m/s		706	235	310	
CV4651	m/s		393	125	-60	Failed
CV4652	m/s		393	125	52	Failed
CV4653	m/s		400	145	-60	
CV4654	m/s		0	145	65	
CV4655	m/s		369	144	-85	Failed T51.21,22, and 25
CV4656	m/s		369	144	-60	Failed T51.21,22, and 25
CV4657	m/s		369	144	15	
CV4661	m/s		369	144	65	
CV4662	m/s		369	144	115	
CV4663	m/s		418	145	-85	
CV4664	m/s		418	145	-60	
CV4665	m/s		418	145	15	Failed
CV4666	m/s		418	145	65	
CV4667	m/s		418	145	115	
CV4670	m/s		380	125	120	
CV4671	m/s		380	125	120	
CV4676	m/s		398	140	120	
CV4681	m/s		380	125	120	Failed
CV4682	m/s		380	125	120	Failed
CV4683	m/s		398	140	120	Failed
CV4684	m/s		398	140	120	Failed
CV7701	m/s		650	85	1700	Failed

Sensor	Parameter	Frequency (Hz)	Location			Comments
			R (cm)	θ (deg)	Z (cm)	
CV7702	m/s		650	85	1700	Failed
CV7704	m/s		650	85	1700	
OA2015	Shell Expansion	1.00	1003	270	0	
OA3015	Shell Expansion	1.00	1003	270	0	
OA3016	Shell Expansion	1.00	1003	270	-100	

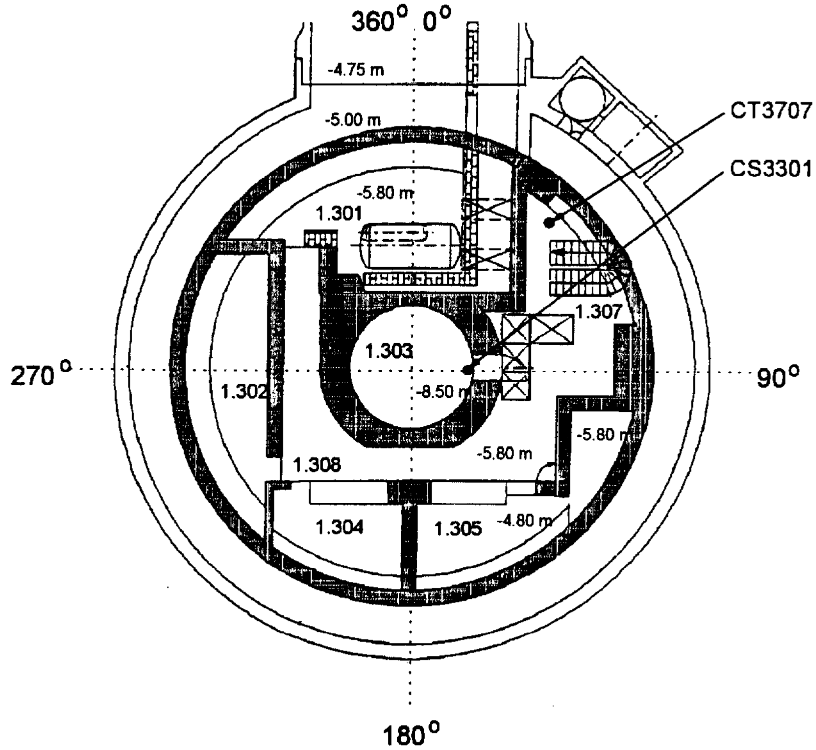

Figure 3.35: Level 1.200/1.300 at the -6.5 m Elevation for T51.2

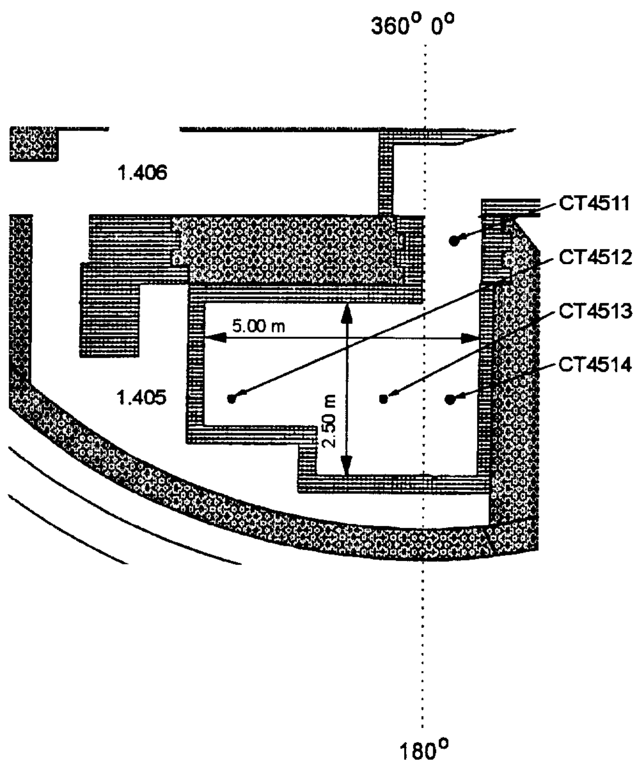

Figure 3.36: Fire Room at the -0.7 m Elevation for T51.2

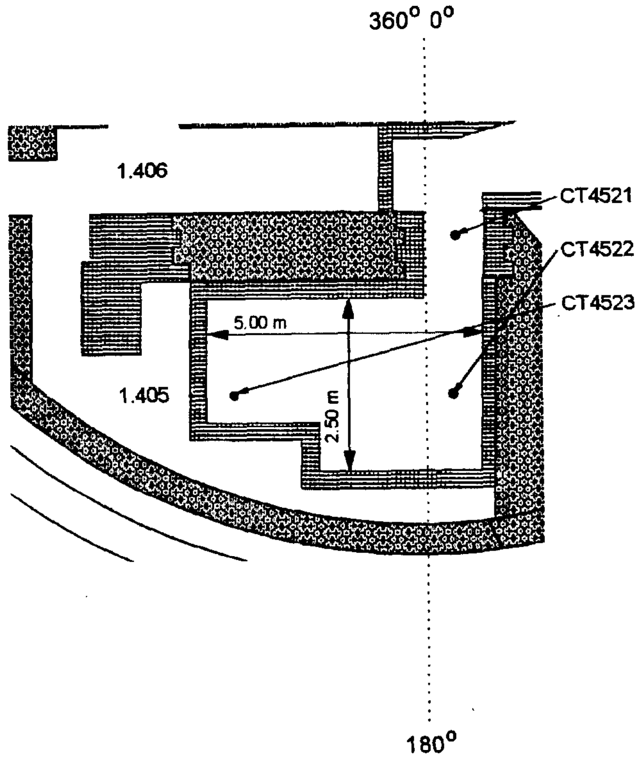

Figure 3.37: Fire Room at the +0.2 m Elevation for T51.2

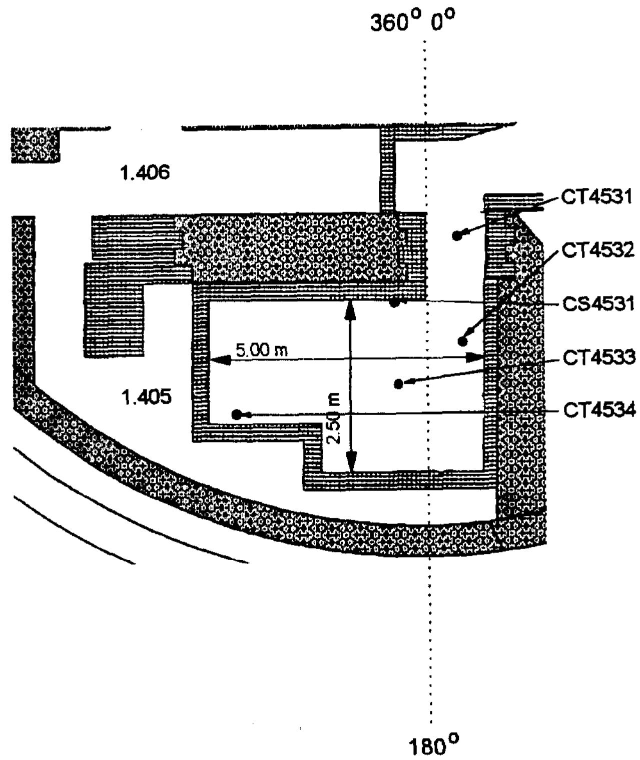

Figure 3.38: Fire Room at the +1.1 m Elevation for T51.2

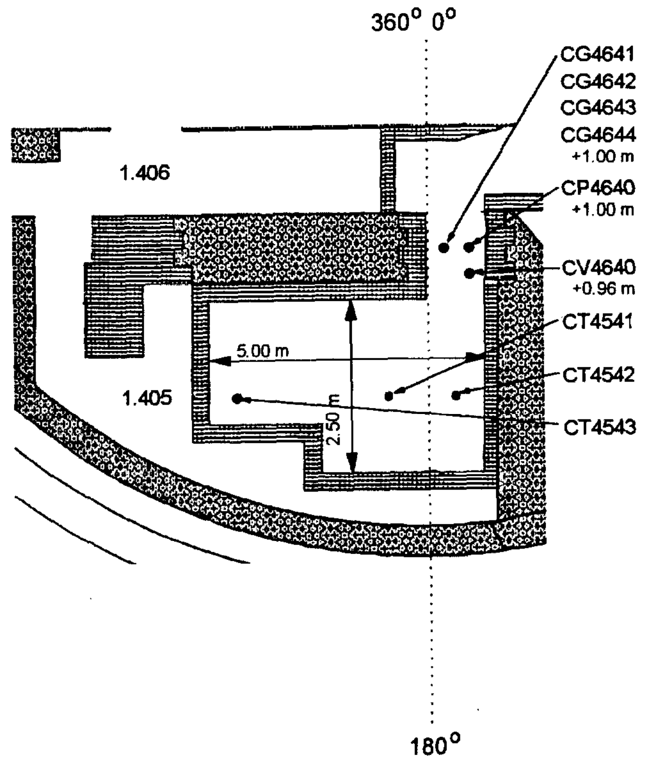

Figure 3.39: Fire Room at the +1.7 m Elevation for T51.2

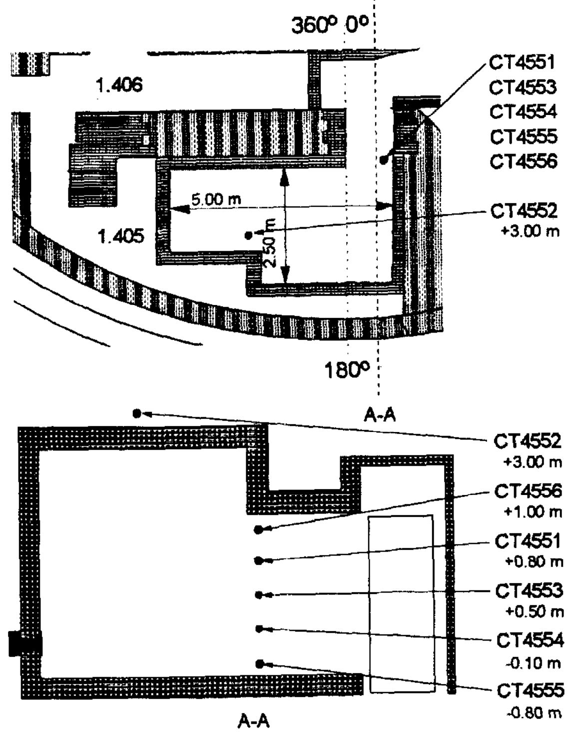

Figure 3.40: Fire Room Vertical Cross Section for T51.2

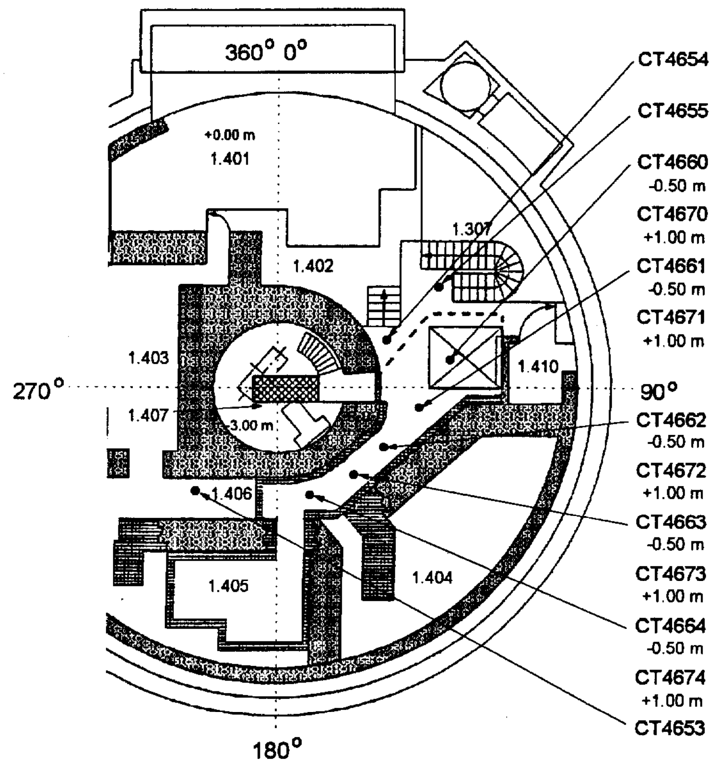

Figure 3.41: Level 1.400 TC's at the +0.0 m Elevation for T51.2

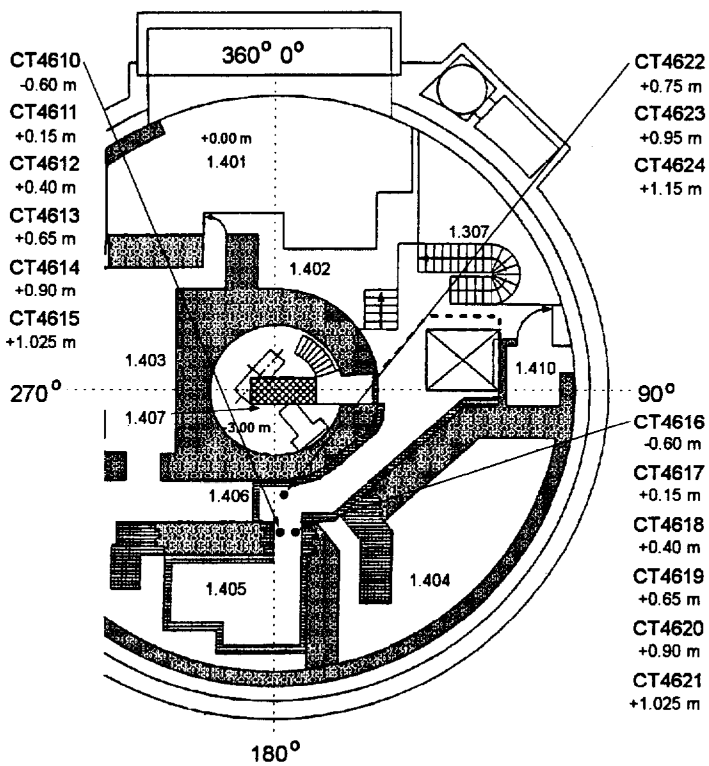

Figure 3.42: Fire Doorway TC's at the +0.0 m Elevation for T51.2

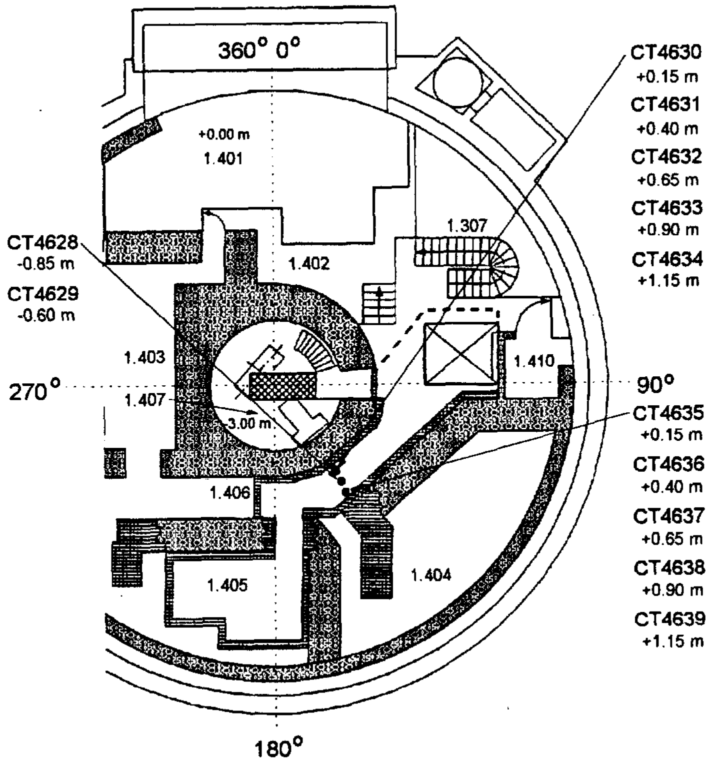

Figure 3.43: Fire Hallway TC's at the +0.0 m Elevation for T51.2

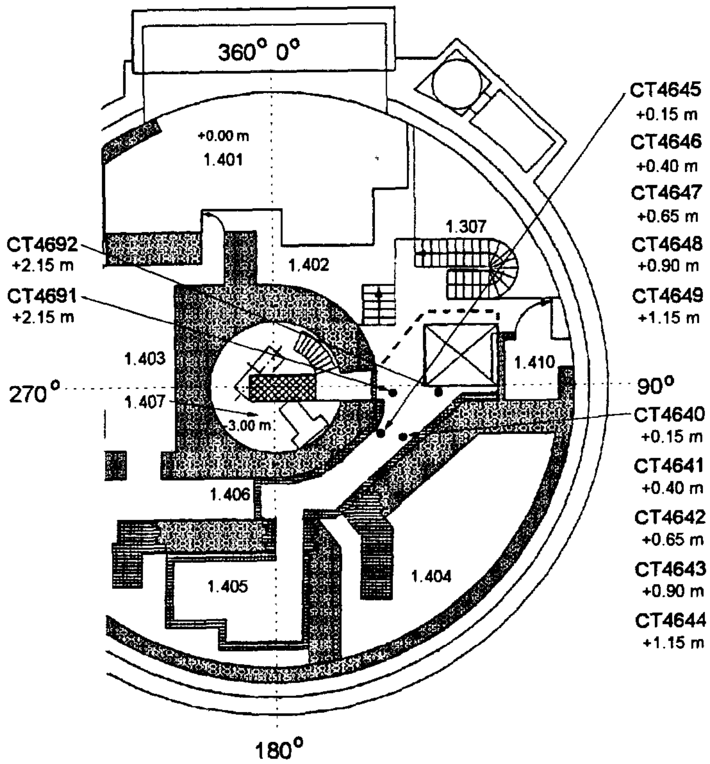

Figure 3.44: Fire Level Hatch TC's at the +0.0 m Elevation for T51.2

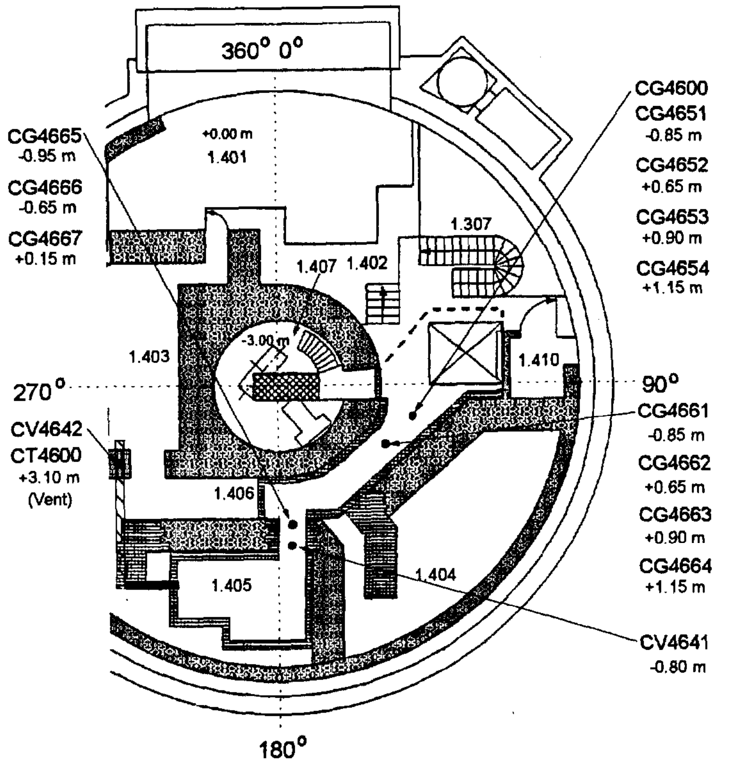

Figure 3.45: Level 1.400 Gas Sensors and Fire Room Vent Pipe Sensors for T51.2

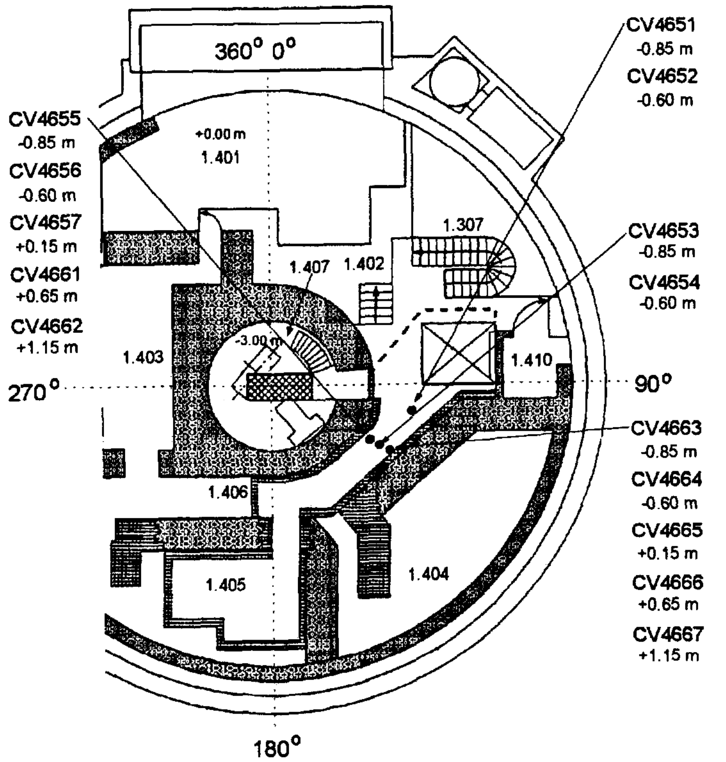

Figure 3.46: Fire Hallway Velocity Sensors for T51.2

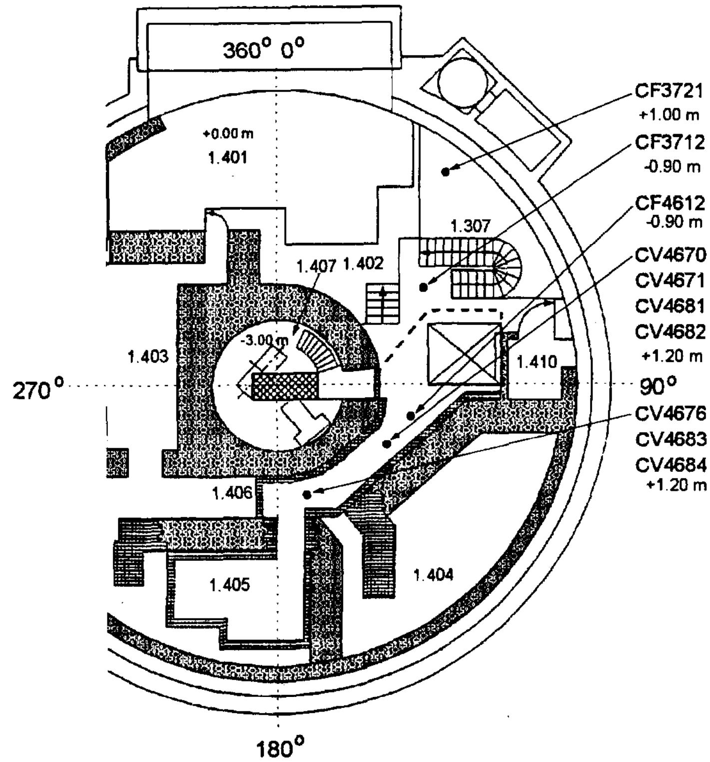

Figure 3.47: Level 1.400 Velocity Sensors for T51.2

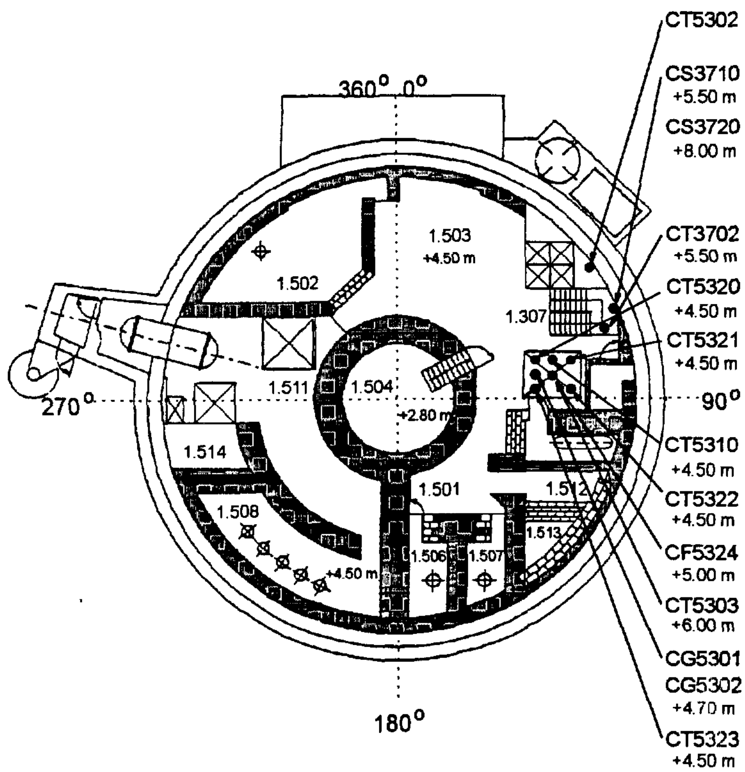

Figure 3.48: Level 1.500 at the +6.0 m Elevation for T51.2

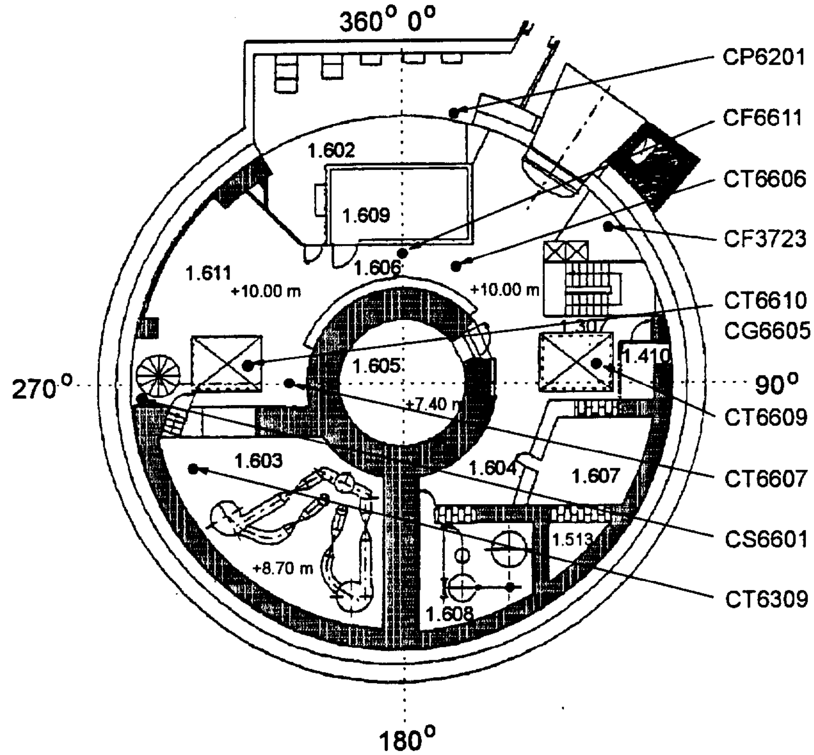

Figure 3.49: Level 1.600 at the +12.0 m Elevation for T51.2

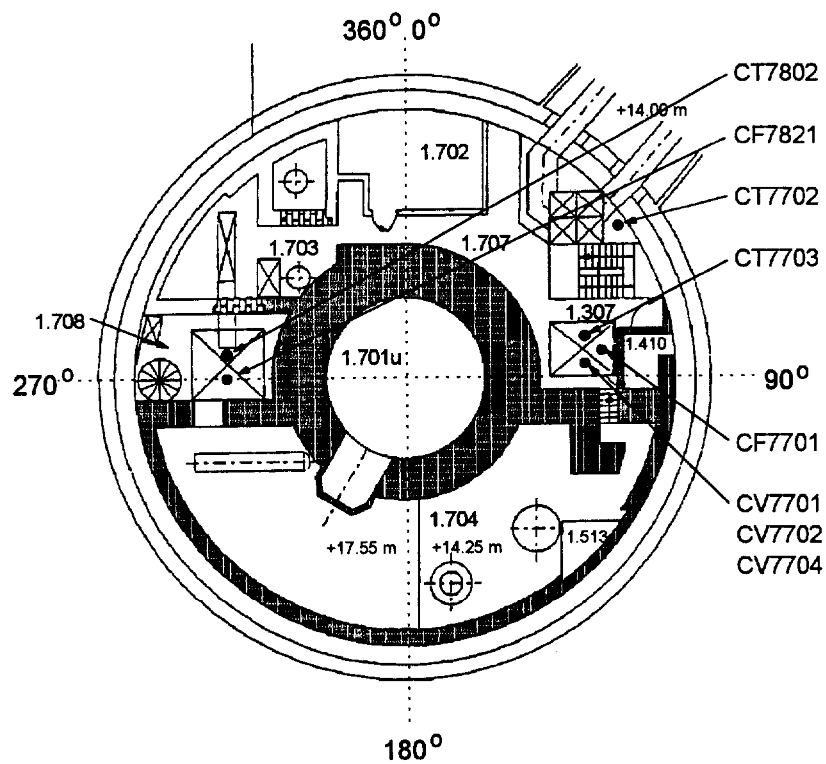

Figure 3.50: Level 1.700 at the +17.0 m Elevation for T51.2

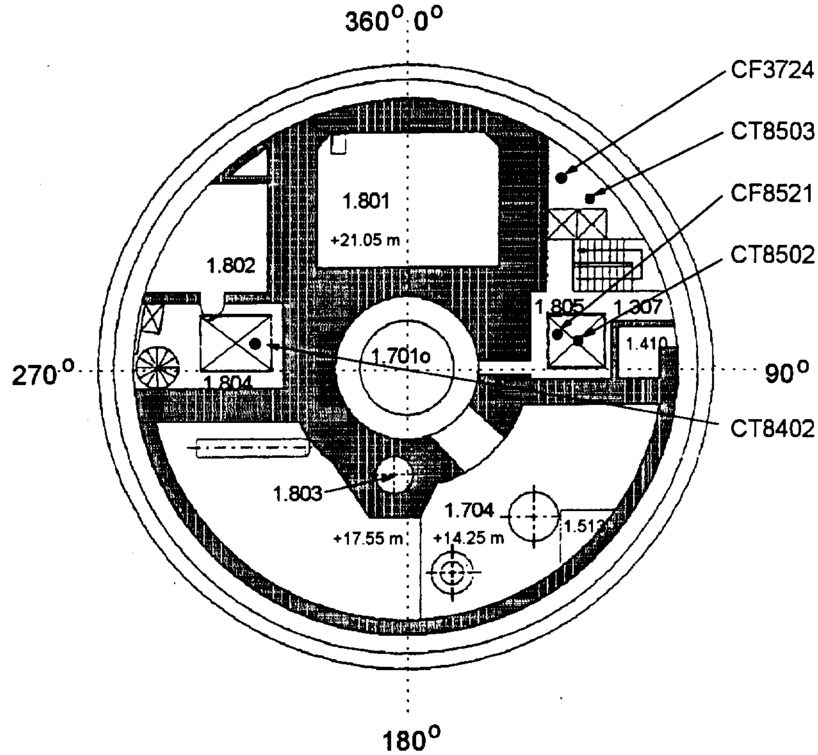

Figure 3.51: Level 1.800 at the +23.0 m Elevation for T51.2

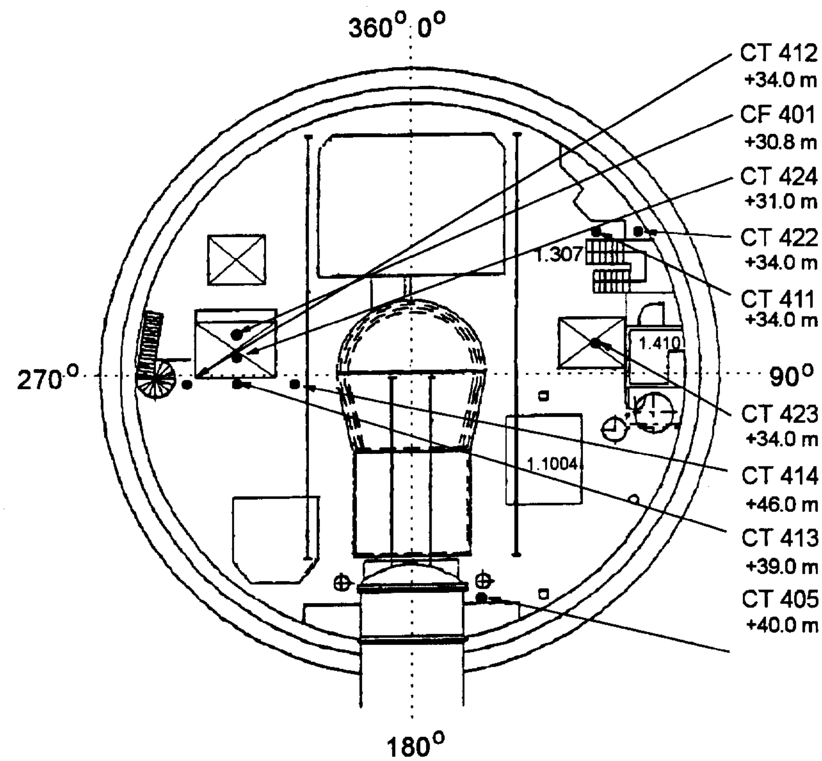

Figure 3.52: Dome Level at the +31.0 m Elevation for T51.2

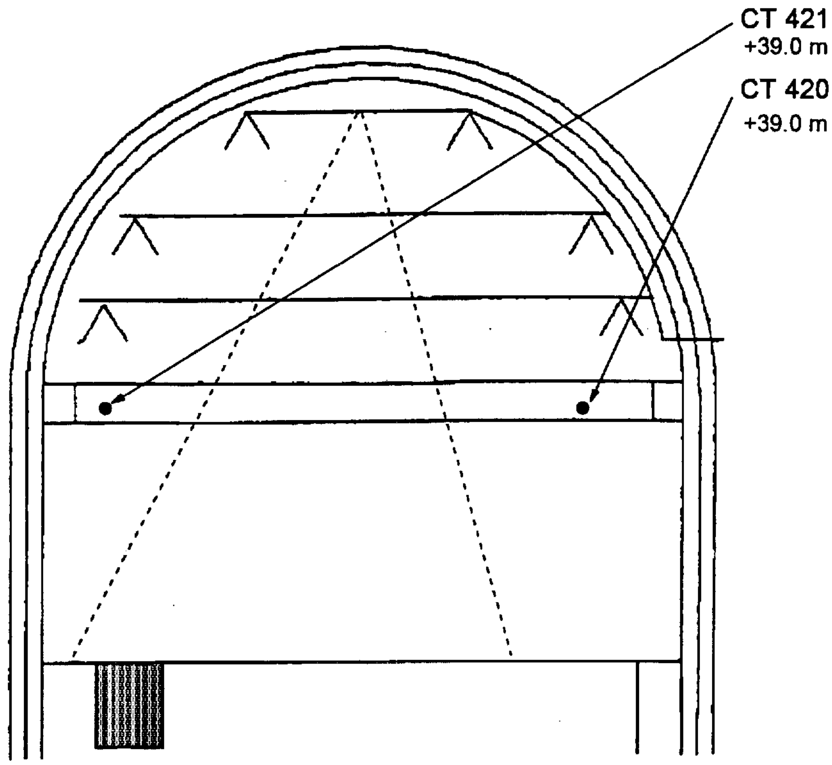

Figure 3.53: Dome Vertical Cross Section for T51.2

4 TEST EXECUTION

The test execution procedure for the gas fire tests was relatively simple. Approximately one half hour before the start of each test the data acquisition system was activated. After verifying the operation of the data acquisition system the appropriate burners were started, as given in Table 1.1. One hour after the start of the burners, the burners were shut off. After thirty minutes of cooldown, the containment ventilation systems were activated to exhaust the facility. Data recording was deactivated approximately forty minutes after the burners were shut off.

Data collected during each test was archived on reel-to-reel magnetic tape. During the archiving process the start of the fire was set to be zero minutes and ten minutes of data before the start of the fire was written. For an unknown reason, when the data for test T51.23 was archived the start of the fire was set to approximately -130 seconds with the data still starting at -600 s. The data for T51.23 indicates that the length of the fire was still 60 minutes. Data was archived until 100 minutes after the start of the fire (100 minutes plus 130 seconds for T51.23).

5 OVERVIEW OF EXPERIMENTAL RESULTS

This section contains selected results from the gas fire tests performed in the HDR facility. Data from selected instruments for three tests are shown in the first subsection to give a general overview of the transient data. Results representing maximum zonal values from the test series are then given followed by selected individual parameters illustrating the effects of ventilation system changes. Plot legends in this section indicate the instrument names and elevations; the instrument locations can be identified in Section 3 of this report. Transient temperature and velocity data documented the first and third subsections are shown as the change in the plotted parameter from the value at the start of the fire. This was done to remove the effects of slightly different initial temperatures in the HDR facility for the different tests.

5.1 Selected Results

The three tests whose results are shown in this section are T51.11, T51.19, and T51.21. These tests with respective fire powers of 229 kW, 1255 kW, and 716 kW span the range of fire intensities examined during this test series. The first two figures, Figures 5.1 and 5.2, show upper and lower layer temperatures in the fire room.

The following observations hold:

- The higher the fire power the faster the thermal response is in a particular layer.
- Temperature differences between hot and cold layers decrease with increasing fire power.
- Evidently, post-flashover conditions were obtained in experiment T51.19, e.g. the fire totally engulfed the whole fire room with the lower layer even somewhat hotter than the upper layer.
- Except for the lowest fire power, T51.11, temperature of both layers continuously increase over time for both experiments T51.19 and T51.21, indicating transient conditions throughout the respective test period.
- For the lowest fire power, steady-state conditions are reached for both layers four minutes into the experiment. This indicates that no new energy transfer processes occur thereafter and that a stable stratification prevails.
- Immediately after shutting off the gas burners, temperatures of both layers rapidly decrease, with the lower layer portraying a faster cooldown response than the upper layer for all fire powers tested.
- Probably as a results of continued cold, fresh air supply, the lower layer temperatures decrease faster and reach lower temperatures during the 30 minute cooldown period.
- Contrary, the upper layer temperature response during cooldown is slower and is maintained at higher values over the 30 minute cooldown period displayed. This delayed cooldown response is caused by reduced flow velocity, possibly stagnation, and the lower layer as the only heat sink.
- In summary, whereas the fast thermal response of the upper gas layer dominates the initial heatup phase, the lower gas layer controls the cooldown phase after the fire ceased.

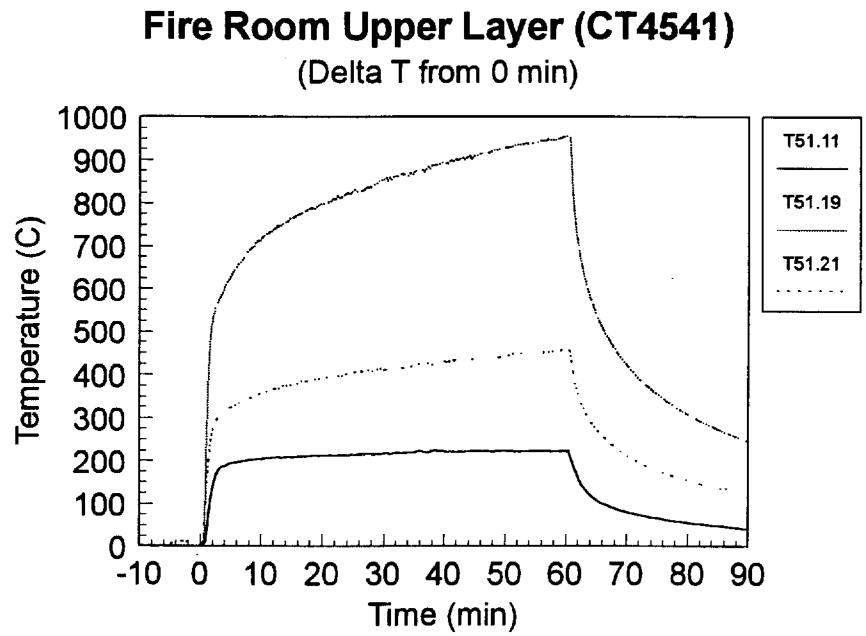

Figure 5.1: Fire Room Upper Layer Temp.

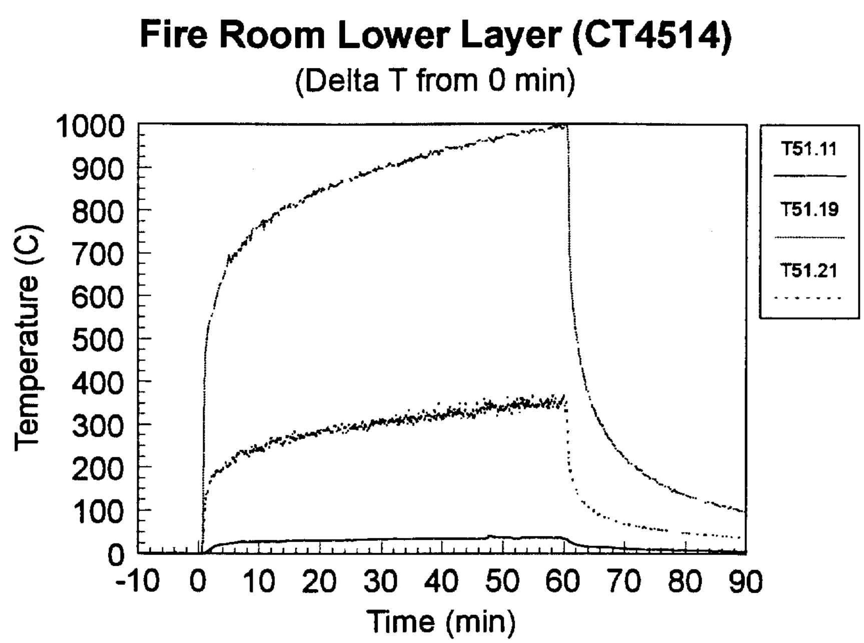

Figure 5.2: Fire Room Lower Layer Temp.

The second two figures below, Figures 5.3 and 5.4 show temperatures in the hallway midway between the fire room and the hatch.

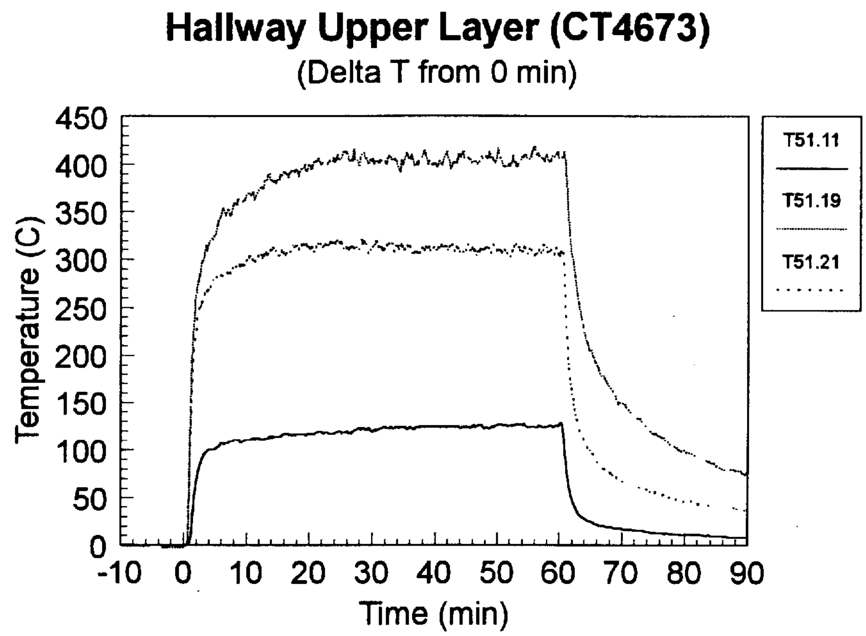

Figure 5.3: Hallway Upper Layer Temp.

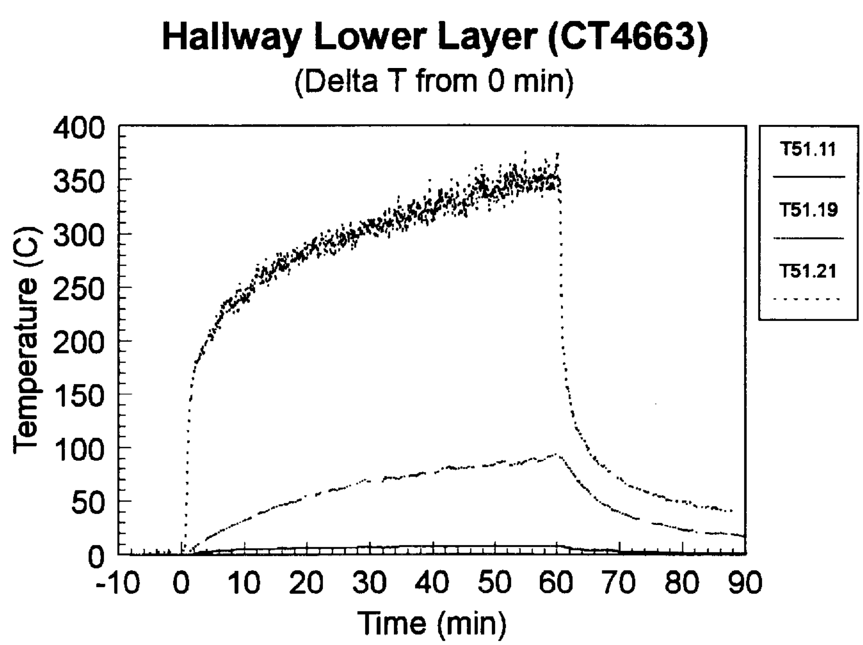

Figure 5.4: Hallway Lower Layer Temp.

The following conclusions can be drawn:

- Most importantly, the comparisons between the two sets of figures 5.1/5.2 and 5.3/5.4 clearly indicate that gas layer temperatures are less than half their values in the fire room. This means that over the rather short distance downstream of the fire room exit highly effective, energy transfer processes take place.
- The upper gas layer reaches quasi-steady state conditions after 10 minutes for T51.11, 20 minutes for T51.21, and 30 minutes for T51.19; e.g. as a function of the fire power at the upper layer location indicated by CT4673.
- Contrary, the lower gas layer temperature continuously increases over the duration of the fire.
- For higher powered fires, upper and lower layer temperatures, especially the latter, show high frequency fluctuations. These are indicative of thermal mixing layers.
- Upon completion of the fire, the respective cooldown characteristics show the same features as already observed and discussed for the fire room.

Figures 5.5 though 5.7 below show temperatures in the main staircase hatches between the 1.400, 1.500, 1.700, 1.800, and 1.900 levels and the dome. Note that each figure uses a different scale.

These experimental results can be summarized as follows:

- Figure 5.5
  - Comparisons between the set of figures 5.3/5.4 and 5.5 indicate an additional, substantial decrease in the temperature between the midway of the hallway and the hatch. Temperatures are again halved.
  - The temperature traces for all fire powers indicate the existence of both low and high frequency fluctuations, with the low frequency showing some characteristic periodicity. This may results from countercurrent flows over the height of the vertical shaft formed by the main staircase hatches.

- Figures 5.6 and 5.7
  - Temperatures of the fire induced gas plume gradually decrease with axial elevation.
  - Nevertheless, the temperature signals clearly indicate that the gas plume reaches the operating deck. Therefore, the fire initiated at the low level of the fire room encompasses and impacts the building over the total height potentially transporting smoke particles into the dome region.

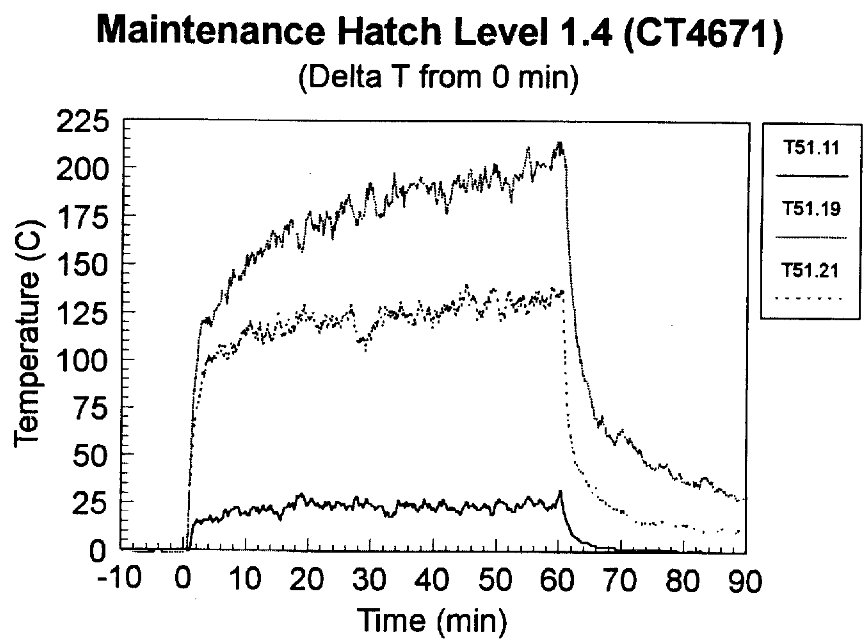

Figure 5.5: Main Staircase Hatch Temp. at Level 1.4

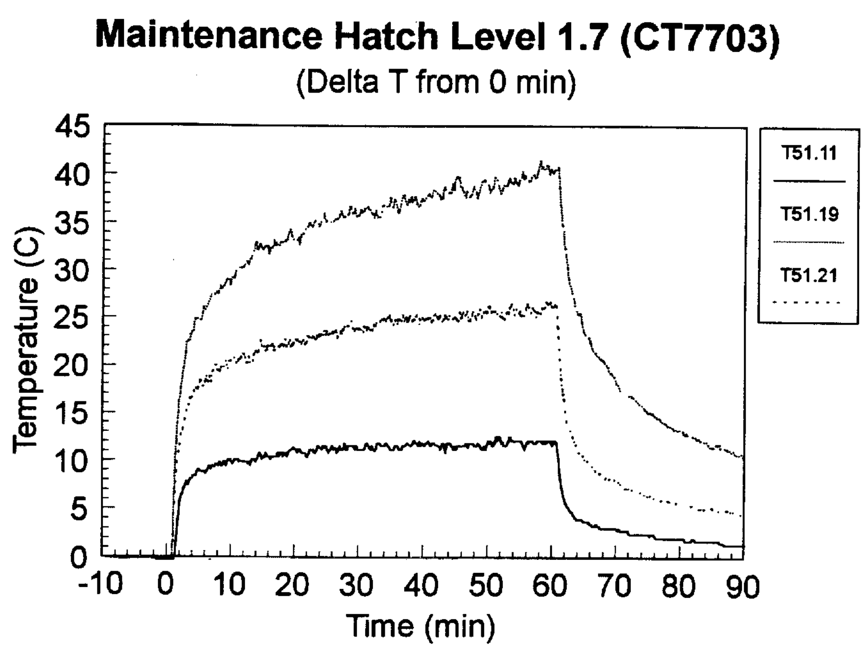

figure 5.6: Main Staircase Hatch Temp. at Level 1.7

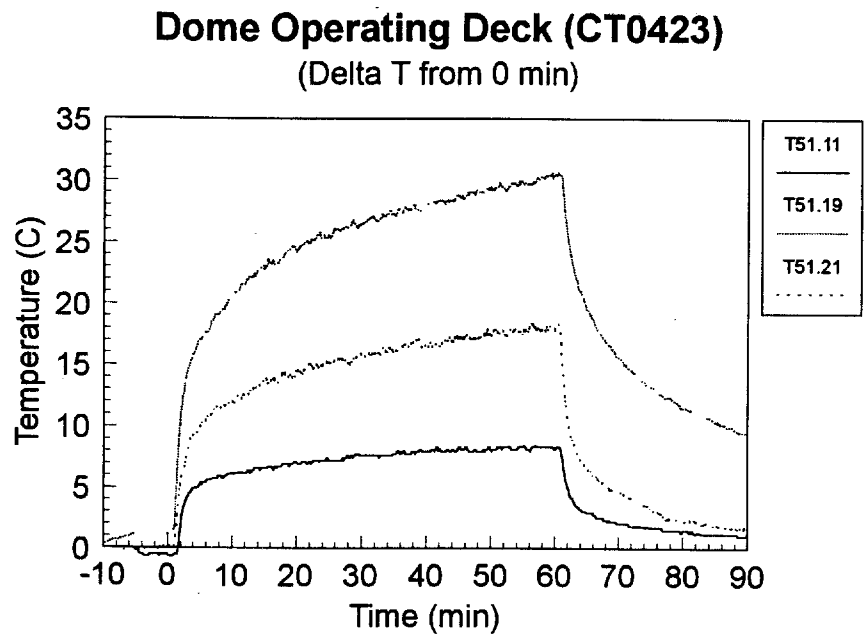

Figure 5.7: Main Staircase Hatch Temp. at Operating Deck

Figures 5.8 and 5.9 below show O_2 and CO_2 concentrations in the upper layer of the fire room doorway. The major observations can be summarized as follows:

- Oxygen consumption and carbon dioxide production in the upper gas layer increase nearly instantaneously and reach levels dependent on the fire power under examination.
- Oxygen concentration is lowest, 5 v/o, and CO_2 highest, 8 v/o, for the highest power test.
- For the lowest power test, steady state concentrations are attained shortly after fire initiation, whereas for the higher fire powers, O_2 consumption and CO_2 concentration continue to increase over time.
- Once the fires ceased, oxygen is replenished in the upper layer and CO_2 production is ceased and drops to 1 v/o nearly instantaneously.

Figures 5.10 and 5.11 show measured velocities in the upper layer at the doorway and in through in the main staircase, maintenance hatch between levels 1.7 and 1.8. These figures provide a rough picture of the convective currents at the fire room building level, horizontal flow, and in the high rise vertical shaft, vertical flow. The following conclusions can be drawn from these figures:

- The horizontal upper gas layer velocities range between 2 m/s and 7.3 m/s depending on the fire power applied. All velocity signals show fluctuations.
- The vertical gas plume velocities range between 1 m/s and 3.5 m/s high up in the vertical shaft. All velocity signals show fluctuations which are evidently dependent on the fire power, e.g. the plume interface with the environment changes its size as a function of fire power.
- Once the fire ceases, velocities of the upper gas layer and plume in the shaft decrease. However, driving forces are large enough to sustain substantial movement of the containment atmosphere for continued cooldown.

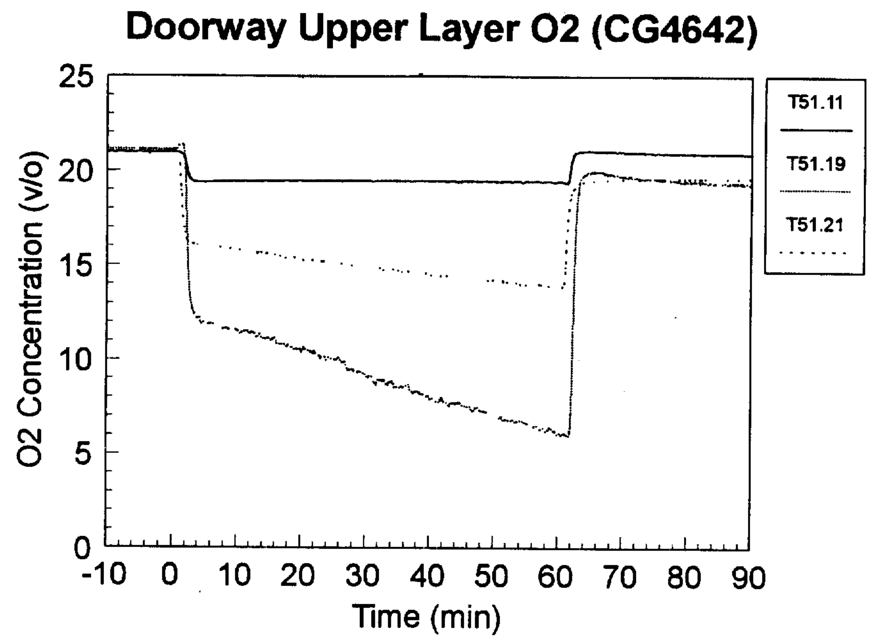

Figure 5.8: Doorway Upper Layer O_2

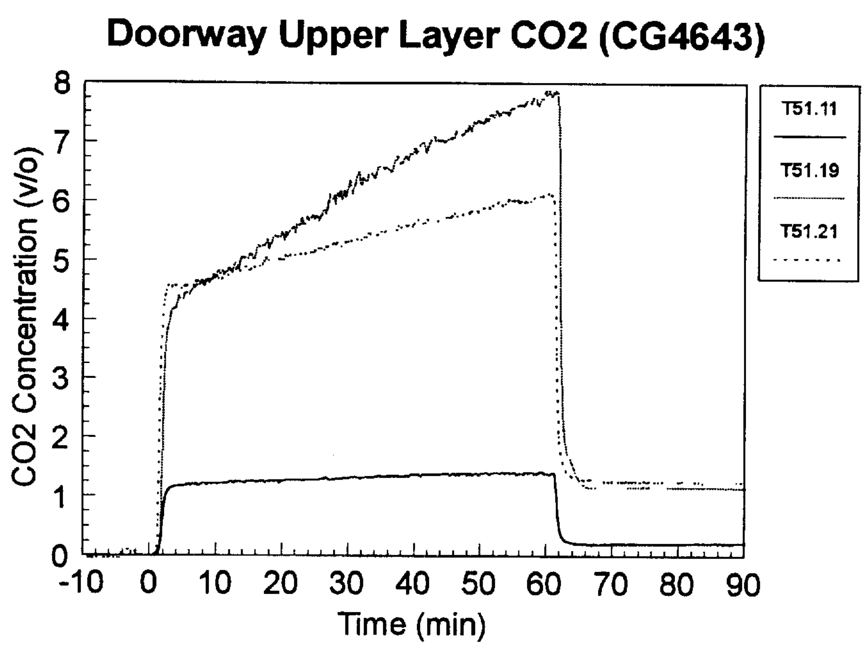

Figure 5.9: Doorway Upper Layer CO_2

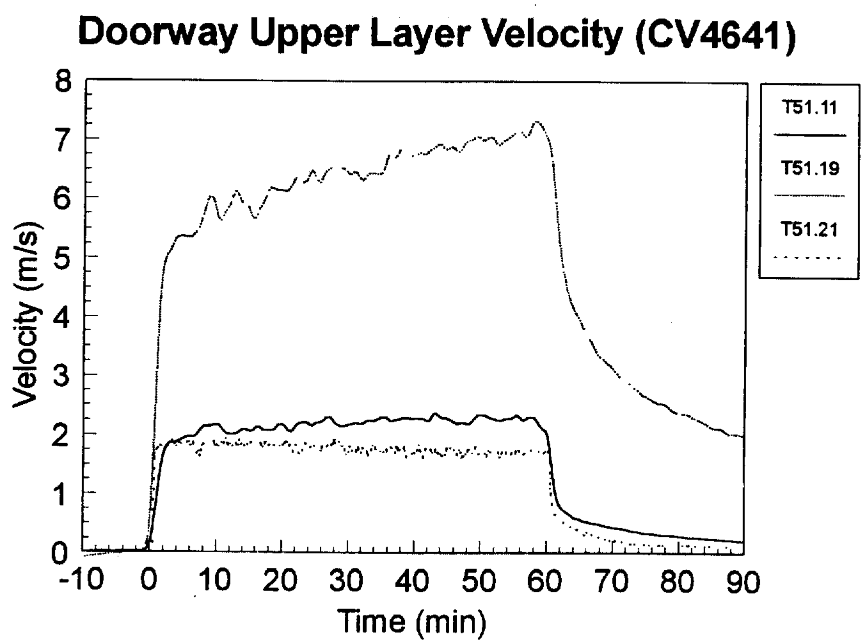

Figure 5.10: Doorway Upper Layer Velocity

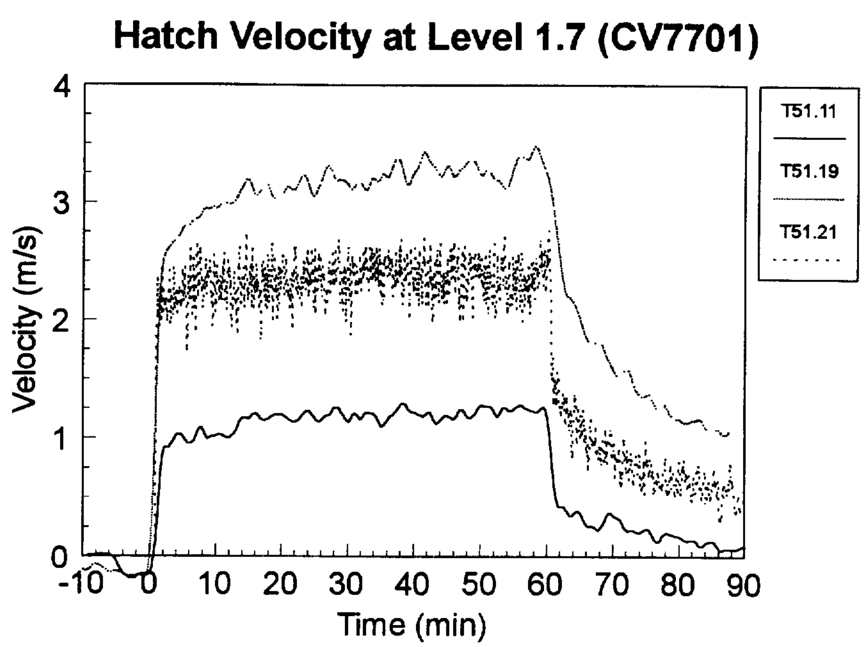

Figure 5.11: Main Staircase Hatch Velocity at Level 1.7

5.2 Representative Experimental Results

The following figures include data from tests T51.11-15, T51.19, T51.21, and T51.23, e.g. as a function of fire power. Data from tests T51.22, T51.24, and T51.25 are not included in this section as those tests feature a different ventilation system configuration from the other tests, and, thus, are not directly comparable. The figures show data at 58 minutes into the fire, and thus, represent maximal values for the tests. Figures 5.12 and 5.13 compute temperatures measured by thermocouples in the upper half and lower half of the fire room. Data are plotted versus the fire power used in the test. The following observations can be made from these figures:

- Upper and lower gas layer temperatures linearly increase with fire power up to about 800-1000 kW. For higher fire powers, temperatures asymptotically approach a maximum value.
- The upper gas layer has a uniform temperature.
- The lower gas layer shows a distinctive temperature distribution across the layer height for powers up to 1000 kW.
- For powers greater than 1000 kW, the whole fire room becomes completely flame engulfed and temperatures as high as 1000 °C prevail everywhere, e.g. conditions of nearly uniform fire room temperature exist.
- Replicated experiments such as T51.23, 1011 kW, and T51.24, 1025 kW, lead to excellent agreement between the respective comparable data given the complexity of the facility and the fact that these experiments were performed several months apart.
- This observation does not hold for the set of experiments T51.21, 716 kW, and T51.13, 692 kW, which should actually produce comparable data. The apparent differences between T51.21 in comparison with experiment T51.13 were obviously caused by the fact that different groups of burners were used for the two tests. T51.13 used the four central burners of the six available, whereas, T51.21 was performed with the four outer burners, all but the two central burners. This selection caused a lower temperature region in the center and also provided closer proximity of the side burners to the wall for energy transfer.

Figures 5.14 and 5.15 compare temperatures along the upper and lower layers of the hallway leading from the fire room to the maintenance hatch. Most of the observations made above for the fire room still apply to the hallway. In addition the following conclusions can be drawn:

- CT4670 which is located below the hatch does not appear to be in the plume from the fire in any test, indicating that the plume passes through the right hand side of the hatch.
- Lower layer temperatures in the hallway are close to ambient away from the fire room. Near the fire room doorway the temperatures are much higher, indicating that a large degree of mixing between the layers occurs along the hallway and in the vicinity of the doorway.

Figures 5.16 and 5.17 display the O_2 and CO_2 concentrations measured in the upper layer of the fire room doorway. As to be expected the data indicate that as fire power increases the hot gasses leaving the fire room become increasingly depleted in O_2 and increasingly enriched in CO_2. At the highest fire powers the data becomes more scattered due to intense turbulence and mixing that occurs at the fire room exit.

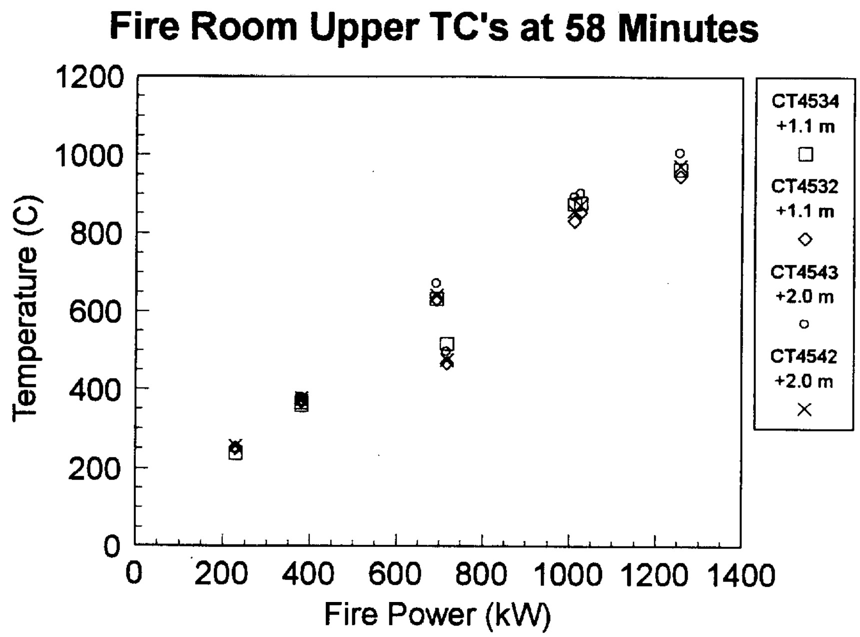

Figure 5.12: Fire Room Upper Layer Temp.

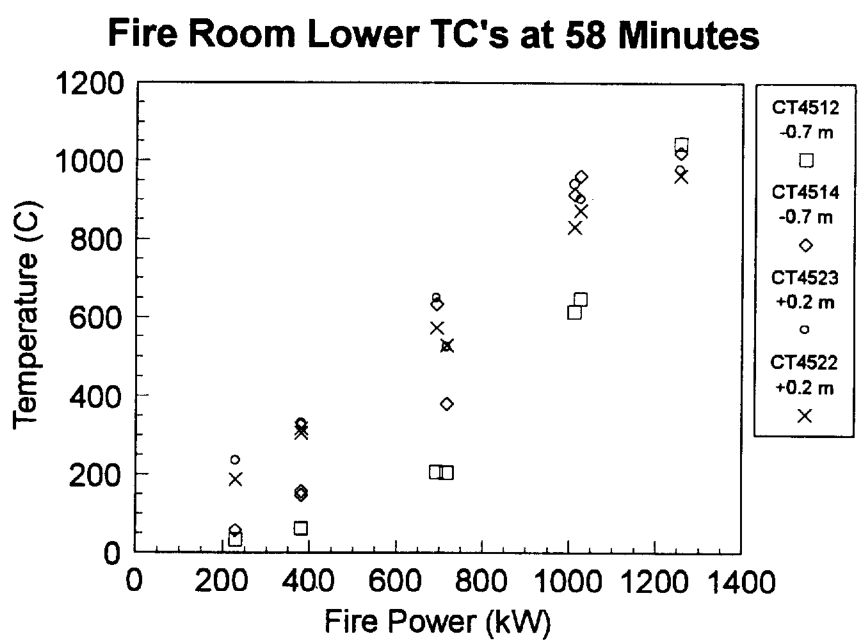

Figure 5.13: Fire Room Lower Layer Temp.

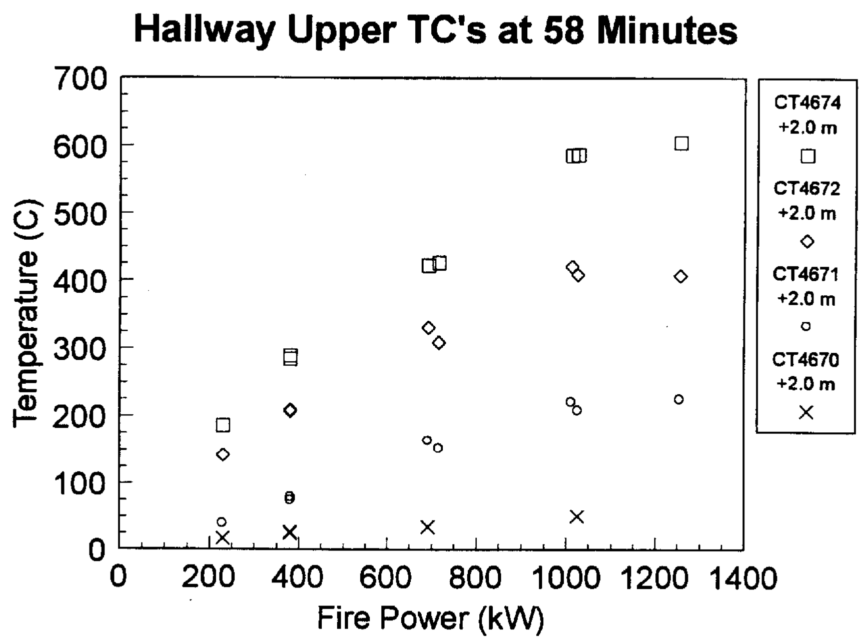

Figure 5.14: Hallway Upper Layer Temp.

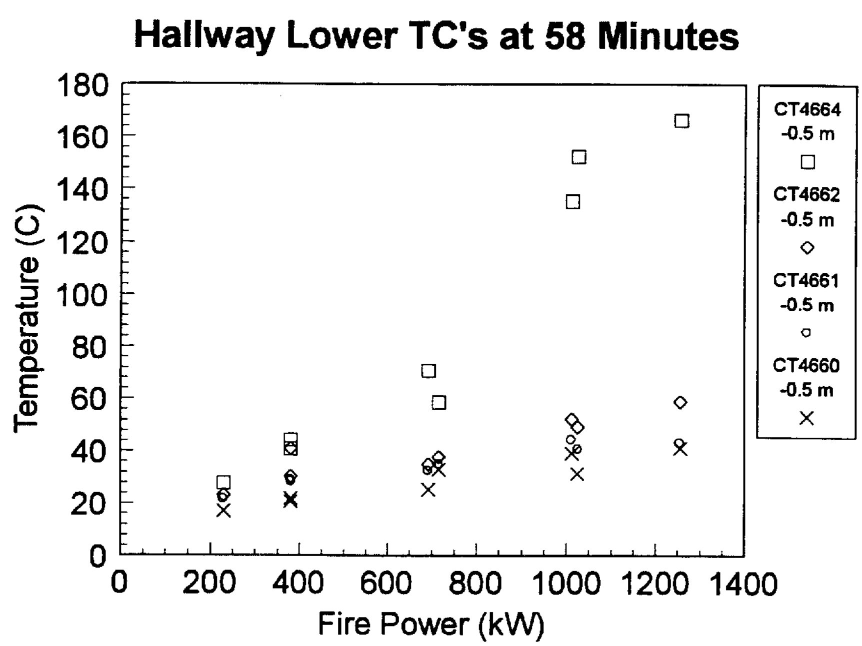

Figure 5.15: Hallway Lower Layer Temp.

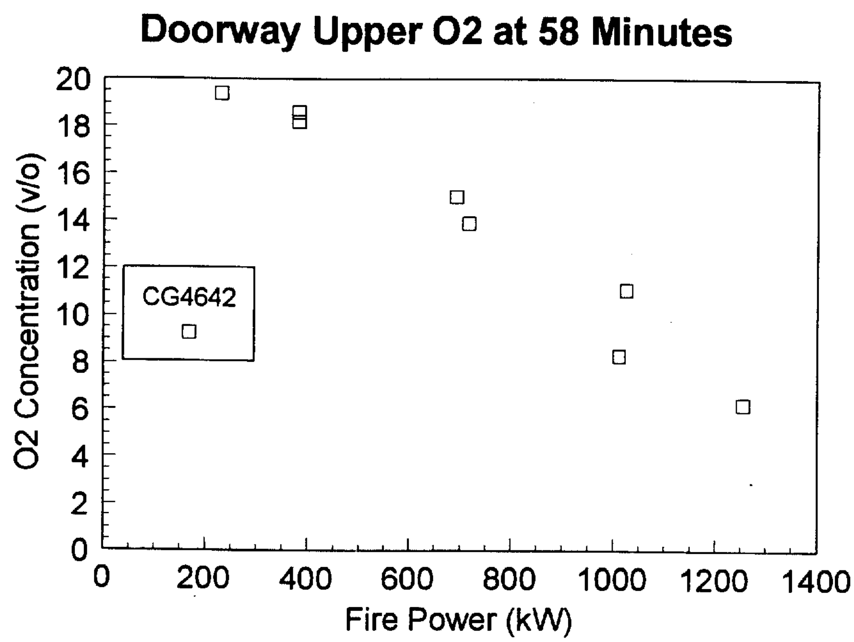

Figure 5.16: Doorway Upper Layer O_2

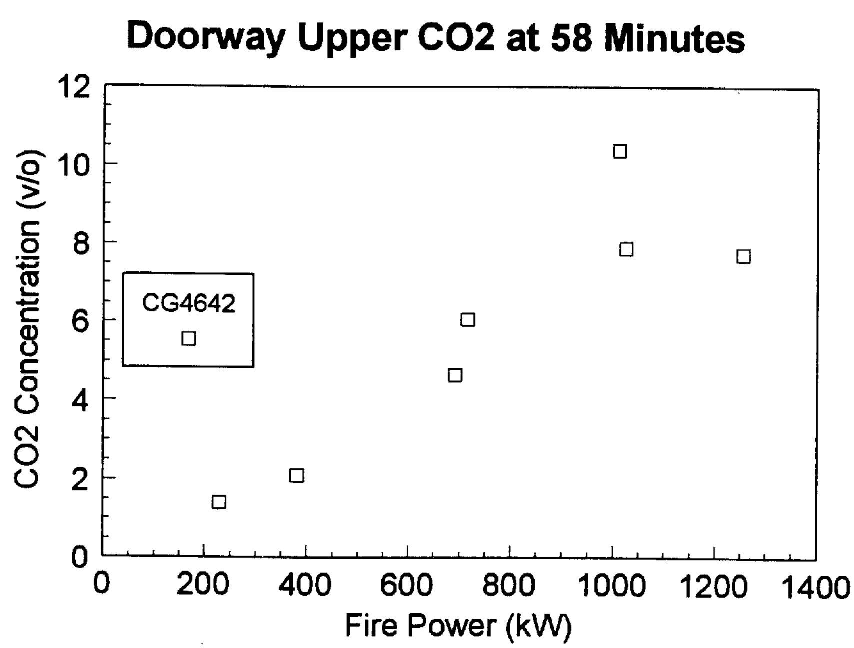

Figure 5.17: Doorway Upper Layer CO_2

Figures 5.18 and 5.19 on the next page show temperatures and velocities along the vertical flow path formed by the maintenance hatches at the main staircase. These figures indicate the following:

- A plume moving up through the hatches with continuous decrease in temperature at higher elevations.
- The plume velocity increases as fire power increases.
- For the repeated tests T51.21 (716 kW) and T51.23 (1011 kW) the CT5303 sensor location does not appear to be in the plume for these tests.
- The repeated tests also show a larger scatter in velocity which along with the temperatures clearly demonstrates the fluctuating nature of buoyant plumes. The maximum velocities at 23 m are about 4 m/s.

Figures 5.20 and 5.21 compare temperatures at the upper deck by the main staircase, around the top of the dome to the upper deck by the spiral staircase, and then down the vertical flow path formed by the maintenance hatches by the spiral staircase. The continuously decreasing temperature along this flow path indicates that the plume from the fire does not spread across individual floors to the spiral staircase, but rather creates a large circulation loop inside the containment building. This is further demonstrated in Figures 5.22 and 5.23 which trace temperatures for individual fire tests from the fire room, through the hallway, and then along the circulation path defined above.

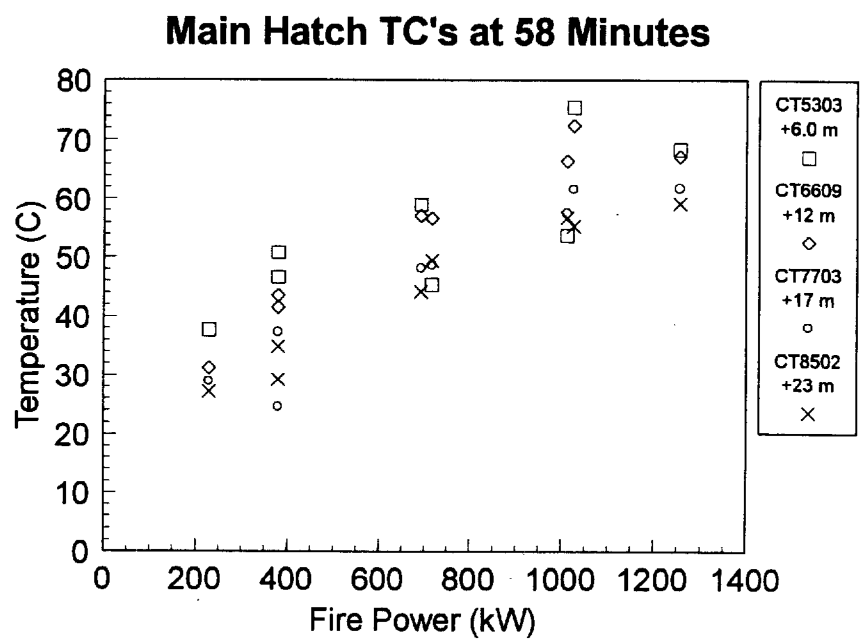

Figure 5.18: Main Staircase Hatch Temps. at Multiple Levels

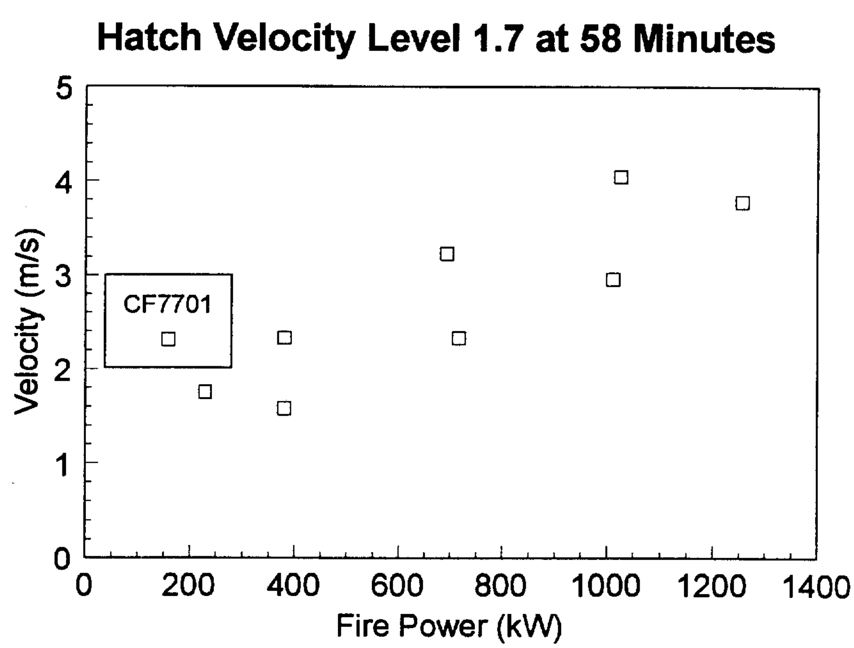

Figure 5.19: Main Staircase Hatch Velocity at Level 1.7

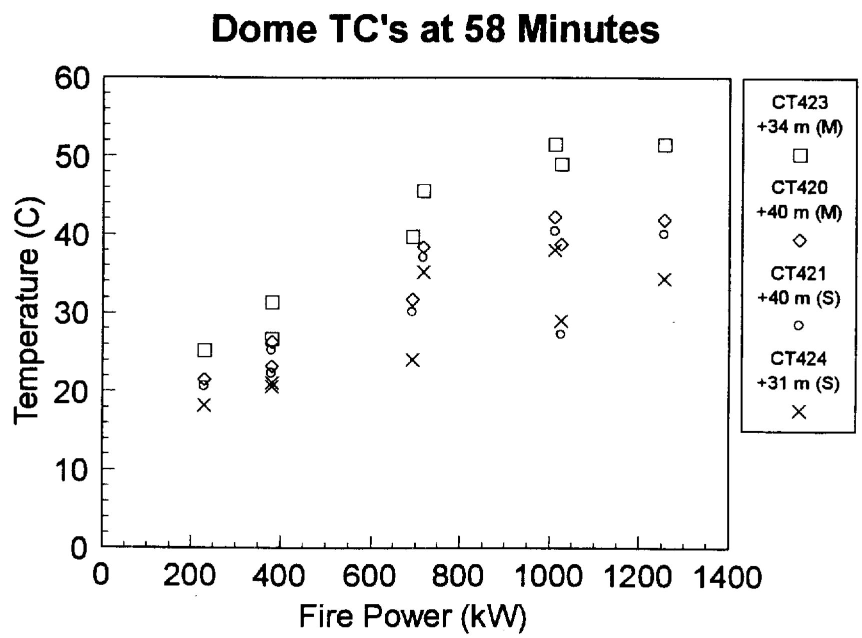

Figure 5.20: Dome Temperatures

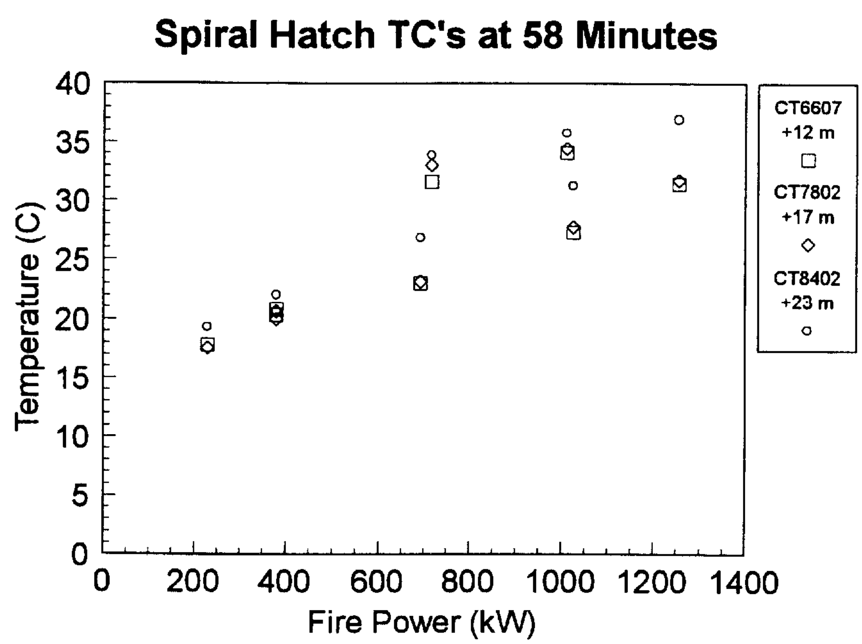

Figure 5.21: Spiral Staircase Hatch Temps. at Multiple Levels

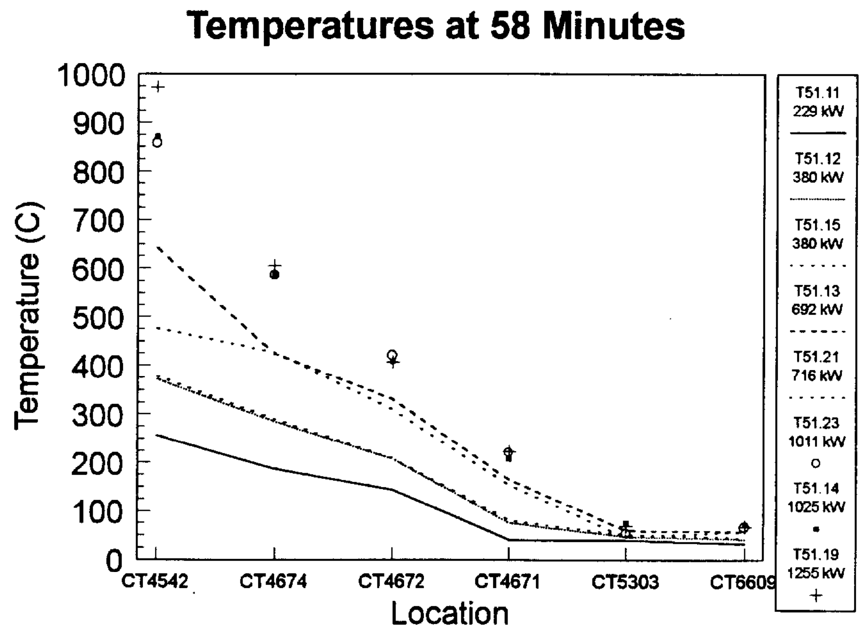

Figure 5.22: Fire Plume Temps. from Fire Room to Main Hatch at Level 1.6

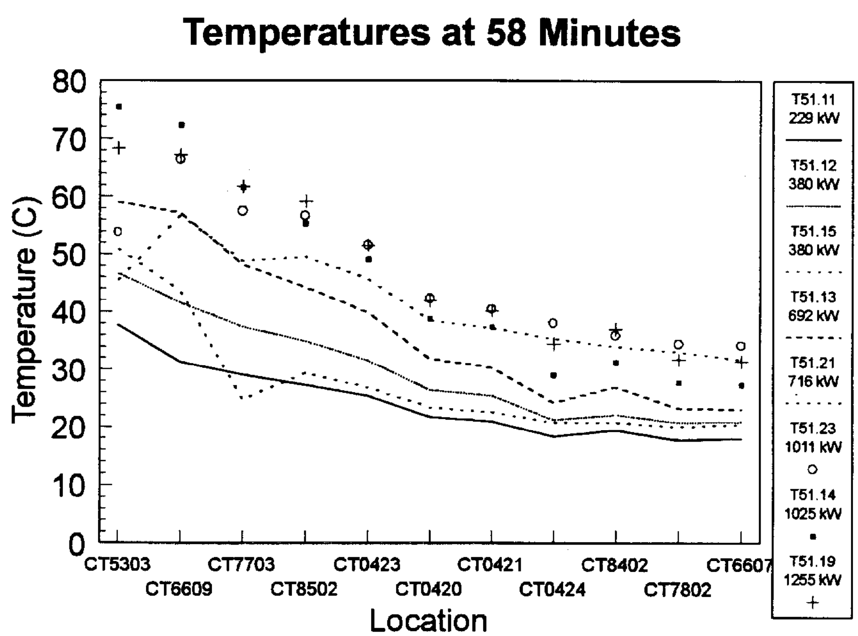

Figure 5.23: Fire Plume Temps. from Main Hatch at Level 1.5 to Spiral at 1.6

5.3 Selected Ventilation Change Data

The final group of gas fire tests included three tests were the fire room ventilation was changed. The additional ventilation system is described in Section 2 of this report. The charts following compare selected instruments for tests T51.21 and T51.22 and for tests T51.23 and T51.25. Tests T51.21 and T51.23 involved no changes in the ventilation. Test T51.22 was a repeat of T51.21 with the additional vent fully open for the first 30 minutes of the fire, 75% open for the next 15 minutes, and 25% open for the remainder of the test. Test T51.25 was a repeat of T51.23 with the additional vent fully open for the first 30 minutes of the fire and fully closed for the remainder of the test.

Figures 5.24 through 5.27 show temperatures in the hot and cold layers of the fire room. Having the vent open at the beginning of the fire resulted in lower fire room temperatures. Closing the vent in test T51.22 to 75% open from 100% open did not have much effect on the hot layer temperature, but it did affect the cold layer temperature. Closing the vent to 25% open in T51.22 or fully closed in T51.25 caused the fire room temperatures to quickly increase.

The next two figures, Figures 5.28 and 5.29 indicate that temperatures in the main staircase, maintenance hatch at the 1.600 level. These figures show that the extra ventilation in the fire room reduced the temperature in the shaft formed by the hatches. As in the fire room, the 100% to 75% ventilation change did not have much effect on the temperature, but the ventilation change to 25% open or fully closed caused a rapid increase in the temperature.

The final two figures, Figures 5.30 and 5.31 compare temperatures in the spiral staircase, maintenance hatch at the 1.700 level; the additional ventilation exited at the hatch on the 1.600 level. With the vent fully open there was a much higher temperature seen on the spiral staircase side of the building which indicates that a significant flow occurred through the additional ventilation. Unlike the other instruments shown, CT7802 displays large responses to any of the changes made in the room ventilation including the 100% open to 75% open change in test T51.22. In tests T51.2, completely closing the vent resulted in the temperature quickly resuming the same profile it had in test T51.23.

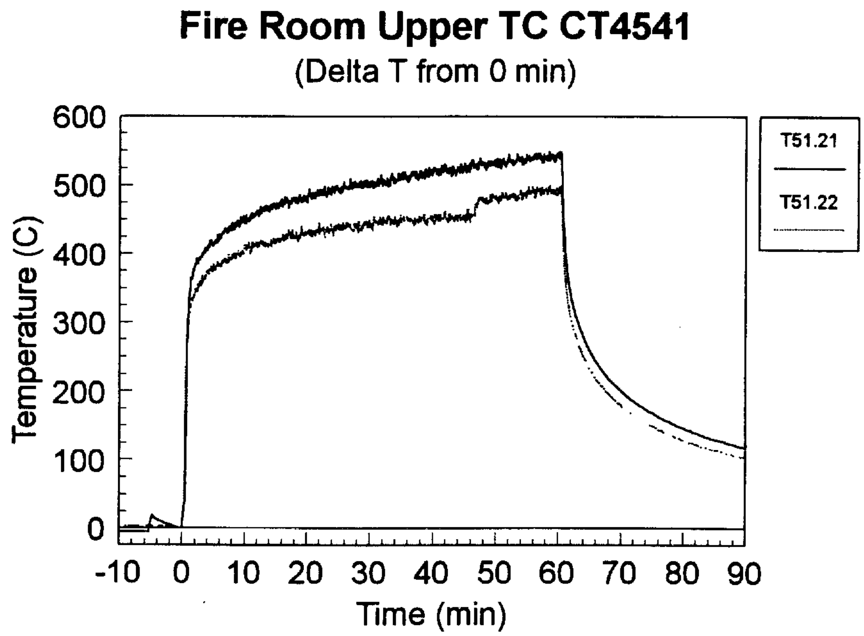

Figure 5.24: Fire Room Upper Layer Temps. for T51.21 and T51.22

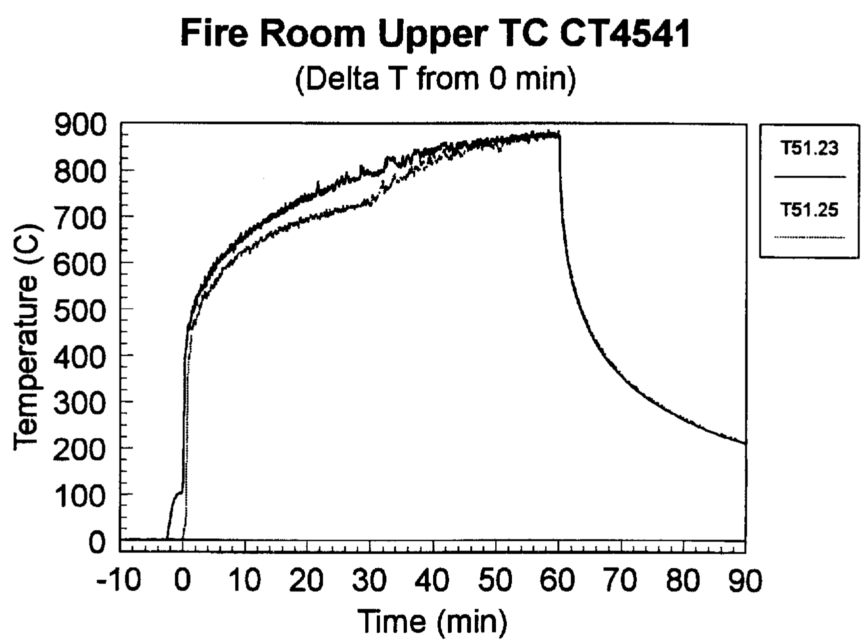

Figure 5.25: Fire Room Upper Layer Temps. for T51.23 and T51.25

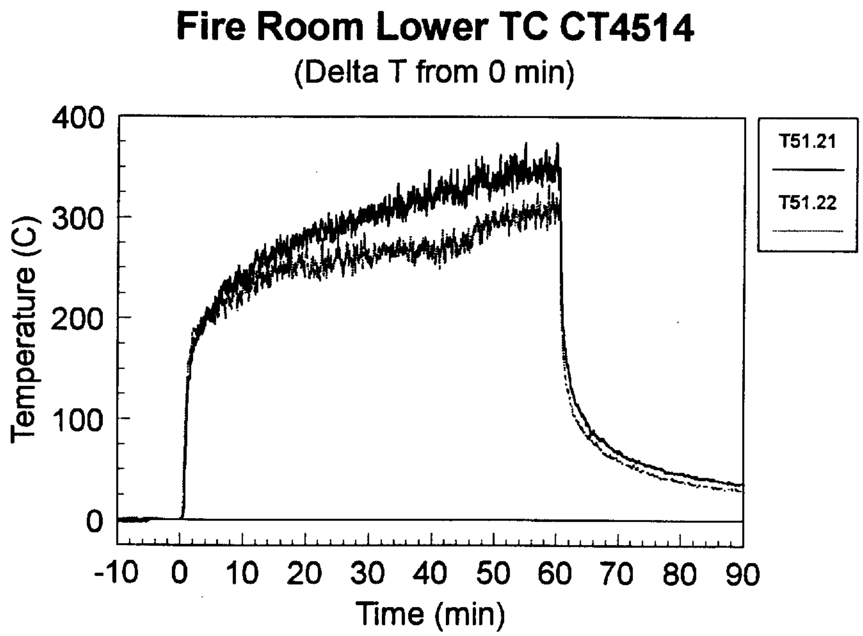

Figure 5.26: Fire Room Lower Layer Temps. for T51.21 and T51.22

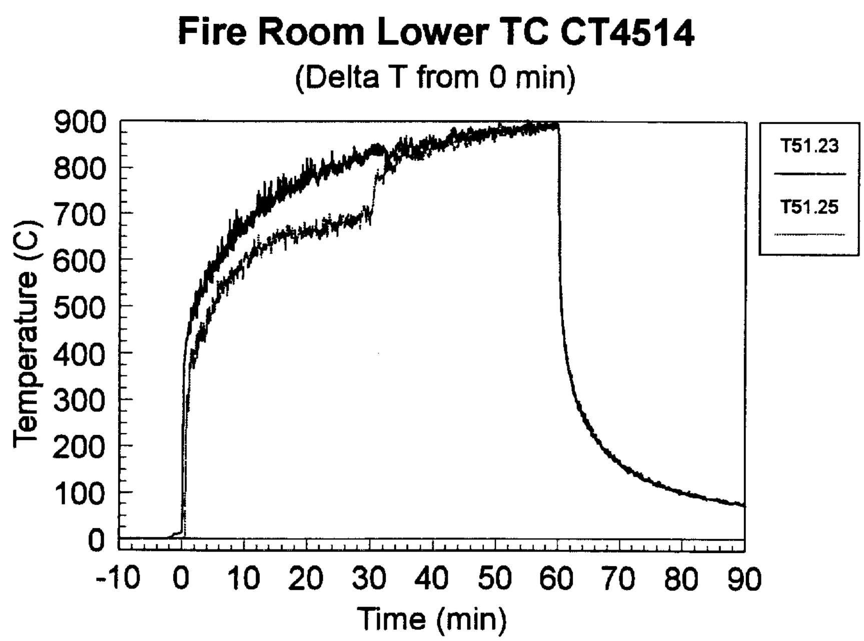

Figure 5.27: Fire Room Lower Layer Temps. for T51.23 and T51.25

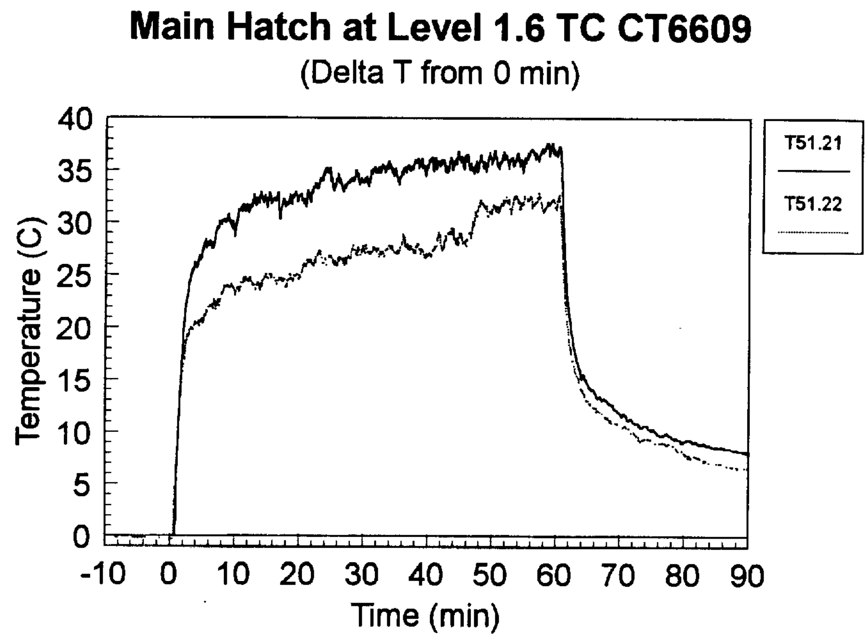

Figure 5.28: Main Staircase Hatch Temp. at Level 1.6 for T51.21 and T51.22

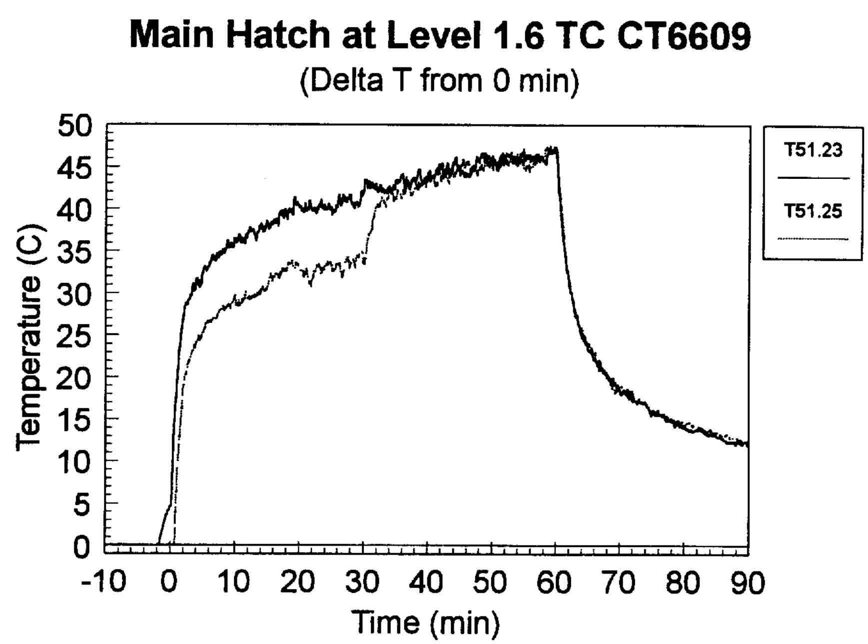

Figure 5.29: Main Staircase Hatch Temp. at Level 1.6 for T51.23 and T51.25

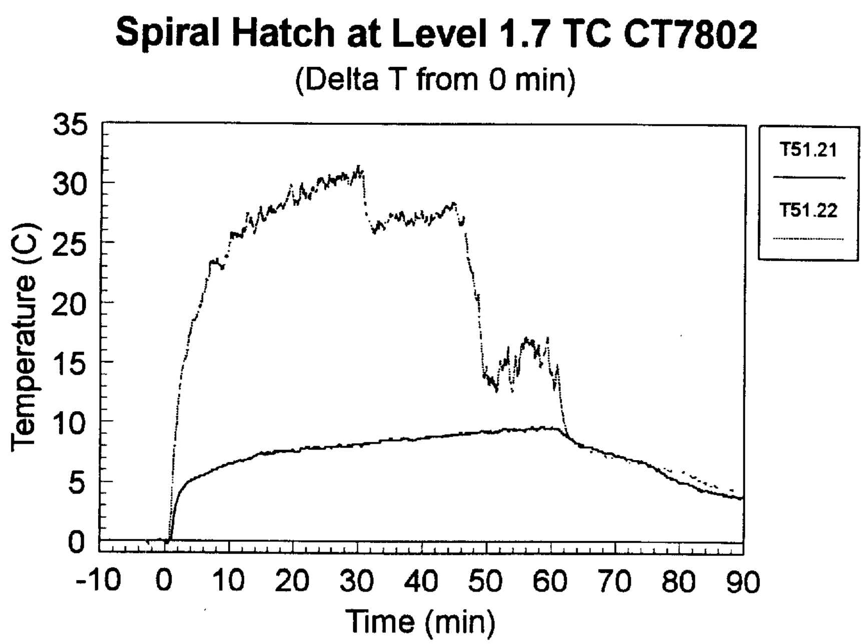

Figure 5.30: Spiral Staircase Hatch Temp. at Level 1.7 for T51.21 and T51.22

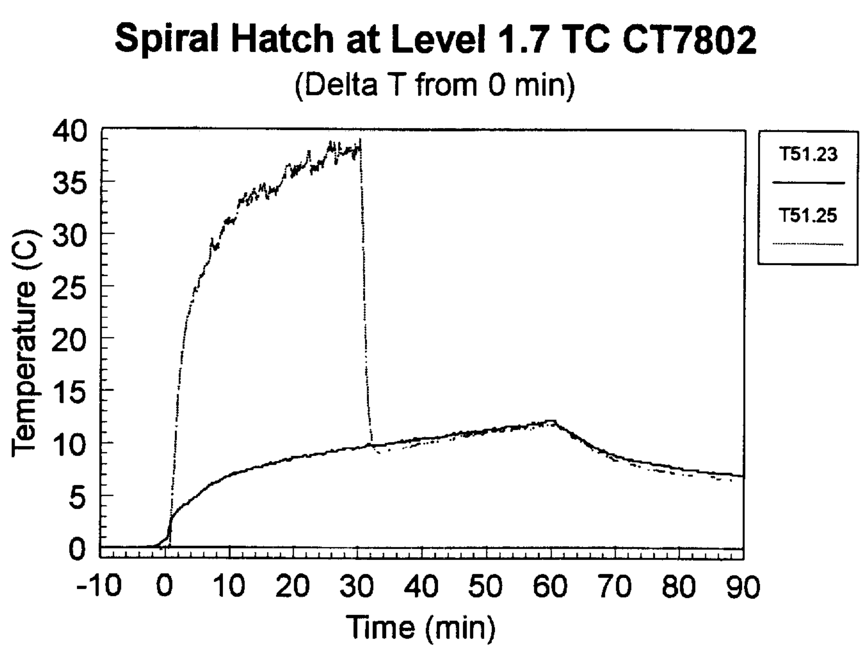

Figure 5.31: Spiral Staircase Hatch Temp. at Level 1.7 for T51.23 and T51.25

6 POTENTIAL OF EXPERIMENTAL DATA FOR CODE VALIDATION

One of the primary purposes of the HDR fire experiments was to create a database of experimental data for use in code validation and model development. This section will discuss aspects of the T51 fire tests and their instrumentation that can be used for code validation. The tests will be discussed in terms of zone models, containment system codes, and field models.

6.1 Zone Models

Zone model fire codes, such as CFAST [30] and MRFC, operate by assuming that in a fire situation every room in a building can be represented by two layers: a hot layer containing the combustion products from the fire and a cold layer which is oxygen rich. A number of elements of the instrumentation plan for the T51 test were established for the purpose of collecting data for the evaluation of zone model codes. Some of these elements are discussed in this subsection.

6.1.1 Layer Height

The key, computed parameter calculated by a zone model code is the layer height. The instrumentation plan for the T51.1 tests was such that layer heights are only obtainable in the fire room and the fire room doorway. For the T51.1 tests the fire room was instrumented with an array of thermocouples that had four axial levels and the doorway with a rake of thermocouples having five axial levels. The remainder of the facility lacked vertical rakes of thermocouples. The T51.2 tests, with its increased sensor map, added the hallway as a location where the layer height can be determined. The hallway contained four rakes at two cross sections along its length with five axial levels each and additional gas concentration sensors. This allows the determination of the layer height from the doorway to the curtained area. As with the T51.1 tests the remainder of the containment does not contain sufficient thermocouples to determine layer height.

6.1.2 Layer Temperatures

For all the T51 tests sufficient thermocouples are availble to evaluate the layer temperatures in the fire room, the fire room doorway, the hallway, and the curtained area. For the T51.1 tests the hallway contained three pairs of thermocouples along its length, one near the floor and one near the ceiling. The curtained area contained two such pairs. The T51.2 tests with its added rakes in the hallway and curtained area greatly improved the ability to determine layer temperatures in those locations. The T51.2 test also added thermocouples above the maintenance hatch between the 1.400 and 1.500 levels which can yield some information about the 1.500 level.

6.1.3 Mass Flow Rate

In those locations were layer height and velocity information exist or where a velocity sensor is located in a maintenance hatch, mass flow rates between compartments or between levels can be determined. In the case of horizontal flow the doorway dimensions and layer height information is used to determine the flow area of the layer. This along with the ideal gas law and layer temperature then yields the mass flow rate. For vertical flow, assuming that the plume occupies the whole hatch can also yield a rough estimate of the mass flow estimate.

For the T51.1 experiments only two velocity sensors were functional. These were located in the upper layer of the fire room doorway and on Level 1.700 over the main staircase maintenance hatch. The T51.19 test added number of additional velocity sensors. Therefore, in addition to the T51.1 locations, mass flow rates under the curtain, up the main staircase pipe channel, on Level 1.500 over the main staircase maintenance hatch, and on Level 1.700 over the spiral staircase maintenance hatch. The T51.2 tests added numerous velocity sensors in the hallway as well as in the lower layer of the fire room doorway.

6.1.4 Ventilation System Flows

The additional ventilation system added for T51.2 was instrumented with thermocouples and a velocity sensor. Thus, the natural convection flow through the pipe can be easily determined via the same method as used for vertical flow through the maintenance hatches.

6.2 Containment System Codes

Containment system codes, such as GOTHIC [31] and RALOC, owe there origin to the nuclear power industry. The need to evaluate the effects of loss-of-coolant accident scenarios in a containment building requires thermal hydraulic codes that accurately model the two-phase, thermal-hydraulic response of a large building to a source of energy, mass, and momentum, e.g. a break in a reactor coolant pipe. Contaiment system codes commonly use the lumped parameter method, that is a compartment is considered to be a single point whose properties represent the volume-averaged properties of the compartments. By modifying the source to be combustion gases and radiant heat rather than steam and water, contaiment system codes can be applied to computing the effects of fires on large structures. These codes usually model all vent between compartments, heat transfer to structures, sprays, ventilation systems, etc. In the case of GOTHIC, the discretization options also include a combination lumped and distributed parameter nodalizarions (1-D, 2-D, and 3-D).

For the purpose of fire modeling some adjustments to the typical lumped parameter approach must be made. In order to appropiately generate the bouyant driving force for fire drive flow, the fire compartment and any immeadiately adjoining rooms cannot be modeled as lumped volumes. Rather each room must be subdivided into a network of lumped volumes to allow for thermal stratification in these compartments.

6.2.1 Compartment Temperatures

As many regions outside the fire compartments and adjoining compartments are modeled as lumped volumnes, this results in more useable temperature information in the T51 data set than for the zone models. For all the T51 tests temeperatures can be obtained for the fire room, the doorway, the hallway, the curtained area, the 1.400 level outside the curtain, at each level for both the ascending and descending flow through the maintenance hatches, room 1.603, and the connecting hallway between the spiral and main staircases. These locations represent the entire circulation loop induced by the gas fires.

6.2.2 Compartment Mass Flows

For the most part, system codes rely on single openings to connect compartments. Therefore, the T51.1 tests are not very useful for system codes for comparing mass flows due to the lack of velocity sensors. The T51.2 tests with multiple sensors in the door way and hallway plus in the hatches is much better suited for use with system codes.

6.2.3 Wall Heat Conduction

Test T51.19 featured heat transfer blocks. The data from these sensors show the time dependent heat transfer into the HDR surfaces. As the storage and release of energy into structures is very important in nuclear accident analysis, system codes tend to contain robust algorithms for heat conduction into layered structures, e.g the wall surfaces. The measurement blocks used in the HDR were designed for the purpose of evaluating these algorithms as well as obtaining the transient behavior of the heat transfer coefficient.

6.2.4 Ventilation Systems

Contaiment system codes such as GOTHIC also contain explicit models for ventilation systems including time and trip dependent settings for valves and blowers. Thus the fresh air supply can be explicitly modeled for all the tests. For the T51.2 tests, the additional ventilation system time dependent nature can be modeled for comparision with the instrumentation located within the additonal duct.

6.3 Field Models

Field models, such as FLUENT [32], FLOW-3D, and NIST-LES [33], operate by solving a discretized form of the three dimensional equations for mass, momentum, and energy conservation. For most real structures, accurate resolution of the velocity, temperature, and species field for a fire require a large number of computational nodes. Therefore, use of field models is typically restricted to smaller subsets of a larger structure to reduce the computational resource requirements. This subsection will discuss fire phenomena in the HDR facility that could be used for field model validation.

6.3.1 Entry Effects

The cold air returning into the fire room creates a cold plume which moves along the floor of the fire room until it is convected upwards. The thermocouple arrangement inside the fire room provides some information on this cold jet. This information along with velocity and gas sensors in the doorway can be used to qualitatively verify a field model of the fire room.

6.3.2 Asymmetric Flow Effects

There are two major asymmetries in the HDR that can be resolved with the instrumentation mapping. Each of these can be used to validate field model codes.

The first is the arrangement of the fire room burners and the L-shape of the fire room. A comparison of tests T51.13 and T51.21, as shown in Section 5, shows that the choice of burners can impact the temperature field seen in the fire room. Field models should be able to duplicate this.

The second is the hallway. The hallway is not a straight path leaving the fire room. Rather it has a 90° bend followed by a gradual curving of the hallway. In the T51.2 tests 2D grids of velocity sensors and thermocouples were placed at different cross sections in the hallway, see figures 3.42-44 and 3.46. These grids provide excellent data for use in evaluating a field model.

6.3.3 Gas Layer Mixing

The plume of hot gasses leaving the fire room into the hallway will entrain gases and create vortices which will cause some mixing with the lower layer. Some of this can be seen in the temperatures inside the hallway. However, a better indication of this mixing is by comparision of the CO_2 profile in the doorway with the profiles measured at two locations inside the hallway. This kind of information is invaluable to a field model in order to validate the diffusive and convective transport terms used in the model.

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Between 1984 and 1992 four major test series were performed in the HDR containment encompassing various fuels and three different axial positions in the high-rise, multi-level, multi-compartment facility. At that time, each HDR fire test series was accompanied by extensive efforts to evaluate the predictive capabilities of a variety of fire models and codes developed in different countries by both blind pre-test and open post-test computations. A quite large number of open issues remained in the area of fire computer code predictive qualities upon completion of the HDR program.

KEY WORDS (MAXIMUM OF 9; 28 CHARACTERS AND SPACES EACH; SEPARATE WITH SEMICOLONS; ALPHABETIC ORDER; CAPITALIZE ONLY PROPER NAMES)

fire tests; computer models; nuclear reactors

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