COMPARISON OF MEASURED DATA FROM THE HDR-T51 GAS FIRE TESTS TO PREDICTIONS MADE BY CFAST

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ABSTRACT

The HDR test facility in Karlstein, Germany, was a decommissioned, research reactor whose containment building was converted into a test bed for containment safety studies. One test series involved burning various types and amounts of fuel at different levels inside the facility. The first fire test group was the T51 gas fire tests which burned propane premixed with air. Major objectives of the T51 tests were to assess what fire loads could be tolerated without damaging the facility's structural integrity, to determine the ability of the facility's ventilation system to remove combustion products and allow reentry of personnel, and to collect basic data on fire induced heat and mass transfer for the purpose of evaluating computer fire codes.

The tests were performed in a specially prepared and insulated fire room in the lower half of the containment building. The fire room was connected to a narrow hallway which emptied into a vertical shaft leading to the containment's large, hemispherical dome. A second vertical shaft paralleled this shaft on the opposite side of the containment and allowed for a counter-current, return flow. Eleven gas fire tests were performed to examine the effects of varying fire power and fire room ventilation openings. Since the fuel was premixed, the fires were unconstrained; thus, fire powers are specified based on the fuel mixture mass flow rate, an easily measured quantity. This combined with a ten minute period of pretest data collection resulted in a set of experiments with well known boundary conditions, an important consideration when determining the performance of a computer simulation.

Simulations of a selected experiment from the T51 series were made with a beta release of CFAST Version 3, a zone model fire code developed by the Building and Fire Research Laboratory at NIST. Results are compared to measured data from the HDR facility, and the predictive quality of CFAST is discussed

OVERVIEW

HDR Facility

The HDR (Heiss Dampf Reaktor) facility, shown in figure 1 [1], was a decommissioned 100 MW$_{th}$ test reactor in Karlstein, Germany, which was used as a test bed for reactor safety studies from 1975 to 1993. The containment building was an 11,000 m³ , 60 m tall by 20 m in diameter building containing all piping and equipment associated with a

nuclear power plant in multiple compartments with complex interconnections. The building contained 62 internal compartments of varying sizes including a large hemispherical dome of approximately 5,000 m³. Long vertical channels in the form of two staircases, an elevator shaft, and two sets of equipment hatches were also present. Safety tests performed in this containment included loss-of-coolant accidents, hydrogen release and deflagration, earthquakes, aircraft impact, and fire.
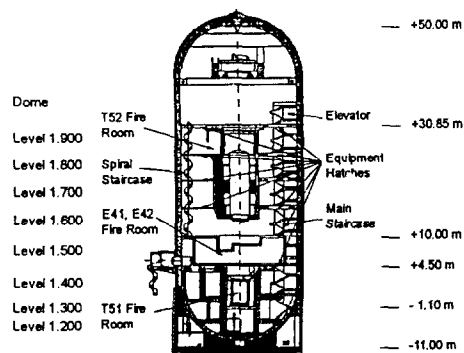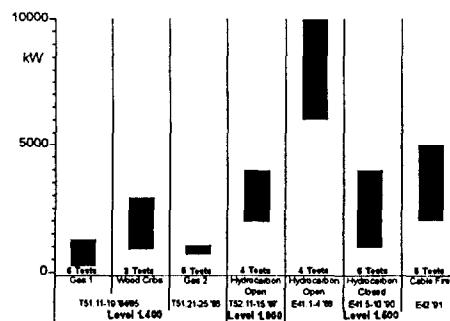

Figure 1: HDR Facility

Figure 2: HDR Fire Test Program

Fire Tests

A total of seven fire test groups, shown in figure 2, were performed at the HDR facility from 1984 to 1991 [2]. These test groups utilized a variety of fuel types, power levels, and locations inside the containment building. The fire tests began with gas and wood crib experiments to assess the basic response of the facility, then proceeded with oil pool fires, and ended with a series of cable fires to examine prototypical fire conditions.

T51 FIRE TESTS

The T51 test series consisted of three groups of tests performed over a period of three years from 1984 to 1986 [3]. The first test group, tests T51.11-T51.15 was a series of five propane gas fires at various power levels with forced ventilation. The second test group, tests T51.16-T51-18, consisted of three wood crib fires with no forced ventilation, with each subsequent test having a higher power level. The final test group in the T51 series, test T51.19 and tests T51.21-T51.25 consisted of six additional propane gas tests utilizing a combination of forced and natural ventilation. For this test series the effects of changing the ventilation of the fire room was examined

The initial objectives of the T51 tests were primarily to assess the ability of the HDR containment to survive the proposed fire test program. The progressive increase of fire powers was designed to assess the overall impact of a fire on the structural integrity of the building. Additionally, as no efforts were made to contain the fire products, the buildup of smoke in the facility during a test as well as the ability of the building ventilation system to remove it afterwards were examined. Lastly, since the fire sources for this test series were not as complex as later tests, e.g. the cable fire, data collected during the T51

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test series provide an excellent basis for judging the performance of computer fire simulations [4].

Fire Floor

A special series of compartments, shown in figures 3 and 4, was constructed at level 1.400 of the HDR containment for the T51 test series. These compartments, constructed of fire resistant materials, were designed to avoid causing damage to the HDR building from the intense heat in the fire room and adjacent compartments as well as to create a flow path for flue gasses from the fire room into the vertical shaft [5]. In addition to protecting the HDR facility this series of compartments creates a well defined, multi-compartment flow path, for use in computer simulations.
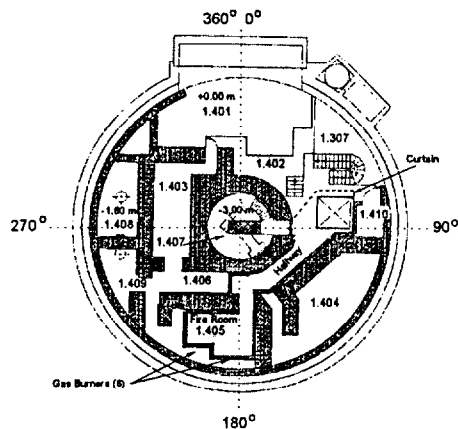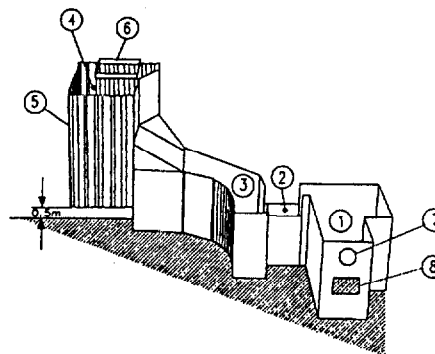

Figure 3: Level 1.400   Figure 4: Perspective View of Level 1.400

The first compartment was a fire room built inside of room 1.405, labeled 1 in figure 4. The fire room had a height of 2.75 m and a volume of 27 m³. The fire room was lined on all sides with 0.25 m of Ytong firebrick, and the ceiling was given additional protection in the form of 3 cm of Alsiflex fireproof mats. Along the wall opposite the doorway, six electrically ignited, gas burners were installed 0.375 m above the fire room floor. These gas burners were fed a combination of propane gas from tanks and air from room 1.603. In the T51.2 tests an additional ventilation duct leading to level 1.600 was installed just below the fire room ceiling, labeled 7. The exit of the fire room was a reduced height entryway 1.01 m wide by 1.5 m long with a 1.975 m height, labeled 2.

The second compartment was a hallway which wrapped part way around the reactor pressure vessel compartment, labeled 3. The ceiling and walls were lined with 0.10 m of Ytong firebrick. The concrete floor contained no protective lining. The hallway was 2.485 m high, approximately 6 m long, and varied in width from 1.140 m to 1.800 m. It has a total volume of 22 m³.

The final compartment, labeled 4, was constructed to force hot gasses from the fire up a maintenance hatch, labeled 6 connecting to level 1.500. This compartment was separated

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from the remainder of level 1.400 by a curtain of Alsiflex, labeled 5. The hatch on the floor of this compartment leading to level 1.300 was closed.

This curtain extended from the ceiling to 0.5 m above the floor. This 0.5 m gap was constructed in an attempt to enhance the return flow from remainder of level 1.400. The open area inside the curtain was centered under a maintenance hatch which was open for this test series as were all hatches above it up to the dome. On the opposite side of the building, by the spiral staircase, hatches were open only from level 1.600 and up. See figure 5 for details of level 1.600.
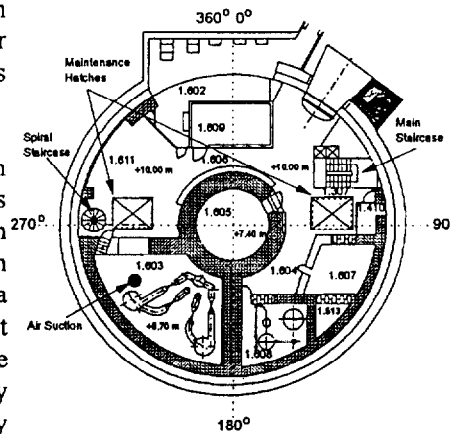
Figure 5: Level 1.600

Instrumentation

Instrumentation for the T51 test series consisted of thermocouples, gas concentration sensors, gas velocity measuring devices, and heat transfer measuring devices [6]. The fire floor was heavily instrumented with rakes of thermocouples in the fire room, the fire room doorway, and the hallway. Additional sensors to measure the hot and cold layer flow rates were positioned throughout the fire floor compartments. Instrumentation throughout the remainder of the containment consisted mainly of thermocouples and velocity measuring devices placed in the maintenance hatches, the main staircase, the spiral staircase, and the dome. A few thermocouples were placed inside rooms in the remainder of the containment, and a few velocity sensors were placed to examine crosswise flow between the two staircase regions.

CFAST MODEL

For this paper test T51.21 was modeled. The test consisted of a ten minute null transient to record the baseline environmental conditions, followed by an hour long 716 kW fire involving all six gas burners, and ended with a half hour cool down period. Data collection rates for this test were on the order of 1.2 Hz. Two different CFAST models were used to model this test. The two models examined the effects of different assumptions on the geometric modeling of the HDR facility.

Fire Model

The T51 series gas tests used propane gas, C_3H_8 with a gram molecular weight of 44 g/mole, as the fuel [5]. Complete combustion of propane yields 4.65×10^7 J/kg and requires 15.6 kg air/kg fuel. During the tests, to aid complete combustion, the propane gas was premixed with air drawn from room 1.603 before passing through the gas burners. Approximately 10% excess air was mixed with the propane. Even with the premixed air a small amount of CO and C are formed during the combustion. For 10%

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excess air these amounts are estimated at 0.042 kg CO/kg CO_2 and 0.022 (kg C)/(CO_2) [9]. Since CFAST calculates combustion based on total air in the compartment, the lower oxygen limit was set to zero to force complete combustion of the propane.

Geometry Model

The HDR test facility has many more rooms and levels then are capable of being directly modeled by CFAST. Therefore, creation of a set of compartments in CFAST to represent the HDR facility required making some assumptions. Two geometric models were created which used slightly different simplifying assumptions. Block diagrams of these models are shown in figures 6 and 7. Table 1 shows the room dimensions and Table 2 lists the vent interconnections for the two models.
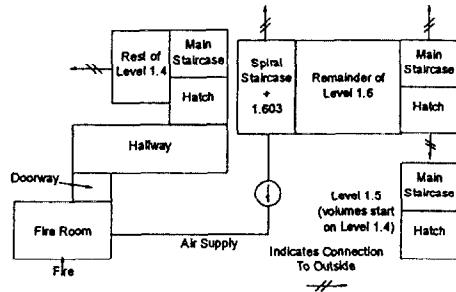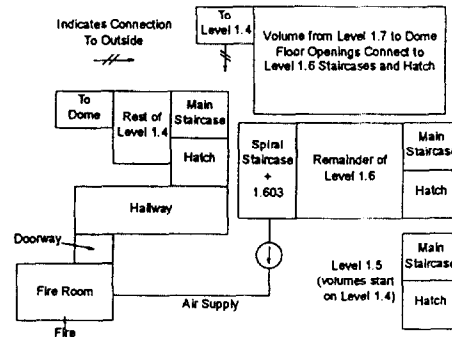

Figure 4: B Model Block Diagram   Figure 5: C Model Block Diagram

The first model, hereinafter referred to as the B model, consists of nine compartments. As the doorway to the fire room has a very small volume in comparison to the other compartments, it and the fire room are lumped together as a single compartment. This room is connected to the hallway by a door. The hallway, the curtained area, and the main staircase are each modeled by a CFAST compartment. The final compartment modeled on level 1.400 is room 1.402. This room as a narrow hallway opening to the remainder of level 1.400, so in order to place some restriction on the airflow under the curtain, this hallway was included in the model and connects the curtained area and the main staircase to the outside environment. In reality this room is connected to the remainder of the containment volume; however, since this location does not see the fire, assuming that it is connected to the ambient conditions is not an unreasonable assumption. Since examination of test data showed no cross flow on the 1.500 level, this level is not included in the CFAST model. Rather the hatch and staircase volumes from the 1.400 level are extended upwards through the 1.500 level to the floor of the 1.600 level. In this manner the elevation information is preserved. The remainder of the B model consists of four compartments modeling level 1.600. All portions of the HDR facility above the 1.600 level were assumed to be part of the outside. The four compartments modeled the hatch area, the main staircase, the spiral staircase + room 1.603, and the remainder of level 1.600.

The second model, hereinafter referred to as the C model, includes as a subset all the volumes and connections present in the B model along with two additional compartments. In the B model level 1.600 is connected directly to the environment. This arrangement essentially precludes return flow down the spiral staircase. For this to occur the volume from level 1.700 to the dome needs to be included in the model. Therefore, the first additional compartment represents the portion of the HDR facility from the 1.700 to the dome. This compartment preserves both volume and elevation. The staircases and hatches from the level 1.600 compartments connect to this volume. The second compartment connects level 1.600 level to level 1.400 at room 1.402, and as such provides for a path for air to return to the fire room under the curtain. In this manner the CFAST model now represents completely enclosed volume; however, CFAST will not run without some form of connection to the outside. This connection is made from the aforementioned volume at the elevation between level 1.400 and 1.600.

Both models also included a ventilation system to model the fresh air supply from room 1.603 to the fire room. The ventilation system consisted of two pieces of duct with a constant speed fan between them. The fan speed was set to give 10% excess air to the fire room. Note that in the actual experiment the system was connected to the gas burners; however, CFAST does not have that capability.

The CFAST model was run as a 5500 s transient. The first 100 s were to allow the ventilation system time to equilibrate. The remainder of the time was a 3600 s fire followed by a 1800 s cooldown period. A one second ramp up and ramp down was used for the 3600 s fire. The remainder of the run was to calculate the cool down of the facility.

Table 1: HDR CFAST Model Room Dimensions

Room #	Room	Model	Depth (m)	Width (m)	Height (m)	Elevation (m)
1	Fire Room	B&C	3.650	2.950	2.750	0.250
2	Hallway	B&C	1.800	4.950	2.485	0.000
3	Level 1.400 Hatch	B&C	2.750	4.300	11.100	0.000
4	Level 1.400 Main Staircase	B&C	2.720	4.330	11.100	0.000
5	Level 1.400	B&C	6.350	1.800	3.500	0.000
6	Level 1.600	B&C	7.920	7.920	4.600	11.100
7	Level 1.600 Hatch	B&C	2.750	4.300	5.050	11.100
8	Level 1.600 Main Staircase	B&C	2.720	4.330	5.050	11.100
9	Level 1.600 Spiral Staircase + Room 1.603	B&C	9.760	9.760	5.050	11.100
10	Levels 1.700 - Dome	C	14.370	14.370	34.950	16.150
11	Level 1.400 to Level 1.600	C	3.000	3.000	13.200	0.300

Table 2: Room Interconnections

Room 1	Room 2	Type[1]	Sill[2] (m)	Heigth (m)	Width[3] (m)	Case
1	2	H	0.000	1.975	1.010	B&C
2	3	H	0.000	2.485	1.800	B&C
3	4	H	0.000	0.500	4.300	B&C
3	5	H	0.000	0.500	2.000	B&C
3	7	V			4.540	B&C
4	5	H	0.000	3.100	2.700	B&C
4	8	V			5.750	B&C
5	Out	H	0.000	3.500	0.800	B
5	11	H	0.000	3.500	0.800	C
6	7	H	0.300	3.500	1.800	B&C
6	8	H	0.000	4.250	3.000	B&C
6	9	H	0.000	4.250	3.000	B&C
6	11	H	0.000	2.400	3.000	C
7	8	H	0.000	4.250	3.000	B&C
7	Out	V		Area = 4.540 m²		B
7	10	V		Area = 4.540 m²		C
8	Out	V		Area = 6.970 m²		B
8	10	V		Area = 6.970 m²		C
9	Out	V		Area = 5.280 m²		B
9	10	V		Area = 5.280 m²		C
11	12	H	3.300	9.800	0.050	C

Materials

A special set of materials was defined for CFAST to use for wall heat conduction. For the fire room and fire room doorway three materials were required. The ceiling used a two-layer material consisting of Alsiflex fireproof mats and Ytong firebrick. The floor used a two-layer material of firebrick and concrete. The walls used a single layer material of firebrick. The hallway required two materials which were firebrick for the walls and ceiling and concrete for the floor. Remaining rooms used the concrete material for all room surfaces. Table 3 gives the material properties and Table 4 lists the surface parameters used in the CFAST model [10].

Table 3: Material Thermophysical Properties

Material	Conductivity (W/m·K)	Specific Heat (J/kg·K)	Density (kg/m³)	Emissivity
Ytong Firebrick	0.24	950	340	0.80
Alsiflex Mats	0.17	1000	130	0.90
HDR Concrete	2.10	879	2225	0.80

Table 4: Compartment Surfaces

Surface	Layer 1 (material)	Layer 1 (m)	Layer 2 (material)	Layer 2 (m)
Fire Room Wall	Ytong	0.25	N/A	
Fire Room Ceiling	Alsiflex	0.03	Ytong	0.25
Fire Room Floor	Ytong	0.25	Concrete	0.50
Hallway Wall	Ytong	0.10	N/A	
Concrete Floor	Concrete	0.50	N/A	

RESULTS

The first set of results, shown in figures 8 and 9, compare predicted and with several measured temperatures in the upper and lower layers of the fire room. Both models overpredict the upper layer temperature and underpredict the lower layer temperature. In the upper layer the C model overpredicts the maximum fire room temperature by 175 °C or 35%, while the B model overpredicts by a more reasonable 65 °C or 13%. In the lower layer the B model underpredicts the lowest temperature trace by over 100 °C and the highest trace by over 250 °C. The C model, while underpredicting the highest traces of the lower layer, does predict temperatures above the lowest trace. However, further model improvements could still be had.
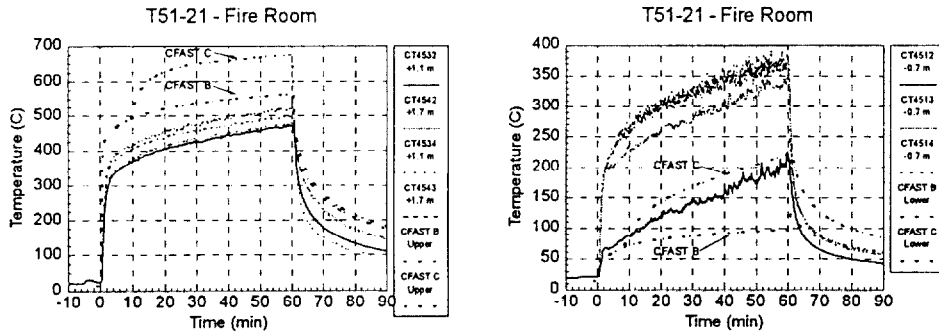

Figure 8: Fire Room Upper Layer Temp.Figure 9: Fire Room Lower Layer Temp.

The second set of results, in figures 10 and 11, examines the CO_2 concentrations in the upper and lower layers in the doorway of the fire room. This location is particularly important as the accuracy here sets a limit on possible accuracy everywhere else in the model. This impacts the ability to rely on CFAST for predicting human survivability. Since the CFAST model included the doorway as part of the fire room, CFAST CO_2 results are actually for the fire room, whereas, the gas sensors were actually located in the doorway. In the upper layer the B model underpredicts both CO_2 measurements shown for the upper layer. Since the CFAST results are for the layer as a whole, one would expect the CFAST results to lie within the measured values shown. Furthermore, the B model shows the CO_2 concentration immediately jumping to a constant value where it remains even after the end of the fire. The C model performs well for this parameter. Its concentration prediction lies within the measured values, and the C model predicts a slow

increase over time of the CO_2 concentration in the doorway which follows the trend shown in the measured data. However, while it does predict a decrease in the CO_2 concentration at the end of the fire, this decrease is small and short lived in comparison to the measured data. In the lower layer the B model predicts no CO_2 presence when in fact the concentration reaches at 0.75 v/o. In this case the code is unable to reasonably predict toxic gas concentrations in the lower layer. The C model performs well. It slightly overpredicts the measured CO_2 concentration, but otherwise agrees with the trend shown in the measured data.
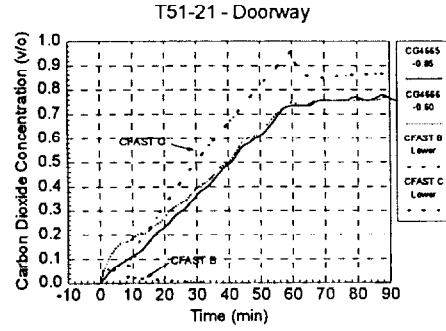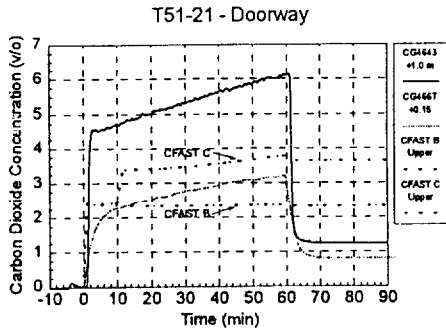

Figure 10: Doorway Upper Layer CO_2 Figure 11: Doorway Lower Layer CO_2

Predicted and measured velocities in the fire room doorway are shown in figures 12 and 13. Since CFAST outputs the mass flow rate and the HDR measured velocity, the CFAST results were converted to velocity using the layer heights and layer temperatures for the fire room and hallway. When comparing the data shown below it is worth pointing out that the CFAST results represent an average for the layer while the measured values are for a single point. The B model overpredicts to some the degree the upper layer velocity. The C model performs well for this parameter. Both models underpredict the lower layer velocity. The magnitude of the differences is not ascertainable, however, due to the sparse measured data, and both models can be said to calculate plausible mass flow rates.
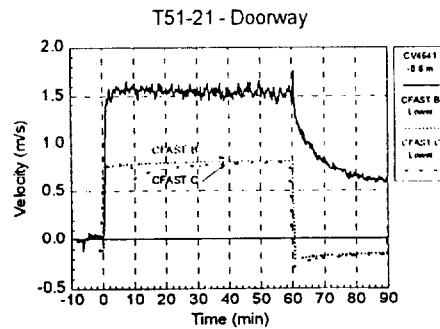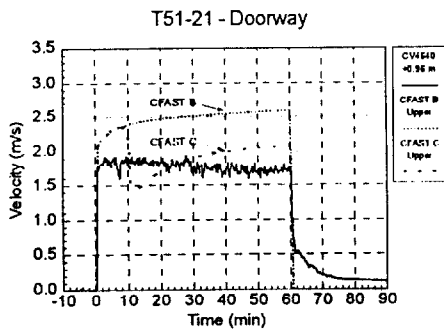

Figure 12: Doorway Upper Layer Vel.   Figure 13: Doorway Lower Layer Vel.

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Moving away from the fire room into the hallway, figures 14 and 15 show CFAST predictions and measured temperatures at different points along the hallway. In the upper layer both models predict values within the range of measured temperatures in the hallway. However, the C model results in temperatures that approximate an average hallway temperature whereas the B model clearly overpredicts the average hallway temperature. In the lower layer the B model underpredicts all of the measured temperatures in the hallway and the C model slightly overpredicts the average hallway temperature in the lower layer.
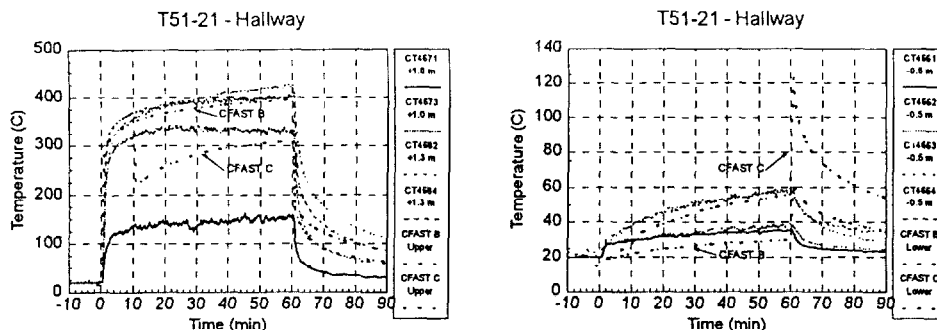

Figure 14: Hallway Upper Layer Temp.   Figure 15: Hallway Lower Layer Temp.

The final set of comparisons is for the maintenance hatch between Levels 1.600 and 1.700. Figure 16 shows CFAST predicted temperatures in the upper layer beneath the hatch compared to measured temperatures above and below the hatch. For both models the CFAST predictions are higher than the measured data. Since the CFAST model C hallway temperatures were reasonably well predicted, this suggests that the reason for the overpredictions is the result of CFAST's underestimation of cold air entrainment into the plume. This conclusion is confirmed by figure 17 which depicts CFAST predicted versus measured velocities at the hatch. For both models CFAST underpredicts the velocity and hence the mixing that occurs. Taking a closer look at the results reveals another problem. The B model starts off having an initial velocity of 1.5 m/s before the fire starts. The C model correctly shows no flow up the hatch before the fire starts. This shows that great care must be exercised when attempting to model vertical flow with CFAST. In the absence of any guidelines for a particular application the use of multiple models can help indicate appropriate modeling assumptions.

CONCLUSIONS

Two CFAST models of the 716 kW, T51.21 gas fire test were executed, and the results were compared to measured data from the experiments. Comparisons were made with layer temperatures, horizontal and vertical flows, and gas concentrations.

The B model which did not included portions of the HDR below the fire room or above level 1.600 performed rather poorly. This model overpredicted upper layer temperatures in all regions the fire plume moved through. It also underpredicted temperatures in the lower layers of compartments. At a first glance this could be attributed to the modeling
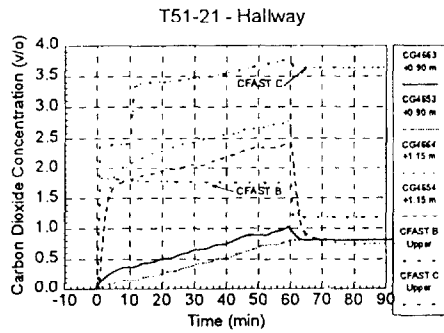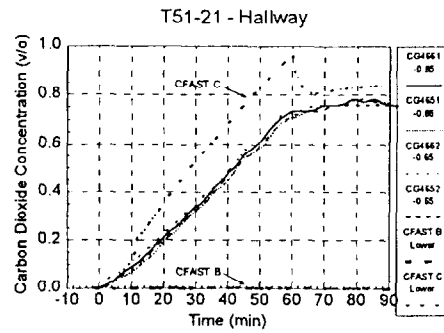
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Figure 16: Level 1.700 Hatch Temp.   **Figure 17: Level 1.700 Hatch Velocity**

assumptions made. Since the B model had room 1.402 open to the outside it could be postulated that the lower layer temperatures were due to the decreased flow resistance for air returning to the fire room. However, the predicted lower layer velocity does not indicate this was the case. The B model also failed in its predictions of CO_2 concentrations. It underpredicted in the upper layer, and it predicted no CO_2 in the lower layer. This latter result indicates that some flaw exists in the codes algorithm for mixing the layer interface at doorways. Lastly, the B model predicts a completely non physical flow up the maintenance hatches. The large upwards flow which is computed even in the absence of the fire's driving force means that the algorithm to calculate vertical flow is in error, or in other words CFAST models must be appropriately adapted such that artificial flows are not created due to effects of model geometry. This must be done be experimentation as there are no guidelines to this effect in the user manual.

Overall, the C model, performed better than the B model. While it had a worse prediction for the fire room upper layer temperature, it did well in predicting the lower layer temperature, the doorway gas concentrations, and the hallway layer temperatures. Considering that the C model's upper layer velocity was well predicted, the elevated fire room temperature suggests the code has difficulties in general with upper layer temperatures in the presence of a fire. In the case of the hatch flow, the C model demonstrates a physically valid flow. That is, no flow predicted until after the start of the fire; however, it underpredicts the entrainment. Though this could be due to the fact that level 1.500 was not included as an additional air volume for the plume to entrain from. Overall, the C model performed reasonably well.

The difficulties which the two models had with different aspects of the fire computations in multi-compartment, multi-level geometry indicate that modeling assumptions are very important in determining the quality of CFAST's results. However, since the modeling assumptions used for the two models were not unreasonable ones, deciding in a blind situation what assumptions to make could result in a meaningless computation. Furthermore, items such as the lack of CO_2 in the lower layer of the B model are puzzling when compared with the C model. It is obvious that further development is required in the areas of vertical flow and in interactions between layers. The results obtained from these two model also indicate a need for model building guidelines for complex geometries such as the HDR facility. CFAST has the potential to perform well, if the

right model is developed. Clear modeling guidelines with the aim of improving model building for a novice code user would greatly enhance the usability of CFAST.

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