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FULL SCALE SIMULATION OF A FATAL FIRE AND COMPARISON OF RESULTS WITH TWO MULTIROOM MODELS

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Table of Contents

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Results with Two Multiroom Models

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ABSTRACT

In 1987, a fire in a first-floor kitchen in Sharon, Pennsylvania resulted in the deaths of three persons in upstairs bedrooms, one with a reported blood carboxyhemoglobin content of 91%. Considerable physical evidence remained.

The fire was successfully simulated at full scale in a fully-instrumented seven-room test called SHARON 2. The data collected during SHARON 2 have been used to evaluate the predictive abilities of two multiroom computer fire codes: FAST 18.3 and HARVARD 6.3.

A coherent ceiling layer flow occurred during the SHARON 2 simulation and quickly carried high concentrations of carbon monoxide (CO) to remote compartments. Such flow is not directly accounted for in either computer code. However, both codes predict well the carbon monoxide buildup in the sixth room, the room most remote from the fire. Prediction of the pre-flashover temperature rise was also good. Prediction of temperatures after flashover that occurred in the room

of origin was less successful. Other predictions of conditions throughout the seven test rooms varied from good approximations to significant deviations from test data. Hypotheses are presented as to the reasons for the differences. At least some are believed to be due to phenomena not considered in any computer models.

I. The Sharon, Pennsylvania Fire

About 2:00 a.m., on Saturday, September 26, 1987, a kitchen fire occurred in a three-bedroom duplex house in Sharon, Pennsylvania. This fire resulted in the deaths of three young women who had been living in the house. Figure I-1 is a floor plan of the building. For the most part, the fire itself was confined to the first floor kitchen and the three victims were on the second floor. All had apparently been awakened, presumably by the upstairs hall smoke detector. Although there was a battery-powered smoke detector in the living room, no battery was found on the first floor after the fire. Two of the victims were found dead of carbon monoxide (CO) poisoning in the center bedroom. The third victim was rescued from the back bedroom but was badly burned; she died later that day. The kitchen had wood-paneled walls and a combustible ceiling, hence the total burning surface in that room was large. The kitchen flashed-over and all the kitchen windows broke. Fire vented out the tops and drew air into the kitchen through the lower portions of the resultant openings. Even so, the fire generated much more gaseous fuel than could be burned by the residual air in the building plus that drawn in through the windows.

Prior analysis by NIST (Nelson [1]) has indicated a potentially lethal condition when:

a. A fire has a large, readily available fuel supply (such as, in this case, the combustible walls and ceiling in the kitchen).

b. There is enough air to sustain a serious fire (in this case, the air drawn through the broken kitchen windows).

c. The fuel source (burning walls and ceiling) continues to supply more fuel to the fire than can be burned by the available air within the building.

d. There is an opening from the burning room (kitchen in this case) to the rest of the building, and potential victims are in that accessible portion of the structure.

It is believed that when this combination of conditions occurs, the fire consumed the oxygen (O_2) in the air in the building and replaces it with lethal products of combustion. The principal harmful products are carbon monoxide (CO) and carbon dioxide (CO_2). In addition, the amount of available oxygen can be reduced below that necessary to sustain life. As has been demonstrated by Zukoski [2], Beyler [3], and others, the CO/CO_2 ratio rises sharply as the fuel to oxygen ratio rises beyond the stoichiometric ratio for the particular fuel.

I-1 Observations from the Fire Scene

The Sharon, PA fire site was investigated by the authors. This on-site evaluation revealed that the conditions described above may well have occurred in this fire. The damage to the building (confined mostly to the kitchen), as well as the apparent causes of death of the victims, support this thesis.

One victim, in the middle bedroom, was reported as having 91% carboxyhemoglobin in her blood, suggesting exposure to fire gases containing large amounts of CO. In the more common process of CO intoxication, the victim's blood carboxyhemoglobin progressively rises to about 70%, at which level the victim dies. After death, the carboxyhemoglobin content of the blood remains unchanged. It is postulated that this victim received a sudden dose of gases containing a high CO concentration. This could explain the high carboxyhemoglobin content in her blood, capable of causing rapid incapacitation and death. There is no data on the blood carboxyhemoglobin of the second occupant of the middle bedroom. No sample was taken from the third occupant, who was still alive when taken from the building.

The first mentioned victim in the middle bedroom was found lying against the inside of the bedroom door, stated by the "first-in" fire fighters to be "closed". It was determined that this door, which was not warped, could still be closed tightly after the fire, but that the door rubbed the jamb: an extra push was required to close it completely. Soot was deposited evenly across the jamb, indicating some flow of soot-laden smoke through the doorway. The window to this bedroom was also found open to a height of about 6 inches. It is postulated that the door to this room had been open, and that flashover in the kitchen drove a massive flow of highly toxic smoke through the building. It is believed that this smoke front affected both victims found in the middle bedroom. It is possible that the first victim, who normally occupied the front bedroom, was in the hallway near the entrance to the middle bedroom and encountered a high concentration of CO. If so, it is likely that her last conscious act was to enter the middle bedroom and close the door.

It is impossible to determine exactly when during the fire the door to this bedroom was closed, but it is likely that at least the victim found against the door received a lethal dose of CO before she could close the room door. For this reason, in the SHARON 2 simulation, the doorway to the room representing the middle bedroom was left open. This also made it possible to examine the impact of the open window on smoke movement and other aspects of the fire.

The authors were aided in their on-site investigation by the Fire Chief James Starkey of Sharon, Pennsylvania and Lt. Robert J. Lucas, the "first-in" fire fighter. They described their actions and the fire as follows: Lt. Lucas, knowing that cries for help had been heard from the partly open window in the middle bedroom, entered the building to conduct search and rescue operations. On his first try, Lt. Lucas had difficulty finding the first floor end of the stairway in the hot, dense smoke. He withdrew to examine the stairway location in the other half of this duplex building. He then reentered but ran out of air before reaching the victims. Meanwhile, another firefighter with a hose "kept the fire from advancing." Then, with a fresh tank, Lt. Lucas reached and rescued the victim in the back room. By this time aid arrived and the other victims were quickly removed by other firefighters. In all, Lt. Lucas entered to search for the victim three times. As a result, he experienced the fire environment during three separate entries into the building over a period of about 25 minutes.

Figure I-2 is a time-line representing a plausible reconstruction of the events. The data for this time line were derived from discussions with Lt. Lucas, an analysis of the physical conditions left by the fire, and analytical simulations of involving extensive surfaces of thin plywood finishes, as had existed in the kitchen.

The landlord, Mr. Nicholas Lisac, also aided in the investigation. He had previously lived in the half of the duplex which burned. He described the arrangement of the kitchen, including the thin commercial plywood paneling that had been installed about three decades ago. The rest of the house was lined with plaster on wood lath, with wood trim, which contributed little to the fuel load.

The kitchen was essentially burned out. The ceiling was gone and the wooden floor joists were badly burned. In one place, roughly over the rear door, the flooring was burned through. Most of the plywood panel wall lining material had been consumed. The wooden kitchen cabinets had been partially consumed, as was the kitchen table.

There was some searing of the dining room ceiling close to the doorway from the kitchen. It is believed that flames extended out this doorway during the fire, but then receded as the oxygen in the upper portion of the space was consumed. There was no other significant burning of the structure or contents outside the kitchen area. As previously mentioned, the fire broke all the kitchen windows, possibly near flashover. The only other open vent from this half of the duplex to the outside was a window in the middle bedroom, found open about 6 inches (0.15m).

Apparently, late in the fire, a local burn-through occurred in the floor of the back bedroom. We also deduced that, late in the fire, a plumbing chase from the closed end of the kitchen to the upstairs bathroom was penetrated. Lt. Lucas reported that he felt heat on his wrist as he crawled through dense smoke to the top of the stairway. His hand may have been close to the flame extending through the chase.

Further physical evidence of temperatures and conditions upstairs was obtained from the back bedroom. Although the victim there was still breathing, she was badly burned. However, her clothes were not burned, indicating that the temperature near the floor was probably not over 350-400F (175-

200C). This temperature level is confirmed by our general knowledge of the thermal degradation of materials, and by the fact that paint on the woodwork above the door was blistered although the wood was not charred. A mark on the wall near the door suggested to the fire fighters that this victim, losing consciousness on her way to the door, fell against the wall. If so, she was likely incapacitated, but not killed, by CO and subsequently burned.

II. The SHARON 2 Test

II-1 Introduction to Part II, the SHARON 2 TEST

The SHARON 2 test, described here, provided an opportunity to diagnose the Sharon fire. It also provided an opportunity to check the predictions of two computer codes, FAST 18 (6) and HARVARD 6 (9), against real multiroom data. A number of strengths and deficiencies have been uncovered for each of these codes. In computer codes that model fire events in a sequence of rooms (such as FAST 18 and HARVARD 6), errors or inaccuracies in any room beyond the fire room are magnified in the subsequent rooms. In the SHARON 2 test, the results in the 5th, 6th, and 7th rooms are therefore the most sensitive to inaccuracies and the most difficult to reproduce. This report emphasizes comparisons in those rooms. In the original Sharon, PA fire, the two CO fatalities occurred in the equivalent of room 6 in the test, and the third (burned) victim was at a position equivalent to room 7, near the junction of rooms 5 and 7 as shown in Figure I-1.

Where predictions from the models differ from the test results, possible reasons are presented.

II-2. Purpose of the test

The SHARON 2 test was conducted to obtain data to:

A. Examine the CO, CO_2 and temperature buildup and oxygen depletion when the supply of fresh air is restricted in the manner believed to have occurred in the Sharon, PA fire.

B. Examine the transport of toxic gases and the resultant temperature distribution where the house geometry, vents, and supply of fuel are similar to those in the Sharon, PA fire.

II-3. Experimental Facility

The Center for Fire Research (CFR) "townhouse" two-story burn test facility was used for SHARON 2. The physical arrangements are shown in Figures II-1, a and b, dimensions are provided in Figure II-2.

The total volume and arrangement of rooms in the structure were similar to those of the Sharon, PA duplex. However, the test structure, had only two upstairs "bedrooms," not three, as at Sharon. One upstairs test bedroom, room 6, was fitted with a "window," opened 6 inches (0.15m), approximately the same as in the Sharon fire. This was the only vent from the test facility prior to opening the simulated kitchen windows.

The kitchen (burn room) windows in the Sharon fire were believed to have been closed until broken by the fire. This breakage, which we assume to have occurred close to "flashover," was simulated by an opening from the burn room to the exterior of the townhouse facility (see Figure II-1). This opening had a ventilation factor ($AH^{1/2}$), somewhat less than the sum of the ventilation factor values for the windows broken by the fire in the SHARON, PA incident[1]. The opening was "closed" with a fitted panel that was pulled away shortly after "flashover." The time of removal of the panel was approximately 134 seconds after ignition.

The walls and ceilings of all rooms in the test facility were lined with ordinary 1/2 inch thick gypsum board, which has properties similar to the plaster finish in the Sharon, PA duplex. Heat transfer to the walls was deemed important in this test. The physical evidence at the Sharon fire scene showed that the temperature of the gases in the upstairs bedrooms was relatively cool. In both the Sharon fire and this test, it is believed that an important element in the cooling of the hot gases was heat transfer to the plaster walls and ceiling. Such cooling would also have an important bearing on the buoyancy driving the toxic gas flow.

In the kitchen at Sharon, heat transfer was from, rather than to, the burning walls and ceiling. In Sharon, almost all of the room lining was combustible and burned during the fire. In the SHARON 2 test, the lining material was gypsum board and, (except for that portion covered by the fuel array) was therefore able to remove some heat from the fire. The fuel in the early stages of the Sharon fire was the plywood paneling and the cellulosic ceiling tiles in the kitchen. The fuel in the SHARON 2 test was wood in the form of cribs and 1/2 inch plywood panels. The plywood panels were mounted as "fins" between rows of wooden cribs. It was calculated that 12 cribs made of 2 x 2 x 10 inch wood sticks, 10 layers high, would drive the burn room ("kitchen") into flashover. Eighteen cribs were used

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[1]For buoyant gases, the flow through an opening is proportional to $AH^{1/2}$, where A is the area of the opening and H is the height.

to insure flashover. The fins were included so that the total exposed area of wood in the test was approximately the same as the burning area of the Sharon kitchen walls and ceiling. All this fuel was arranged on a platform suspended from three load cells in order to measure the weight loss rate of the fuel. A full account of these fuel package calculations is given in Appendix A. The cribs were ignited nearly simultaneously using 250 ml of heptane in 2 inch wide trays arranged underneath the cribs.

During the development of the test plan, there was concern that the cribs would not ignite quickly and that the fins would restrict air flow needed to burn the cribs. A preliminary test with a crib burning in the open demonstrated rapid ignition. It also showed that the burning rate of the crib was not appreciably affected by the presence of the plywood "fins" near the cribs at the spacing used in the test. The test data from the SHARON 2 test fire itself supports the prompt ignition of the cribs but raises questions regarding the burning process of the fuel bed following flashover (See Section II-5).

II-4. Test Instrumentation

Instrument locations are indicated in Figure II-3.

Mass burning rate was obtained from the weight measurements by load cells suspending the platform on which the fuel was placed. In addition, rate of heat release was measured by the oxygen depletion method (ref. 4). The oxygen depletion measurements were taken separately in the main hood exhausting the gases discharged through the window in the burn room and in a secondary hood venting the gases that passed out the upstairs bedroom (Room 6) window.

Gas analyses, including O_2, CO_2, and CO, were made on samples taken from five locations. The locations were:

(a) at ceiling level and at floor level at the soffit between the dining room (room 2) and the living room (room 3);

(b) at ceiling level and at floor level in the bedroom with the open window (room 6); and

(c) at ceiling level in the other bedroom (room 7).

Three additional oxygen samples were taken and analyzed:

(a) from the flow entering the burn room near the floor in the interior doorway; and

(b) near the floor and near the ceiling at the head of the stairs (room 4).

These locations are indicated in Figure II-3.

Nine thermocouple trees, each with eleven thermocouples, were installed as indicated in Figure II-3. They were located:

(a) in the center of the burn room (room 1);

(b) in the burn room doorway;

(c) in the dining room (room 2);

(d) near the soffit in the living room (room 3);

(e) at the top of the stairs (room 4);

(f) in the upstairs hallway (room 5);

(g) in the center of the north bedroom (room 7);

(h) in the doorway of the south bedroom (room 6); and

(i) in the center of the south bedroom (room 6).

Video cameras were installed in four locations. These viewed:

(a) early burn room events through a transparent section of the panel that covered the "window" to the burn room;

(b) subsequent burn room events through the burn room "window" after the panel had been removed;

(c) burn room events through a glass panel in a closed facility doorway; and

(d) the smoky gas flow out the upstairs bedroom window.

Some of the event timing was obtained from these video records.

II-5. Results

Figure II-4 is a time-line overview of the test. The cribs burned as expected; the average burn room upper layer temperature reached 575C at 75 seconds, then dropped to 500C at about 110 seconds. (See the temperature plot in Figure II-6.) The test protocol assumed flashover when the average upper layer temperature reached 600C. In view of the decrease in upper layer temperature in the burn room, the test director concluded that the fire had grown to flashover proportions, but was entering a ventilation-limited phase of burning and would not rise to the designated 600C without an additional air supply. At that point, the command was given to remove the panel covering the burn room "window," simulating fire-induced breaking of the kitchen windows. The panel was pulled away approximately 134 seconds after ignition. The test was continued for a total of about 1500 seconds. Various events, such as ceiling debris falling on the fuel weight platform, were shown by the video recording to have occurred after 800 seconds. The fuel weight loss rate curve also shows discontinuities after 600 seconds. These are probably due to the burn platform walls, or fins, falling off the platform. In view of these events, the analysis has been limited to the first 600 seconds of the test run.

The entire results are available from the Fire Research Information Service of the Center for Fire Research as a printout (Vol. 2 of this report). Average upper layer temperatures are shown in Figure II-6. Burn room temperatures at various heights are shown in Fig. II-7. CO, CO_2, and oxygen concentrations at the soffit are shown in Fig. II-8. The CO, CO_2 and oxygen concentration for room 6 are shown in Figures II-9 and II-10. Upper layer interface heights are shown in Figure II-11. The upper layer interface heights are derived from thermocouple readings using the procedure suggested by Cooper [13]. The position of the interface is considered to be the height at which gas temperature is 15% of the range between the lowest and the highest reading thermocouple on a given tree. Typical temperature versus height profiles are shown for four of the rooms in Fig. II-12. Because of low temperatures and turbulent flow, upper layer heights prior to 60 seconds are mathematically uncertain. Figs. II-13 and II-14 are video photographs through the burn room window at 30 and 60 seconds, respectively. These show the rate of involvement of the cribs. In Fig. II-14, the smokey upper layer has not yet obscured the cribs and the cribs are not yet fully ignited. Shortly after this the cribs were no longer visible.

Fig. (II-15) shows the sooty gas in the burn room after the window aperture has been opened (almost 10 sec. after removal of the panel). Fig. (II-16A), taken about two minutes later, indicates intense stirring, especially horizontal stirring in the burn room. Shown in motion, the black blob near the left edge of the doorway is seen as sooty gas (from elsewhere in the compartment) swirling and mixing with incoming air. It is hypothesized that fuel near the opening burns vigorously in the fresh air entering, providing hot gases and hot soot that pyrolyses fuel elsewhere in the compartment. This vaporized fuel then circulates towards the openings and burns fuel rich in the gas phase. This process is indicated (top view) in Figure II-16B. The result of the strong horizontal inlet flow is vigorous stirring of the burn room gas, large quantities of soot, and large amounts of CO and rapid O_2 depletion as shown in Fig. II-8. It is further hypothesized that the burning in the room in this stage of the fire was controlled by the above mechanisms rather than the traditional plume approximation used in computer models. The impact of this on pyrolysis of fuel, burning rate within the room, and heat transfer are at this time unclear.

The CO concentration (upper layer) in the simulated upstairs bedroom (Room 6) quickly exceeded 50,000 ppm (5%). This CO concentration is known to be extremely toxic and would be sufficient to incapacitate, then quickly kill occupants. The toxic upper layer quickly descended to very close to the floor in both bedrooms. The corresponding 0_2 and CO_2 levels are also lethal, but only the CO effect would leave a measurable marker on the victim in terms of blood carboxyhemoglobin. This is significant in that it demonstrates that other common fire gases contribute to the hazard of such dwelling fires.

The only locations where the thermocouple measurements indicate a fairly sharp discontinuity between the upper layer and a lower layer was in the burn room and at the burn room doorway (Figures II-7 and II-17). Thermocouple tree data in subsequent rooms show a continuous gradation of temperature with height (Fig. II-12).

II-6. Diagnosis of Transient Flow and Mechanism of CO Generation

The flow of fire gases through the building was traced by oxygen content. As seen in Figure II-3, a number of oxygen content measurements were made during the test. These data show some aspects of the flow that can not be diagnosed from the temperature records. Temperature changes occur due to both mixing of gases and heat transfer to the walls and ceiling. Oxygen content changes only by gas mixing: unchanged oxygen content implies that no mixing has occurred even though the gas cools.

Figure II-18 shows oxygen content vs. time at the soffit between rooms 2 and 3, at the head of the stairs, at the ceiling of room 6, and near the floor at the doorway of the burn room.

First, the oxygen content of the flow at the ceiling under the soffit and at the ceiling at the top of the stairs (the two lowest curves in Fig. II-18) are nearly identical for the first 180 seconds, dropping rapidly from 21% oxygen to about 6%. The curve labeled "Soffit-Ceiling" records the oxygen measurement closest to the burn room for the gas flowing out the burn room doorway. It appears this flow negotiated the ceilings of the two rooms between the burn room and the stairway (dropping below the 1 ft. soffit), turned a total of 180° to enter the stairway, flowed up along the sloping roof of the stairway and was then measured by the oxygen probe plotted as "Top of Stairs - Ceiling level," without appreciable mixing. Such "jet" flow has been noted early in the formation of an upper layer by Zukoski, by Emmons and by Heskestad (e.g., Ref. [5]). It has also been seen at CFR in salt water - fresh water modeling experiments some results of which are shown in Fig. II-19. The velocity of the head of this flow has been observed in other experiments as high as about 1 meter/sec.

Fig. II-19 is taken from the videotape of a dyed salt water-fresh water experiment in a transparent model of the SHARON 2 test setup. The work is described briefly in Appendix B. The scaled fire size is 60 kW. This corresponds to a very early time in the SHARON 2 test. Note the "ceiling jet" flow up the stairway in the model while the upper layer downstairs is yet very thin. This is probably analogous to the ceiling jet found in this test by the oxygen measurements.

If the fatality in the Sharon, PA fire who had 91% carboxyhemoglobin in her blood had breathed gas from a similar jet, she might have been breathing over 6% CO (Fig. II-8). Fig. II-19 shows the flow subsequent to Fig. II-18. At this latter time the upstairs corridor had filled down to a level where the salt water flow enters the salt water model of room 6 in the SHARON 2 test. Jet flow phenomena, as described above, are not incorporated into any zone-type fire model including FAST 18 or HARVARD 6.

CO/CO_2 ratios in the flow under the soffit, thought to be the same as in the flow from the burn room upper layer since mixing was minimal, are shown in Table II-A.

Table II-A

CO/CO_2 Ratios in the Burn Room Upper Layer

Time/Seconds	CO/CO_2 Ratio
90	0
134	0.45
160	0.5
200	0.36
260	0.25
300	0.35
400	0.35
500	0.22

These data are derived from Fig. II-8. Note the highest CO/CO_2 ratios occur before the flow from the other portions of the test facility into the burn room is appreciably vitiated (Fig. II-18). It had been postulated, prior to the analysis of the data from the SHARON 2 test, that recycling of CO back into the burn room was a factor in creating high CO/CO_2 ratios. Also, the upper layer CO/CO_2 ratio decreases in the period 400-500 sec. as the floor layer flow drops from 11.5 to 10.2% oxygen indicating that recycle of CO is occurring. To a first approximation, the CO/CO_2 ratio follows the burning rate, Fig. II-5. Note, the ventilation into the burn room was designed in this test to furnish considerably less air than the stoichiometric amount (Appendix A).

III. Introduction to Part III - Model Comparisons

This Section of this report is intended for fire mathematical modelers. Readers with a less detailed interest in models may wish to proceed immediately to Section IV, or directly to Section V (Conclusions).

The SHARON 2 test is a source of comprehensive data on the fire and smoke spread in a multiroom residence. These data are here used to evaluate the ability of two multiroom computer fire codes, FAST and HARVARD 6 to describe the violent fire conditions produced in this test. It should be pointed out that in a multiroom code any error in an intervening room is not compensated for in the next room. Therefore, focussing on the last room, as is done in this report, is a severe test.

III-1. Data and Decisions required by FAST 18 and HARVARD 6

The fuel and species mass input to the program is specified, along with the dimensions of the compartments, connections between them, vents, wall, floor and ceiling materials, and a "limiting oxygen index." The latter is the oxygen concentration below which the program does not allow combustion to occur. When these calculations were performed, a value of 6% was generally used. Currently, it is recommended that a value of 1-2% be used for large fires.

Since the time and memory needed for calculation grows geometrically with the number of rooms, the PC version of the FAST 18 program, used here and in Ref. (6), is limited to six rooms (plus the outside, called room 7). FAST can assess the condition in rooms that are not on the same floor.

HARVARD 6 is limited to a single story; otherwise requires about the same input data as FAST. There are more rigorous internal tests build into the HARVARD 6 code. This adds credibility to the results but also causes it to more readily fail to converge and stop. One way to lead HARVARD 6 to converge and continue to run is to eliminate the wall heat transfer. Since heat transfer is believed to have been very important in both the Sharon fire and the SHARON 2 test, this approach was constrained in this study, as discussed later in this report.

In order to model the buoyancy-related flow in HARVARD 6, the last room was simulated as two-stories tall with the window placed at a height representing the position of the window above the lower floor of the building. This resulted in describing the window as having a sill 14.3 ft. (4.6 m) above the first floor level of the test facility. With this plan it was possible to run HARVARD 6 for 240 seconds before the program failed to converge.

Most of the following discussion focuses on differences between the data obtained in the SHARON 2 test and the predictions of the models. The best correlation obtained between test data and model predictions was in the prediction of the onset and amount of toxic hazard (CO vs time). This is shown in Fig. III-1 for both models. The input information on CO production was the data developed in the burn room in the SHARON 2 test (Fig. II-8).

IIIA. Comparison of SHARON 2 Run Data and Calculation Using FAST

These data were compared with model calculations using FAST. Since the version of FAST used is currently limited to 6 rooms the volumes of the two upstairs bedrooms were combined. The stairway gas flow is known to be complicated, but lacking quantitative information on this flow, FAST was instructed to treat the stairway as a tall, narrow room (designated as room 4) with an open doorway on one wall and a high open window on the opposite wall.

An initial run with FAST was made using the oxygen depletion heat release rate data, Fig. III-2, as heat input to the program. This run demonstrated that the rate of heat release data taken from oxygen depletion readings in the exhaust hoods was not satisfactory. The initial temperature rises calculated by the program were late and inaccurate. A significant time delay occurred in transporting the products that flowed from the townhouse interior to the hood. This was particularly so prior to the removal of the panel covering the burn room window. Therefore, the rate of weight loss measurements from the fuel package weigh platform were used to derive heat release rate input data for both models.

The weight loss rate data are shown in Fig. II-5. Data later than 800 seconds are known to be unreliable due to debris falling on the platform (the rate of weight loss at some times becomes negative). Also, the data from the period from 600 seconds to 800 seconds are uneven and high, possibly due to collapse of the plywood fins from the burn platform. So FAST was run to model the period 0-600 seconds.

For use in the program the fuel-weight loss rate must be converted to heat release rate. Both models require the user to state the heat of combustion. The heat of combustion for wood varies with its water content. A value of 20,000 Kj/Kg was used, which corresponds to 20% water content. This is the low end of the range of water content for wood. It probably corresponds reasonably well to reality, the cribs having been stored for a long time in the controlled 50% relative humidity environment of the test facility.

Estimates for the actual heat released were needed for the HARVARD 6 program. The combustion efficiency of burning cribs, when not oxygen limited, is near 100%, so a value of 100% was assumed for the first 60 seconds of the test. Then a value of 67%, representing fuel rich combustion, was used from 60 to 380 seconds. Examination of the video pictures of flame issuing from the burn room window indicates that after 380 seconds the combustion became continuously less fuel rich until about 1000 seconds. Therefore, a combustion efficiency of 80% was assumed for the period from 380 to 600 seconds. Since the version of FAST used has logic that estimates combustion efficiency, the input data used for FAST was the actual mass loss data.

IIIA-1. Input Run Data for FAST

The file, SHARON 5.DAT, initially used to run FAST is printed out as Figure III-3. The limiting oxygen index was revised for "Run 10A" as discussed below.

IIIA-2. Upper Layer Temperatures

Upper layer temperature calculations are plotted in Figure III-4. These can be compared with the data from test SHARON 2 in Figure II-6.

Note that the calculated temperature-time curves start out more rapidly than the data, have some minor counter-intuitive crossovers in the region 100-200 seconds, sag and then rise again starting at about 500 seconds. Examination of the FAST calculation printout shows that the burning rate in room 1 is severely limited (to about 1 MW) by the oxygen content of the lower layer in that room dropping below 6% (the "limiting oxygen index" set on line 18 in Figure III-2.) Most of the excess fuel burns as it flows out vent 1 (to the outside) while small amounts burn in the upper layers of rooms subsequent to the burn room.

Figure III-5 shows upper layer temperatures calculated by FAST, using the file but with the limiting oxygen index set at 2%. This is done by changing the number 6.0 in the line titled "CHEMI" to 2.0. The burning rate during the first 60 seconds was smoothly adjusted to zero at zero time, and the wall and ceiling material properties were modified so that the calculated heat transfer to them would be less. We call this "Run 10A." The calculated upper layer temperatures are much better behaved, the temperatures in Room 6 reaching 140C. As discussed in the next paragraph, a value of about 180C would match the SHARON 2 test. It is felt that this agreement is satisfactory, especially 5 rooms from the burn room.

The average layer temperature data from the full scale SHARON 2 burn, (Figure II-6) are also really calculated values. Actually, the temperatures in rooms subsequent to the burn room, measured by thermocouple trees with an average of 11 thermocouples per tree, "fan out" in value. See Fig. II-12 for examples. Those on the second floor show an almost linear increase of temperature with height. Conversely those in the burn room (room 1) show a reasonably well defined upper layer and lower layer. The temperatures displayed in Figure II-6 are an average of the thermocouple readings above the calculated interface height.

IIIA-3. Interface Heights

Figure III-6 shows calculated interface heights for the six rooms in the simulation using a limiting oxygen index of 6%. These should be compared with Figure II-11, the "experimental" interface heights. The experimental heights are themselves calculated from readings on the thermocouple trees as the height at which the gas temperature rise is 15% of the maximum temperature rise at that location. As might be expected, these experimental heights are erratic early in the run, before temperature profiles stabilize. There are no experimental data for room 4, which is really a stairway, and the two "bedrooms," rooms 6 and 7, are separate. The layers descend in the same time periods and the burn room layers descend to the same level. In all the other rooms, FAST calculated interfaces descend to the floor, while the levels derived from the test data do not descend quite as far. Because of the method used for data reduction, the indicated test data cannot descend below the lowest thermocouple on the tree. This height was 0.08m. So the test heights of about 0.5m on the first floor and 0.15m on the second floor are probably meaningful (but see also the "drainage" discussion in part IIIB-4 of this report). The FAST calculations indicate a sudden rise in the layer heights of rooms 2, 3, and 4 seen in Figure III-6 after 500 seconds which did not occur. The rise in the interface heights calculated by the model is possibly due to increases in temperature caused by model-predicted combustion of unburned fuel in an upper layer as it encounters higher oxygen concentrations in downstream rooms.

Figure III-7 shows the layer heights calculated in FAST "Run 10A," described above (2% limiting oxygen index). With this relatively minor, but reasonable, change in the input data, the calculated layer height results are much closer to those derived from the test data (Figure II-11). We agree with current instructions that an oxygen index of 1% or 2% be used whenever the burn room temperature is near or above flashover. The asymptotic layer heights in the upstairs rooms are essentially zero, vs a run value calculated from temperature data of about 0.15 meters.

IIIA-4. Gas Composition

Figure III-8 shows the calculated CO concentration in the upper and lower layers in the bedroom, room 6. These are to be compared with data from the experimental run in Figure II-10. The upper level CO agrees fairly well with the data for the first 300 sec., (see also Fig. III-1) then the run data shows a decrease in CO concentration while the calculated concentrations continue to increase. The lower layer calculated CO data starts to rise after 200 seconds, as the lower layer CO does in the run. Then the calculation undergoes obviously irrational behavior. However, the calculated upper layer CO trace closely matches the experimental data in starting time, and time to reach extremely toxic levels (52,000 ppm). The upper layer concentration is used since it is assumed that with its rapid descent, occupants will breath from that layer, at least until time of their collapse.

The reason for any irrational behavior may be that suggested by Fig. III-6. This figure shows calculated interface heights. Note that in rooms subsequent to room 2, the calculated interface drops to near zero after about 200 seconds. Since the lower layer gas concentration is then calculated as a small amount of material divided by a small volume of atmosphere, mathematical imprecision is likely. FAST has layer mixing only in the doorways. Such mixing also occurs in reality along walls and can strongly influence the lower layer.

Similar behavior is seen in the room 6 lower layer O_2 and CO_2 calculations in Figure III-9. The upper layer O_2 and CO_2 calculations nearly match the experimental run data in Figure II-9.

In FAST, the CO calculations are dependent on input values of the CO/CO_2 ratio given to the program. The value used here was 0.5 mole CO per mole CO_2. This was the maximum value produced, as shown in Table II-A, and was produced at the time corresponding to the highest CO concentrations in the upper floor. Since a serious CO hazard occurs at about 1% (10,000 ppm) CO which happened at about 71 seconds (see Fig. III-8) and a serious 0_2 hazard occurs at about 12% (about 200 seconds, i.e., Fig. III-9), the toxic hazard due to CO is of earliest importance in room 6.

Table II-A is based on experimental data taken just outside the burn room. A CO/CO_2 ratio of 0.5 was also predicted prior to the test by Mulholland [8].

To summarize: The gas concentrations calculated for the upper layer are useful predictions, especially early in the fire. The lower layer calculations are less dependable. The lower layer calculation becomes erratic later in the fire, but this is long after all compartments in the building have become untenable due to high CO, high CO_2, and oxygen depletion. Therefore, in this multiroom case, FAST capably predicted toxic hazard. Expertise is required to provide realistic input data.

IIIB. Comparison of SHARON 2 Run Data and Calculations Using HARVARD 6

IIIB-1. Input Run Data for HARVARD[2]

HARVARD 6, Ref. [9], is a multi-room program (up to 10 rooms in this version) but the rooms must all be on one floor. In the SHARON 2 test, the structure was on two floors, and the only vent to the outside that was initially open was on the second floor. If, as proved to be the case, that vent were placed on the first floor in the computed room, the flow through it would not be adequately affected by buoyancy. Making the stairway and subsequent rooms two stories tall did not work - the calculation quickly failed to converge. Finally, the bedroom with the vent in it was specified tall enough to locate the vent at the proper height above the burn room floor. This gave the best results of several attempts for the temperature in room 6, although this run stopped (failed to converge) at about 260 seconds of simulation time. Since the fire starts decreasing at 210 seconds, and the HARVARD Codes are known to have trouble as wall temperatures decrease, the latter failure may not have been due to the tall room.

Further adjustments to the input follow. These are based on experience gained by the author while using HARVARD 6 on large fires. A "specified fire" is entered on HARVARD 6 as a "gas burner." One must defeat provisions that are incorporated to make it a realistic gas burner in order to simulate large fires involving solid fuels.

[2]The version of HARVARD 6 used was HARVARD 6.3 (1985).

- The burner diameter was set at 1.0 meter. This was done to ensure the burner diameter was large enough to allow adequate air entrainment into the gas burner plume to burn all the fuel. A small burner diameter would have its flow restricted by the program, causing the HARVARD 6 model to assume that some of the fuel did not burn.

- The cone half angle of the plume was set at 60° (instead of the default value of 30‘). This shortens the plume, keeping it within the lower layer, so its burning will be less suppressed by the low O_2 content of the upper layer. Also, this low cone angle better imitates the turbulent combustion that actually occurred.

- The input stoichiometric mass air/fuel ratio was set at 2.0 (instead of the more realistic 5.2 or so). This again reduces the chance that low O_2 in the upper layer will throttle the fire.

- The H_2O and CO_2 yield were adjusted to be consistent with the stoichiometric air/fuel ratio of 2.0. As discussed later, this adjustment probably resulted in faulty CO_2 and 0_2 predictions.

The initial efforts to reproduce the temperatures in Room 6 that occurred in the SHARON 2 test lead to the following adjustments to heat transfer factors in HARVARD 6.

- The smoke content of the gases was set at 0.02 gm C/gm gas. This was done to reduce the effect of soot in causing radiative heat loss to the walls. A value of 0.02 is possible for ordinary wood fire smoke, but a higher value would be more likely for the fuel-rich burning of the SHARON 2 test. We return to this point in the next section. An even lower "smoke content" would have given better results.

- HARVARD 6 allows the user to select convective wall heat transfer coefficients. The default convective wall heat transfer coefficients were reduced from 5 to 0.5 watts/m^2 deg. C minimum, and from 50 to 5 maximum. (The program increases the value linearly from minimum at ambient to maximum at 100 degrees or more above ambient. This was an attempt to raise the upper layer temperature in room 6 to about 200°C. However, the highest it got was about 100°C, then it dropped with time. As seen later, this problem was more likely the result of the excessive calculated heat loss from the hottest upper layer gas by radiation.

A provision to open a vent during the calculation has not yet been installed in HARVARD 6, (it exists in a later version of HARVARD 5) so the vent simulating the broken window in the burn room, vent 1, was open from the start of the calculation.

Figure III-10 shows the complete input data for the calculation with HARVARD.

IIIB-2. Upper Layer Temperature

Layer temperature calculated results are shown in Figure III-11. Compared to the run data, Figure II-6, the burn room temperature is higher, and other temperatures are lower than the data. A possible reason for these low temperatures is seen (for instance at 140 sec) from the burn room energy balance on the run printout. The calculated energy rate from the burn room out the open downstairs window is 0.90 MW; that from the burn room into room 2 is 0.93 MW. At this time, the fire size is 4.73 MW. The remaining 2.9 MW energy release is calculated as lost to the floor and walls of the burn room (mostly radiation) and disappears from the subsequent calculation. This is believed to be the reason the room 2 temperatures (and those of subsequent rooms) are low. The enthalpy loss from the burn room is over predicted by a factor of four or so. This may be due to radiation shielding of the hot gas by dense soot sheathing it. Such shielding is not accounted for in the model.

IIIB-3. Layer Heights

Layer heights are shown in Figure III-12. Recall room 6, an upstairs bedroom, has been raised to a ceiling height of 5.9 m to gain buoyancy of flow through its window. This explains the odd shape of the room 6 curve. The layer height curve for the other bedroom, room 7, is probably closely representative of a realistic room 6.

These layer heights can be compared with the layer heights calculated from the experimental run data, Figure II-11. The heights in Figure II-11 are levels where the temperatures measured on thermocouple trees are 15% of the maximum temperature rise. Probably the heights calculated in Figure III-12 more closely correspond to those represented by a 2-layer system, based on a layer that would contain all the upper layer enthalpy if it were all at the calculated temperature.

Unfortunately, the individual thermocouple readings show that, except for the burn room, this is not a 2-layer system. Subsequent to 100 seconds, the HARVARD 6 calculations of layer heights for rooms 1, 2, and 3 agree fairly well with the test data. Rooms 4, 5, 6, and 7 calculations do not agree with the data since HARVARD 6 cannot properly handle the single level in rooms at different elevations.

IIIB-4. Toxic Gas Concentrations and Room Doorway Flow

Figure III-13 presents calculated CO-upper layer percentages in the two upstairs bedrooms, rooms 6 and 7, and Figure III-14 shows calculated O_2 and CO_2 upper layer concentrations in those rooms. These are to be compared with experimental data in Figures II-9 and II-10. Two major features are immediately obvious:

- HARVARD calculates concentrations for room 6 that are quite different from room 7, whereas data taken during the run, using separate sets of gas analysis instruments, shows the conditions in the two rooms to be nearly identical. Recall that room 6 has a window to the outside and room 7 does not.

- The hazard due to CO in room 6 is well predicted. That due to oxygen depletion lags the data by about half a minute, and that due to CO_2 is not well predicted.

Let us consider these features in order. A plot of the calculated upper and lower layer mass flows through the doorways of rooms 6 and 7 and the window in room 6 shows only mild flows into and out of room 7 compared with the room 6 flows (Fig. III-15). It is obvious the flow out the window in room 6 is a major factor affecting gas concentrations in the upper layer. The program calculates that room 7 quickly fills with upper layer gas from the hallway (room 5) and thereafter the calculated flow through the doorway is somewhat blocked by the gas in that room developing nearly as much buoyant pressure as the gas in the hallway. The data from the test, showing near-identical gas concentrations in the two rooms (rooms 6 and 7), shows that some mechanism to enhance flow through the doorways is not simulated. The non-modeled flow is vigorous and important.

Further confirmation that flows into rooms 6 and 7 are in fact similar is given by referring to experimental time-temperature data taken during the SHARON 2 test and plotted in Figures III-16, III-17, and III-18. Figure III-16 shows experimental temperature-time curves from a thermocouple tree in room 5, the upstairs hallway. Note, there is not a distinct upper layer and lower layer; instead, there is a continuous gradation of temperature with height. The temperature starts to rise about 50 seconds into the run.

Room 5 feeds rooms 6 and 7. Figure III-17 shows experimental temperature traces in room 6 and Figure III-18, in room 7. These two rooms have similar profiles. (The 0.91 m high thermocouple trace in room 6 is faulty.) This further supports the conclusion that the flow into and out of the two rooms is about the same, even though only room 6 has a vent to the outside, and therefore some important gas flow physics is not included in the model. It is known (Ref. [10], [11]) that cooling of the hot gas at the wall of the compartment locally reduces its buoyancy, causing "drainage" of gas down the wall to the floor of the room. It is possible that such cooling occurred in the Sharon 2 test and that some of this cooled gas flowed out the bottom of the doorway, causing equivalent flow in at the top.

The second problem, the non-identity of calculated and experimental gas concentrations, especially CO_2 and O_2, probably stems from the adjustments of stoichiometric air/fuel ratio made in the input data so that the fire heat release would not be restricted by oxygen depletion. An air/fuel stoichiometric ratio of 2.0 was specified. A value of about 5.2 would be reasonable (for cellulose). The CO_2 level in room 6 at 260 seconds is calculated by the program to be about 3.5%. If this were increased by the ratio 5.2/2.0, the result would be 9.1% versus a measured value of 14%. This helps.

Both values, however, are the result of a complex integration and mixing of flows up to a given time, so an instantaneous ratio is only an approximate correction.

IIIB-5. Smoke Detector Warning Time

In the Sharon PA fatal fire, the smoke detector in the upstairs hallway (room 5) appeared operational and may have alerted the occupants. However, the smoke detector in the downstairs living room (room 3) might not have had batteries in it. The question arises: Would this detector, if operational, have furnished warning in time to allow escape through the downstairs living room? It is impossible to answer this question because we do not know how rapidly the fire started in Sharon PA. The speculation below raises questions that should be addressed in future work. Since the SHARON 2 test used an accelerant to start the fire, the initial development in the test was probably faster than the actual fire.

Figure III-19 plots CO concentrations and layer heights in room 3 (the living room) and room 5 (the upstairs hall) versus time. The data are taken from the HARVARD 6 calculation, but would be similar if we used the FAST 18 calculation or the experimental data. Unfortunately, we did not include smoke detectors in our test, so we have no basis for verifying a prediction of time of smoke detector operation.

Nober [12] in his work on the response of persons in residences to smoke detector alarms found that sleeping persons need an average of 50 seconds to awake and then complete meaningful action (telephone the fire department or reach the front door of the residence).

IV. Brief Comparison of Computations with Data from Rooms 5, 6, and 7

One feature of this SHARON 2 test and analysis is the emphasis on the development of hazard in rooms remote from the fire (rooms 6 and 7). The following charts, Figures IV-1 to IV-7, add no new information to that presented in the body of this report, but facilitate comparison of the data and the calculations.

These seven charts are "snapshots" of the conditions existing in rooms 5 (the upstairs hallway) and rooms 6 and 7 (the upstairs bedrooms) at 30-second intervals. The doorways are indicated on each side of room 5, and the window, scaled to height and size, on the other side of room 6.

Plotted for each room is the upper layer height. Where the data exist, temperatures and CO concentrations are listed for each layer. The columns headed "DATA," are experimental values. There are certain blanks in the calculated values. Since the "FAST" calculation was for six rooms, there are no FAST results for room 7. Since the height of room 6 was artificially increased in HARVARD 6 to put the window of that room at the experimental elevation (to achieve buoyant flow), the layer heights for room 6 in HARVARD 6 are fictitious, and are not plotted. Experimental CO information in these rooms exists only in three places - both layers in room 6 and the upper layer of room 7, hence these are the only places for which the calculated values are listed for comparison. Lower layer temperatures and lower level CO concentrations are not included in the standard HARVARD 6 printout, and they are not listed. If they were included, the numbers would not be meaningful since the necessary physics to transfer heat and mass from the upper layer has not been included in HARVARD 6. Notwithstanding these extensive caveats, let us examine the results.

IV-1. Layer Heights

Mathematical fire modelers look first at changes in layer heights to judge whether their calculations are working well. Here we have the advantage that we can compare the calculated heights with real data. Looking first at FAST in rooms 5 and 6 we see the FAST layer height is usually below the experimental height, but the agreement is rather good at 60 and 90 seconds (Figures IV-1 and IV-2). However, at longer times the FAST layer drops to the floor of room 5, and eventually to the floor of room 6. The experimental layers stay about 1/3 meter above the floor.

HARVARD 6 layer heights, although they drop with time in rational fashion in rooms 5 and 7, are always significantly higher than the "DATA." Recall, however, that the "DATA" heights are calculated on the basis of the temperature increase at the layer being 15% of the maximum temperature increase. This tends to correspond with the visible smoke layer. If the criterion were 50% instead of 15%, basing the height on average energy content, the experimental level would be closer to the HARVARD 6 level. Although both FAST and HARVARD 6 give reasonable calculated data, the layer heights are certainly different, and neither always agrees with the experiment.

IV-2. Layer Temperature

The most significant layer temperatures are the upper layer temperatures. Neither computer program has paid close attention to the lower layer temperatures, which are affected by physical phenomena not included in the programs.

Considering that these fire gases originate in room 1 where the temperature can be on the order of 900C, and we calculate too much heat loss by radiation when the fire grows large, the calculated values in rooms 5, 6 and 7 are remarkably consistent with the measured values. All three sets are in the same temperature range and rise reasonably with time. The experimental data are generally less than the calculated values early on, then greater than those calculated at later times. Experimental values are really the average of all thermocouple readings above the layer height, which is also derived from the same thermocouple readings. If we had chosen a 50% temperature rise criterion for layer height instead of the 15% criterion, the "experimental" value of temperature would be the average of fewer, hotter thermocouples, and hence be higher.

There are anomalies in the temperatures calculated by each of the mathematical models. For instance, in the upper layer of room 5, FAST calculates at 30 second intervals: 59, 95, 189, 268, 237, 200, and 166°C. The first four values overstate the experimental temperature increase. The next three decrease instead of increase. The sixth, 200°C, closely matches the experimental reading but fortuitous since the calculated temperature continues to decrease to 166°C. The HARVARD 6 calculated temperatures in room 6 are: 42.5, 64.2, 113, 99, 190, and 82°C. Perhaps the last three readings are affected by whatever instability caused this run to halt at 260 sec.

It should be pointed out that both programs are fairly accurate in timing the development of a thermal hazard.

V. Conclusions

V-I. Validity of the Simulation

A. The measurements in the full-scale simulation agreed with the physical evidence in the accidental fire. Therefore, the phenomena that caused the deaths in the accidental fire probably also occurred in the simulation. It is likely, though not yet fully proved, that the criteria discussed by Nelson [1] and listed in Part I of this report are appropriate. Further study of the phenomena associated with this fire scenario is needed.

B. The CO levels measured in the simulation in room 5 were sufficiently high that a brief inhalation of CO rich gas from a ceiling jet could cause a high blood carboxyhemoglobin reading, as was measured in one of the victims.

C. The temperature in the upstairs bedrooms in the simulation was about 180°C, (about 350°F). This agrees with the observations that one victim (in room 7, whose door was open) was burned, but her clothing was not burned, and that paint was blistered from the woodwork, but the wood was not charred. This evidence indicates that the SHARON 2 simulation reasonably reproduced the fatal Sharon PA fire.

D. The test demonstrated that CO is not the only toxic hazard. However, hazardous concentrations of CO occur before hazardous concentrations of CO_2 and 0_2 deficiency. Shortly thereafter, hazardous temperatures occur.

II. Validity of the Models

A. Both FAST 18 and HARVARD 6 are excellent for predicting the upper layer average content of CO, CO_2, and O_2 in rooms remote from the fire, when given the proper input data. This includes burning rate vs time and the yield of CO and CO_2 from the fire. Currently, these input data cannot be calculated and so test data or estimates must be used.

B. Upper layer temperatures following flashover in the burn room were not predicted well by either model. The temperatures approximated by the models for the room of origin were closest to the test data. The deviation increased with distances from the fire. Both models apparently suffer from an apparent overprediction of heat loss by radiation from burn room upper layer gas, and this causes the temperature in subsequent rooms to be low. For this case, the user entered value for the "limiting oxygen index" parameter in FAST had a major effect on the calculated temperatures. The previously nominal 6% worked poorly in this case. The currently recommended value of 2% was much better. A value of 0% overpredicted the burn room temperature.

C. Layer heights are well predicted, by both models in this case, only in the burn room. Rooms downstream of the burn room did not have discrete thermal layers. If the layer height is defined as the height at which the temperature rise is 15% of the total rise, FAST does best in the downstream rooms. If the layer height is defined as the height at which the gas would contain the upper layer enthalpy if it were at the indicated temperature, HARVARD 6 does best in these same rooms.

D. A post flashover, fully involved fire, with a distributed fuel bed cannot be modeled by a single burning plume. The burning is very heterogeneous. The video pictures give the impression of hot, near-stoichiometric combustion of gas near vents where air enters, creating hot products and hot soot. It is hypothesized that the stirring of the gases in the room, especially horizontal stirring, carried this hot gas deeper into the compartment, where fuel rich combustion occurred, and heat transfer to the fuel created more fuel gases by pyrolysis. These gases then partly circulated back near the vents and partly burned. In this case, the process creates CO contents over 6%, CO/CO_2 ratios of 0.5.

E. Hot gases flowing out of the burn room created a ceiling layer jet that remained coherent while flowing through several compartments. It lost heat, but did not mix with the ambient gases. It was traced by oxygen analysis. Since it had a high CO content, it created a localized toxic hazard in subsequent compartments more rapidly than the models predicted. (Such a jet is not currently included in any zone model.)

F. There was some mechanism operative in the SHARON 2 test that encouraged substantial flow of hot gas through the open doorway of a dead-ended room. This mechanism also is not simulated in the models. It may be related to heat transfer from the hot gas to the walls of the room, such that the cooled gas loses buoyancy and flows out the doorway allowing the entry of hot gases at the top of the doorway.

G. The SHARON 2 test data exist as a printout available in the Fire Research Information Service collection at CFR as volume 2 of this report. They are available for other comparisons with calculated parameters, or for evaluating improved models.

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Appendix A
Fire Load for Bldg. 205 Test (Townhouse) to Simulate Sharon, PA Fire

Introduction and Summary

The fire load in the Sharon, PA fire was 1/4" plywood lining a kitchen 4.9 m x 2.4 m x 2.4 m high, plus the cellulosic ceiling tile in that room. The burn room in the "townhouse" is 8' x 8' x 8' high. The design will use wood cribs to drive the room beyond flashover, plus plywood "fins" to provide additional pyrolysis surfaces. All this must be on a weigh platform which will fit within the room and itself will be part of the fuel load.

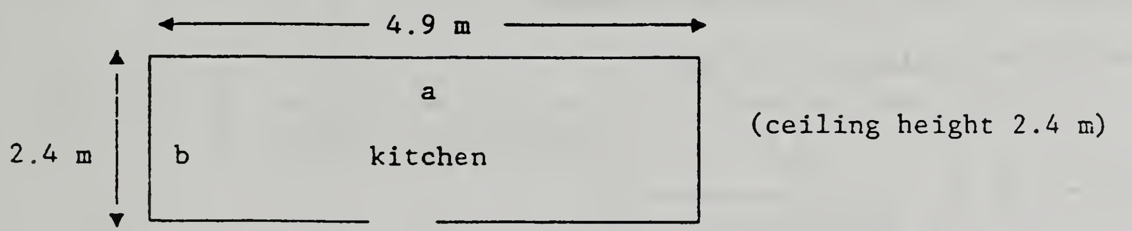
The results are:

18 cribs, using 1.4 x 1.4 x 10" sticks, pine, 3 per layer, 10 layers high.
Weigh platform triangular, (nearly), 7' x 7', plywood.
2-side walls on weigh platform, 7' x 7' plywood.
4-"fins", 7' x 4' - plywood.

All the above plywood should be 1/2" thick. The whole assembly will weigh about 405 lbs.

Discussion:

A. Evaluate the Sharon, PA Burning Surface Area:



let area of wood = h(2a x 2b) 0.75
= 12.4(4.8 x 9.8) 0.75 = 26 m^2

The factor 0.75 compensates for areas not wood (door, windows, sink) and shielded areas, i.e., behind the refrigerator.

Area of ceiling = 4.9 x 2.4 = 12 m^2
Assume the floor, plastic tile, burns only slowly
Total burning area - 12 + 26 = 38 m^2

B. Calculate burning rate needed to flash-over the Bldg. 205 burn room.

To simulate the Sharon, PA fire, a "room" will be built in the Bldg. 205 townhouse facility. the room will be 8' x 8' x 8' with 2 vents. Vent No. 1 will be a 6.5' x 2.5 ' doorway. Vent #2 (closed until the room is at flashover) will represent the kitchen windows in the Sharon fire. It will have the same $A\sqrt{H}$ as the doorway above, and in fact could be a doorway. The walls will be 0.5" gypsum board.

Assuming the windows vent is open, calculate an equivalent doorway (sum the values of $A\sqrt{H}$).

$$A\sqrt{H}_{door} + A\sqrt{H}_{window} = A\sqrt{H}_{\text{"effective" door}}.$$

$$(6.5)(2.5)\sqrt{6.5} + (6.5)(2.5)\sqrt{6.5} = (6.5)(W_e)\sqrt{6.5}$$

$$W_e = 5.0' = \text{effective door width}$$

The cribs should be able to flash-over the room with both vents open. In the real fire, only the door was open until the windows broke, and that will be simulated in the test. However, we don't want the room to drop out of flashover when vent #2 is opened, so we will provide enough heat release by cribs to maintain flashover with both vents open.

From fireform (3) menu #5, Thomas' flashover correlation (on fireform floppy disk), the required heat release rate is <u>1366 btu/sec</u>.

From reference (4), calculate the heat release rate, Q, needed to raise the ceiling layer temperature for this gypsum-walled room to 600°C, the temperature at which flashover will occur.

Equation 15 from reference (4) is:

$$\Delta T = 6.85 \left[\frac{Q^2}{(A_o\sqrt{H_o})(h_k A)} \right]^{1/3}$$

ΔT in °C, $T_o = 295$°K, $\Delta T = T - T_o$

Q in Kw

A_o = area of vent, m^2

A = area of enclosure, m^2

H_o = is height of doorway, m

h_k = is in KW/m^2-K, a constant evaluated below.

Now apply this to the Bldg. 205 townhouse burn room.

dimensions = 8' x 8' x 8' = 2.44 x 2.44 x 2.44 m

doorway H_o = 6.5' = 2m

A^o = 2.5' x 6.5' = 0.76 x 2 = 1.52 m^2

A = 6(2.44 x 2.44) = 35.7 m^2

for gypsum walls: (Table 2, NBSIR 83-2712)

$$P = 960\ \mathrm{Kg/m^3}$$
$$C = 1.1\ \mathrm{KJ/kg\cdot K}$$
$$k = 0.17 \times 10^{-3}\ \mathrm{KW/m\cdot K}$$
$$\alpha = 0.16 \times 10^{-6}\ \mathrm{m^2/s}$$
$$\rho ck = 0.18\ (\mathrm{KW/m^2 1})^2 s.$$

In this case d = 1/2" = 0.0127 m = wall thickness

$$t_p = \left(\frac{pc}{k}\right)\left(\frac{d}{2}\right)^2 = \frac{(960)\ (1.1)}{0.17 \times 10^{-3}} \cdot \left(\frac{0.0127}{2}\right)^2$$

$$= (6211)\ (0.000090) \times 10^3 = 0.25 \times 10^3 = 250 \text{ seconds}$$

T_p is the "penetration time" for the thermal wave in the walls. Let the fire duration be 250 seconds (time to flashover).

then $h_k = k/d = \dfrac{0.17 \times 10^{-3}}{0.0127} = 13.4 \times 10^{-3} = 0.0134$ (agreeing with ref. 4 value of 0.0132)

Using this value of h_k

$$\Delta T = 6.85 \left[\frac{Q^2}{(A_o\sqrt{H_o})\quad(0.0134A)}\right]^{1/3} \text{(doorway vent only)}$$

$$\Delta T = 6.85 \quad \frac{Q^{2/3}}{\left[(1.52)(1.42)(0.0134)(35.7)\right]^{1/3}}$$

$$\Delta T = \frac{6.85}{(1.033)^{1/3}} \quad Q^{2/3} = 6.78\ Q^{2/3}$$

For flashover, $T_{ceiling}$ = 600°C, ΔT = 580°C

$$580 = 6.78\,Q^{2/3}, \quad Q^{2/3} = \frac{580}{678} = 8.5. \qquad (1.054\ \text{KW/btu, sec})$$

$$Q^{1/3} = \sqrt{85.5} = 9.25$$

$$Q = (9.25)^3 = 797 = 800\text{KW} = 759\ \text{btu/sec}$$

Now double the $A_o \sqrt{H_o}$ (2 vents)

$$\Delta T = 6.85 \left[\frac{Q^2}{(A_o \sqrt{H_o})\ (0.0134A)}\right]^{1/3}$$

$$= 6.85 \frac{Q^{2/3}}{(2.066)^{1/3}} = \frac{6.85}{1.274} Q^{2/3} = 5.376\,Q^{2/3}$$

let ΔT = 580°C

$$Q^{2/3} = \frac{580}{5.376} = 107.9$$

$$Q^{1/3} = 10.39,$$

$Q = (10.39)^3 =$ <u>1122 KW</u> = <u>1064 btu/sec</u> (minimum heat release)

So on the is ref. (4) basis, more accurate than the Thomas correlation, we need at least 1122 KW from the cribs alone.

C. <u>Crib design</u>

What kind of crib(s) will promptly (less than 10 minutes) develop 1060 btu/sec = <u>1120 KW</u>?

If heat of combustion of wood is 15 x 10^3 joules/gm. (A crib approaches 100% combustion efficiency):

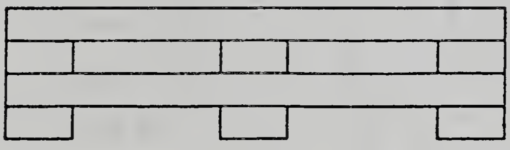
Burn rate = 1,120,000/15 x 10^3 = <u>75 gm/sec (wood burn rate for flashover</u>)

Air flow rate for this crib would be ~ 6(75) = 450 gm/sec.

Ref (2), page 37.

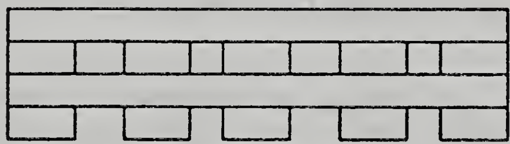
Four cribs yielded a mass loss rate of 25.6 gm/sec.
Minimum number of cribs = (75/25.6) x 4 = 11.7 or 12
To be certain of sustained flashover, use 50% excess = 18 cribs.

These cribs are:



- 10 layers high
- 3 per layer
- sticks are 1.4 x 1.4 x 10" (spacing between sticks = 2.75")

An alternate crib design, from Ref. 1, with a mass loss rate (±20%) of 5.6 gm/sec (lasted ~700 seconds) was:



- 10 layers high
- 5 sticks per row
- sticks are 1" x 1" x 10" long

and we would need: 75/5.6 = 13.4 or 14 of these, 20 to be certain of sustained flashover.

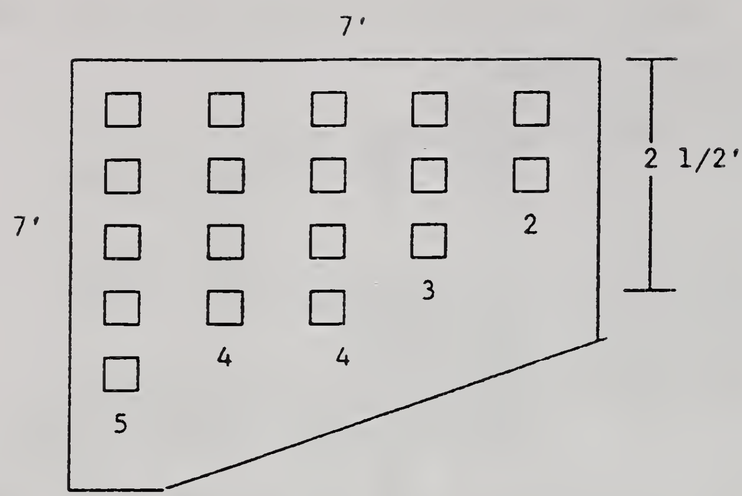
For their longer burning duration, we will use the sticks with 1.4" cross sections (standard 2 x 2's).

The weight of 18 of these cribs will be:

18 (4150 gm/crib) = 74700 gm
= 75 kg
= 165 lbs

D. Weight platform design

They would fit on the weight platform design below and leave 4+inch spacing between cribs so that air can get into each crib.



E. Calculate Additional Burning Area Needed to Simulate Pyrolysis of the Sharon Kitchen After Flashover

First look at the ventilation limit. According to FIREFORM No. 17 (3), for a doorway 6.5' high and 2.5' wide, at 100% combustion efficiency (like a crib), the ventilation limit occurs at 3038 btu/sec. We have designed cribs for (1.5) (1000) = 1590 btu/sec.

With both vents open, (each vent calculated separately) the ventilation limit occurs at 3038 + 3038 = 6076 btu/sec. So the burning, cribs alone, is fuel controlled.

Calculate the effective burning area of a crib

According to Gross (1), sticks in a crib burn as if exposed on 2 sides only. For the crib chosen, this area is:

each layer = 1.4" x 10" x 2 x 3 = 84 m^2
each crib = 10 x 84 = 840 m^2 = 0.54 m^2
(1 m^2 = $(39.37)^2$ in^2 = 1550"^{2})

Since we have 18 cribs, effective crib area is

18 (0.54) = 9.7 m^2

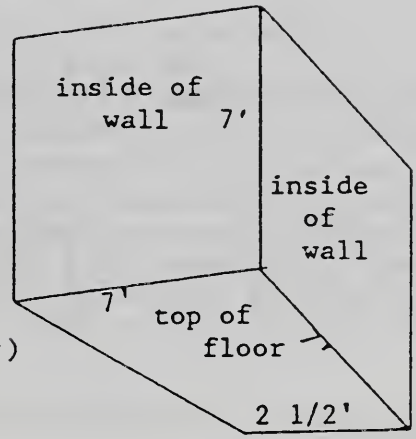
We now calculate how much more wooden surface is needed to total 38 m^2. (need 28.3 m^2 more)

Calculate area of weigh platform and two side walls. Side walls are 7' x 7'

area of base = 7 x 7 x 1/2
= $25'^2$

area of sides = 7 x 7 x 2
= $100'^2$

total area = $125'^2$
= <u>11.6 m^2</u> (1 m^2 = $10.76'^2$)
($1'^2$ = 929 cm^2 = .0929 m^2)



So we need "fins" to add more area.

Amount needed = 38 - 9.7 - 11.6 = 38 - 21.3 = <u>16.7 m^2</u>

These "fins" will burn on both sides. Their maximum height will be 7' (to fit within the room).

Total area needed = 16.7 x 10.76 = $180'^2$ (both sides).

area/side = 1.80/2 = $90'^2$.

At 7' high, the total width = 90/7 = 12.85'.

Since plywood sheets come in 4' widths, use 12.85/4 = 3.2 such fins (4 of them).

The plywood in the real fire was 1/4" thick, but burned from only one side. So, since this wood burns from 2 sides, <u>make it 1/2" thick</u>.

F. <u>Now check how far we are above the ventilation limit</u>. (We chose the area and vents to simulate the Sharon, PA kitchen)

9.7 m^2 of effective crib area corresponds 1590 btu/sec., so 38 m^2 corresponds to 38/9.7 (1590) = 6229 btu/sec.

So we are 6229/6076 = 1.03 times the ventilation limit with both vents open. and 6229/3038 = 2.05 times the ventilation limit with the door, only, open.

The wood burning rate is calculated here as if it were all in cribs. Actually, with the room in flashover, most of the wood will burn faster than this, so the burning should be strongly ventilation controlled.

G. Calculate weight of wood.

The cribs weigh 4150 gm each.

weight - 18 x 4150 - 74,700 gm
- 165 lbs (crib weight)

side walls - 7' x 7' x 1'/24 x 2 - $4'^3$

fins - 4 x 7 x 4 x 1/24 - $4.6'^3$

base - 7 x 7 x 1/2 x 1/24 - $\underline{1.0'^3}$

$9.6'^3$ (other area)

density of wood - -25#/ft.^{3},

weight of panels - 9.6 (25) - <u>240 lbs</u>. other weight

total weigh of fuel - 240 + 165 - <u>405 lbs</u>. fuel load

(plus reinforcement on base)

<u>References</u>

1. Gross, D. "Experiments on the Burning of Cross Piles of Wood," NBS Journal of Research-C, 66C, No. 2, April-June 1962.

2. Quintiere, J. G., and Mc Caffrey, B. J., "The Burning of Wood and Plastic Cribs in a Enclosure: Volume 1," NBSIR 80-2054, November (1980).

3. Nelson, H.E., "Fireform" - A Computerized Collection of Convenient Fire Safety Computations. NBSIR 86-3308, April 1986.

4. Quintiere, J.G., "A Simple Correlation for Predicting Temperature in a Room Fire," NBSIR 83-2712, June 1983.

Appendix B
Analysis of Salt Water Fresh Water Stairway Flow Tests (Townhouse Simulation)

Introduction

Three tests were carried out in a plastic scale model of the "townhouse" fire facility in Building 205. Dyed salt water was used to simulate the buoyant fire plume. The geometry was the same in all three cases, except that the "door" to the upstairs bedroom (with an open window in the bedroom) was "leaky" for test 2, and open for tests 1 and 3. The purpose of this variation was to see if the presence of the open window was enough to cause a strong flow of smoke through the leaky doorway in the October 87 Sharon, PA fire (which will be simulated at full scale in Bldg. 205). The "Fire" in test 1 was equivalent to 32 kw, and in tests 2 and 3 was equivalent to * kw. Time in this simulation is equivalent to real time.

Another major reason for these tests was to visualize the nature of the flow in a partly enclosed stairway, again simulating the Sharon, PA fire.

Results

a) Effect of Bedroom Door

The leaky bedroom door in room 2 greatly restricted the flow through that bedroom. In that run, the third bedroom rapidly filled with "smoke" but the windowed room smoke was diluted and flowed slowly out the window. If this had happened in the Sharon, PA fire, the person in the back bedroom would have been quickly killed. In the other runs, the smoke rapidly filled the windowed room and created a dense plume out the window.

b) Stairway Flows

In all runs, the initial flow up the top of the stairway rapidly became highly turbulent, thick, and unsteady. Probably there are two reasons for the unsteadiness. One reason is that the formation of the ceiling layer in the room upstairs of the stairway was accompanied by strong sloshing. When the layer was deep, heavy flow would start up the stairwell, and when less deep, less flow. The second reason is that the lowest layer flow entering the stairwell from above, either at the upper floor level or above, interacted the flow coming up the stairwell at an angle and mixed turbulently with it. It is not obvious the steps in the stairwell had much to do with this mixing. The lower layer flow exiting the stairwell had some blue color, indicating a degree of mixing with the upper layer.

c) Event Times

An attempt was made to look at flow differences by timing events on the video tapes of the runs. Events are listed here in seconds of real time:

---

*Probably about 60 kw.

Events

Conditions	Run No. 1 32 kw flow door opened	2 60 kw flow door closed	3 60 kw flow door open
Start	0	0	0
First stairway flow	15.5	10	-
First stairway pulses	21.5 30.5	18, 23.5	-, 23
Flow reaches top of stairs	23	20	17.6
Strong stairway mixing starts	30.5	28	27
Lower layer flow exits stairway	34	26.5	23.5
Layer height 50% in upstairs hallway	38	32	27
Flow enters bedroom with window	44	--	32
Flow out bedroom window	63	65	47
Window flows full	125	118	55

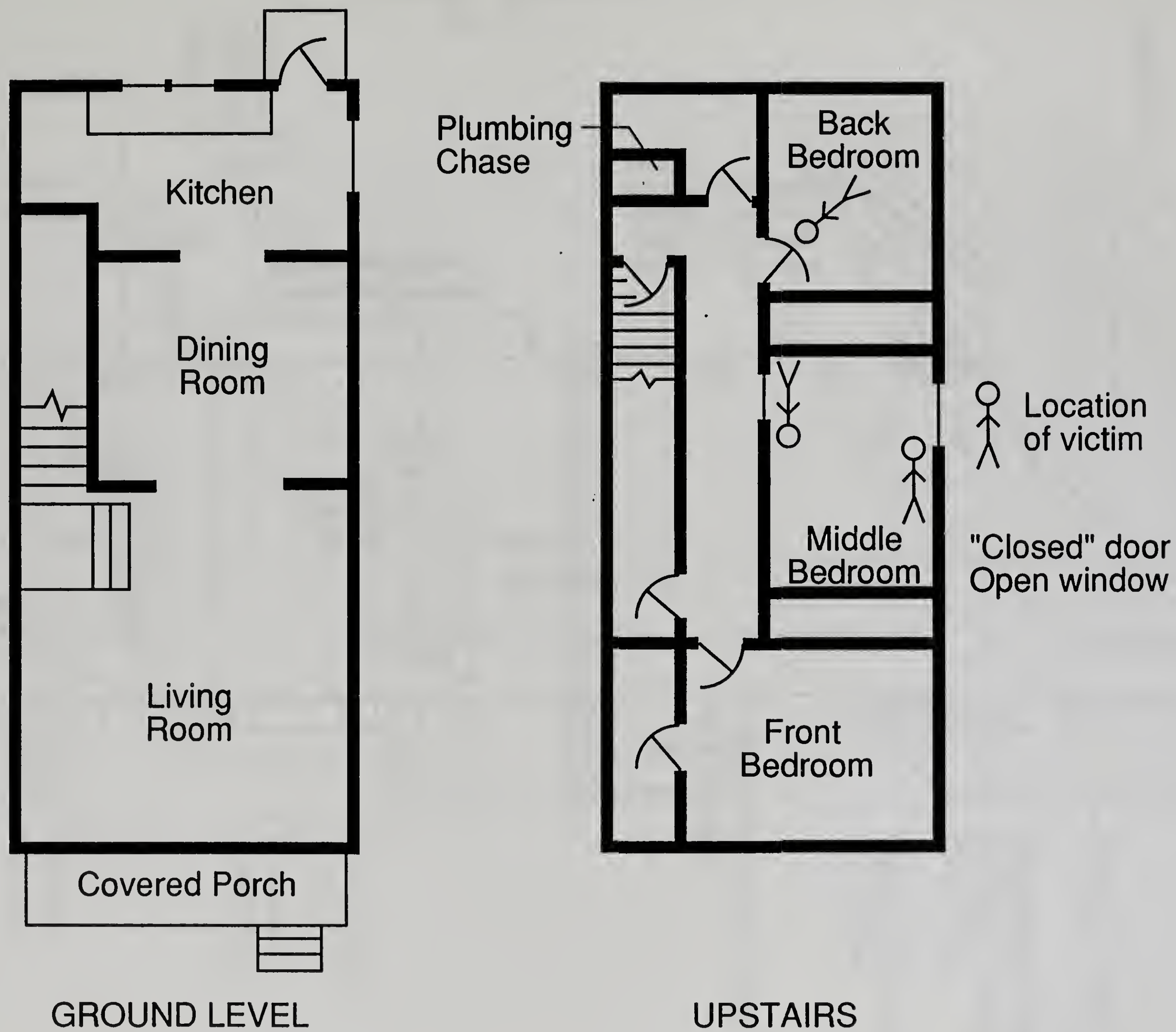


FIG I-1
Floor Plan of Residence
Sharon, PA Fatal Fire

1-1

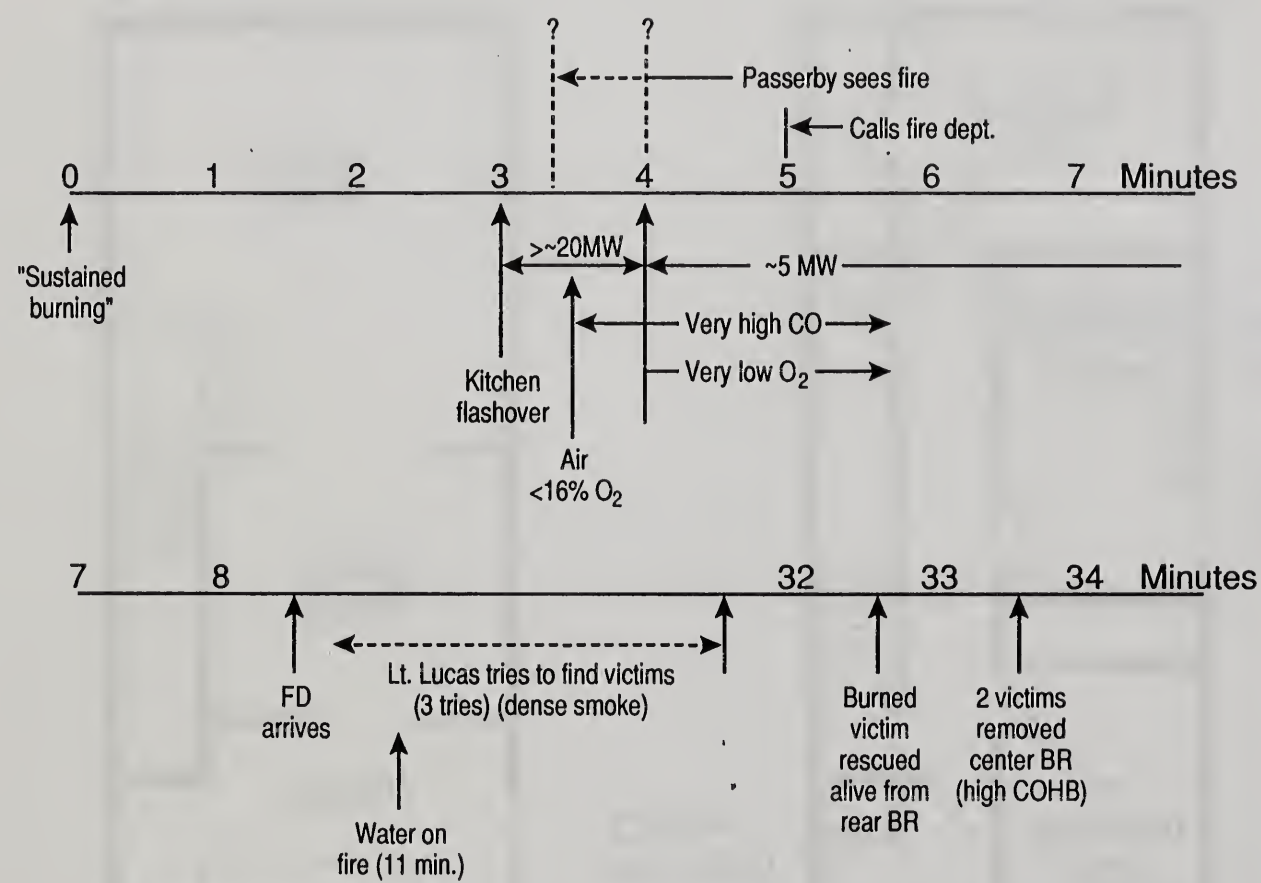
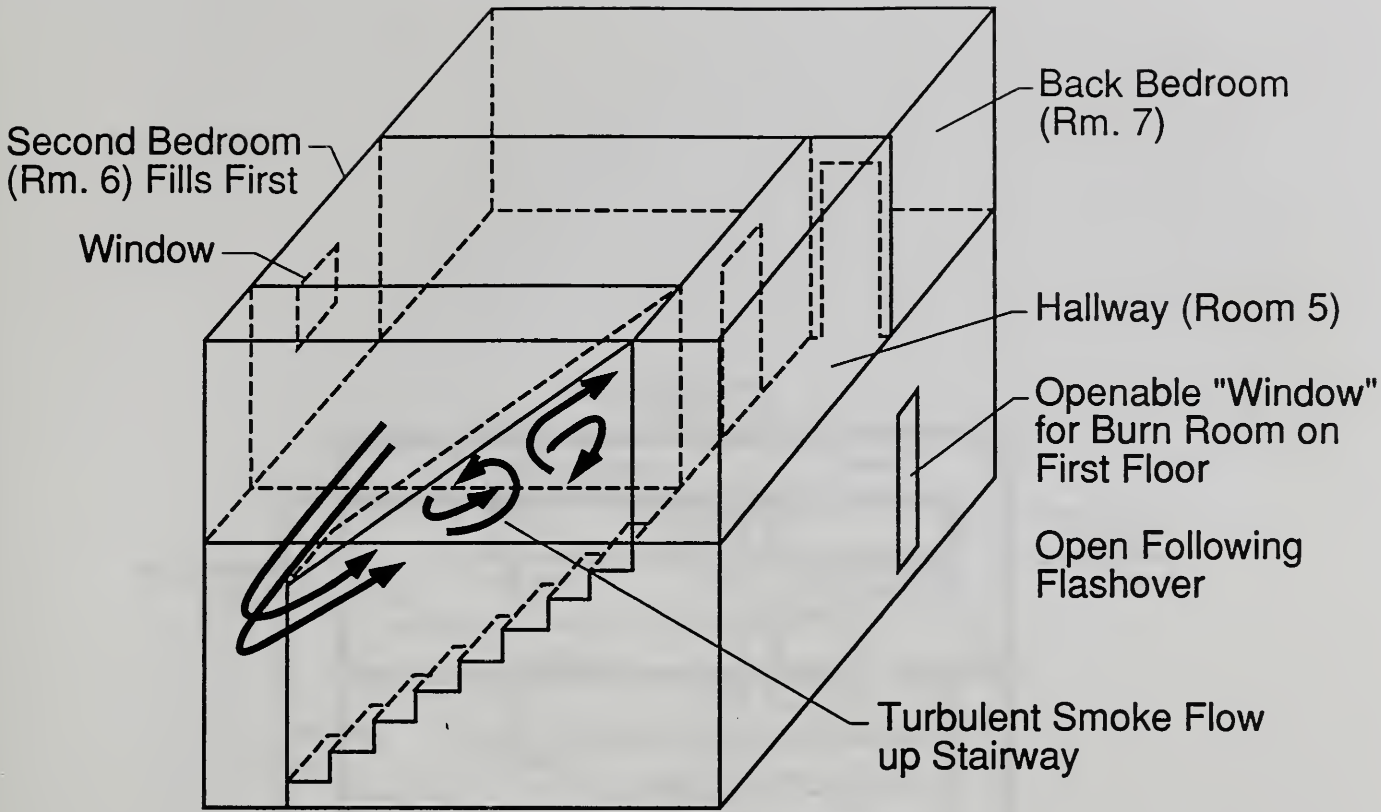
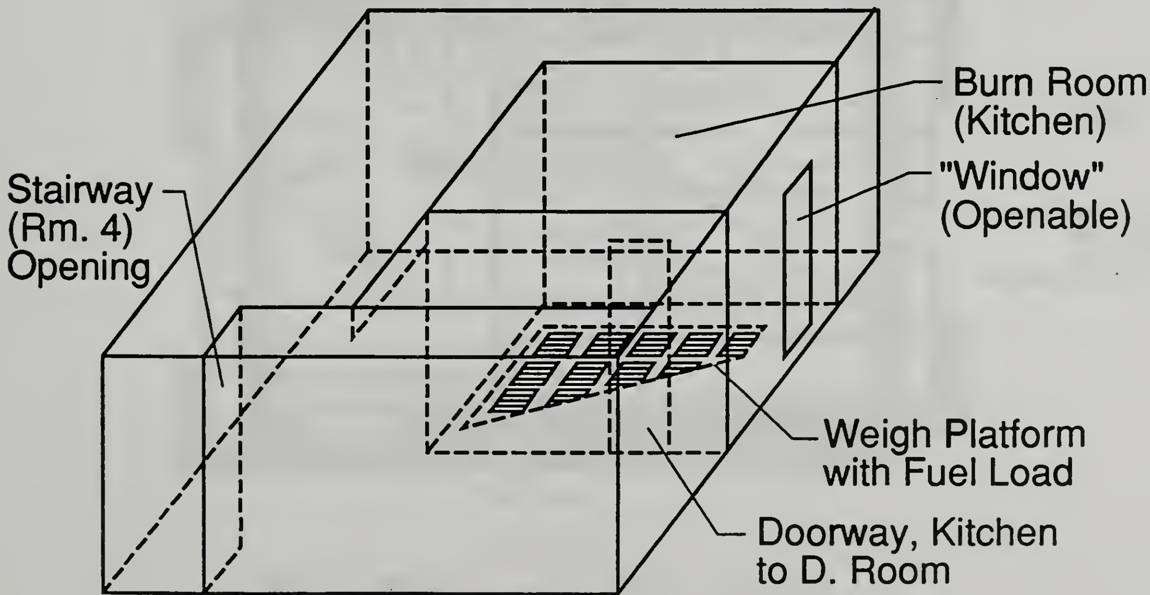


FIG I-2
Plausible Time-Line
Sharon, PA Fire



"TOWNHOUSE" UPPER FLOOR
AND ENCLOSED STAIRWAY



"TOWNHOUSE" LOWER LEVEL

FIG II-1
Burn Facility Arrangement - SHARON 2 Test

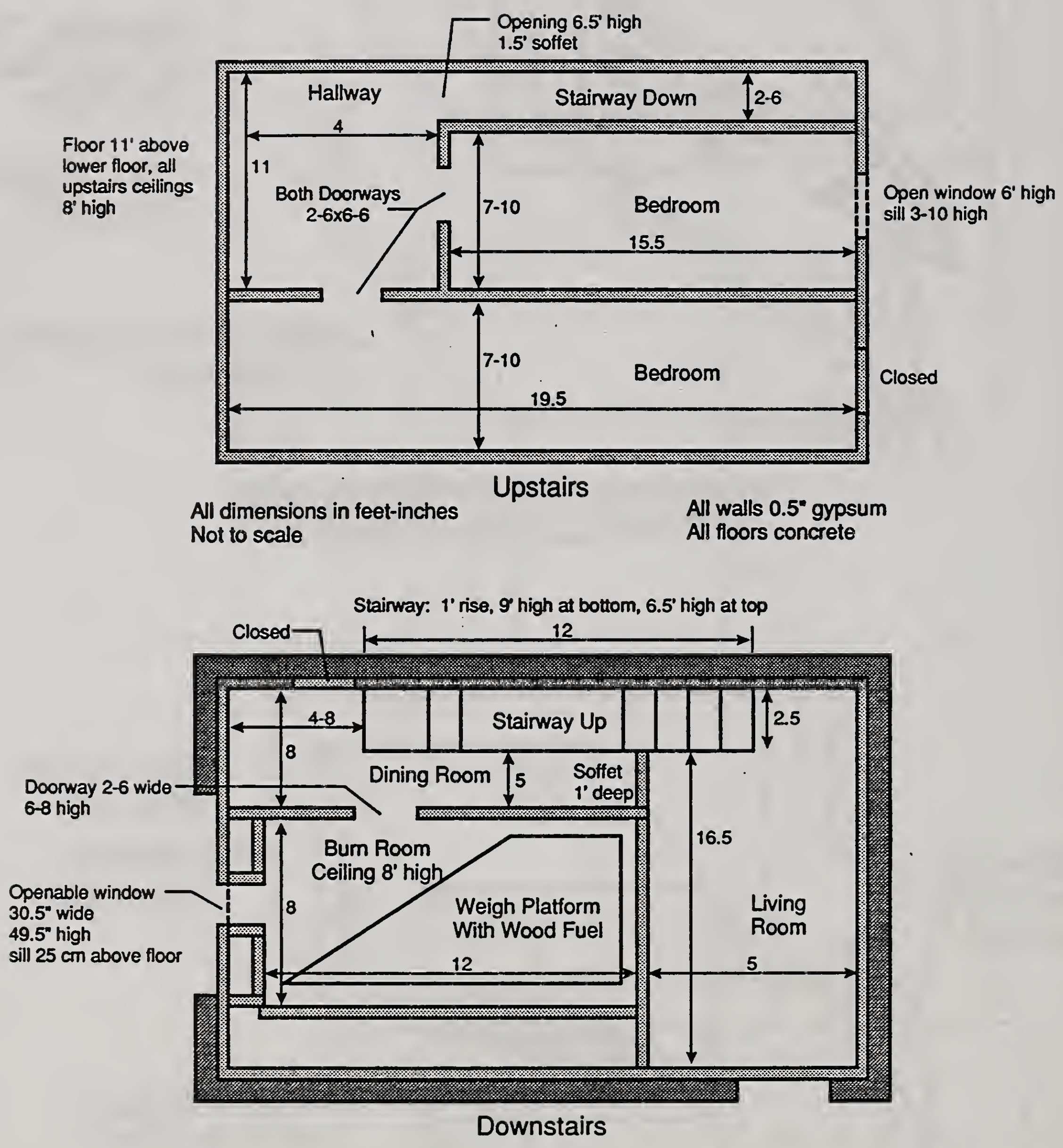


FIG II-2
Facility Dimensions - SHARON 2 Test

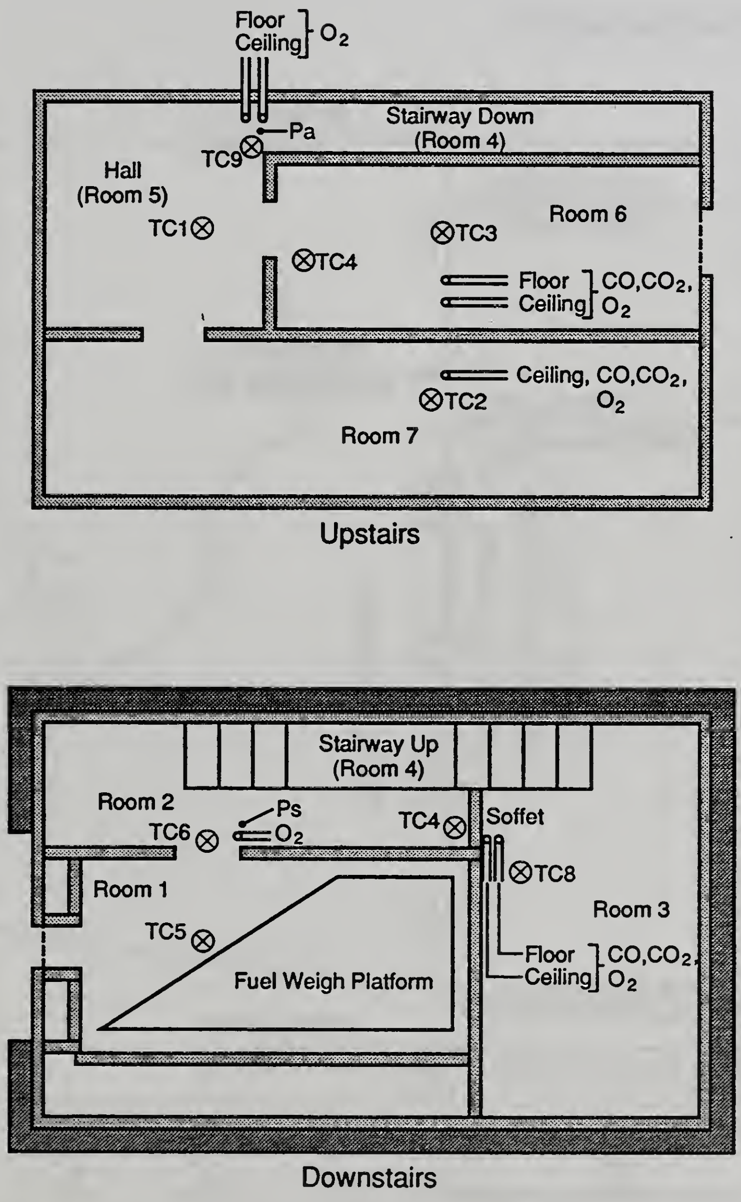


FIG II-3
Instrumentation Locations - SHARON 2 Test

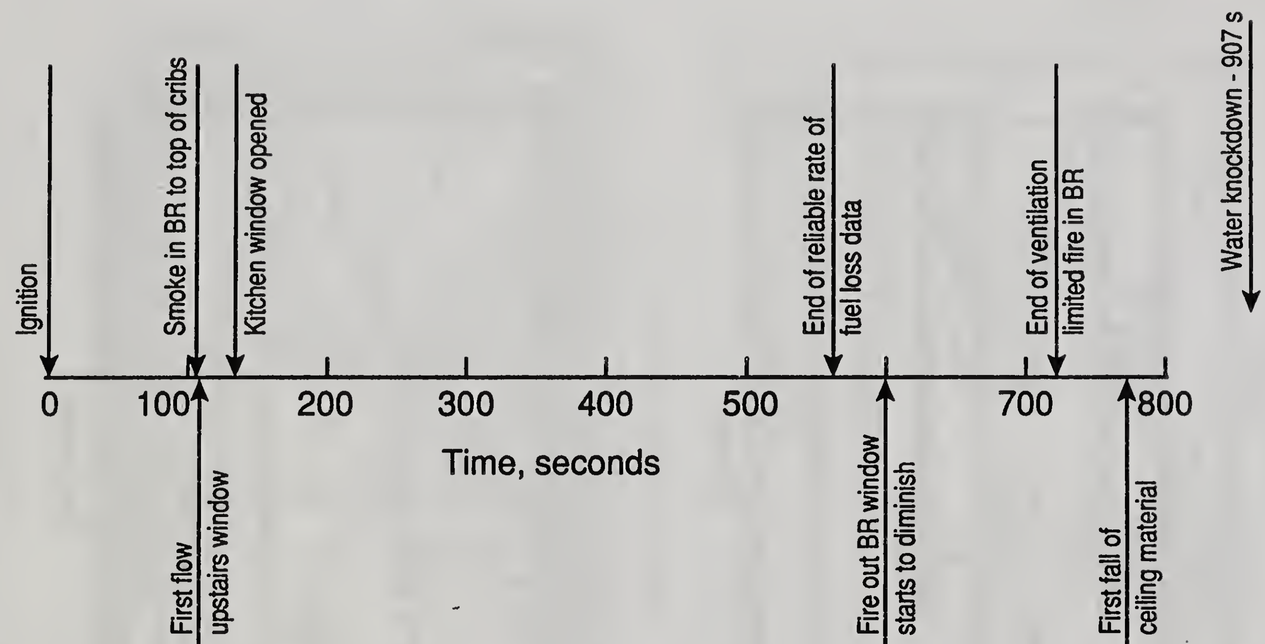


FIG II-4
Time Line - SHARON 2 Test

2-4

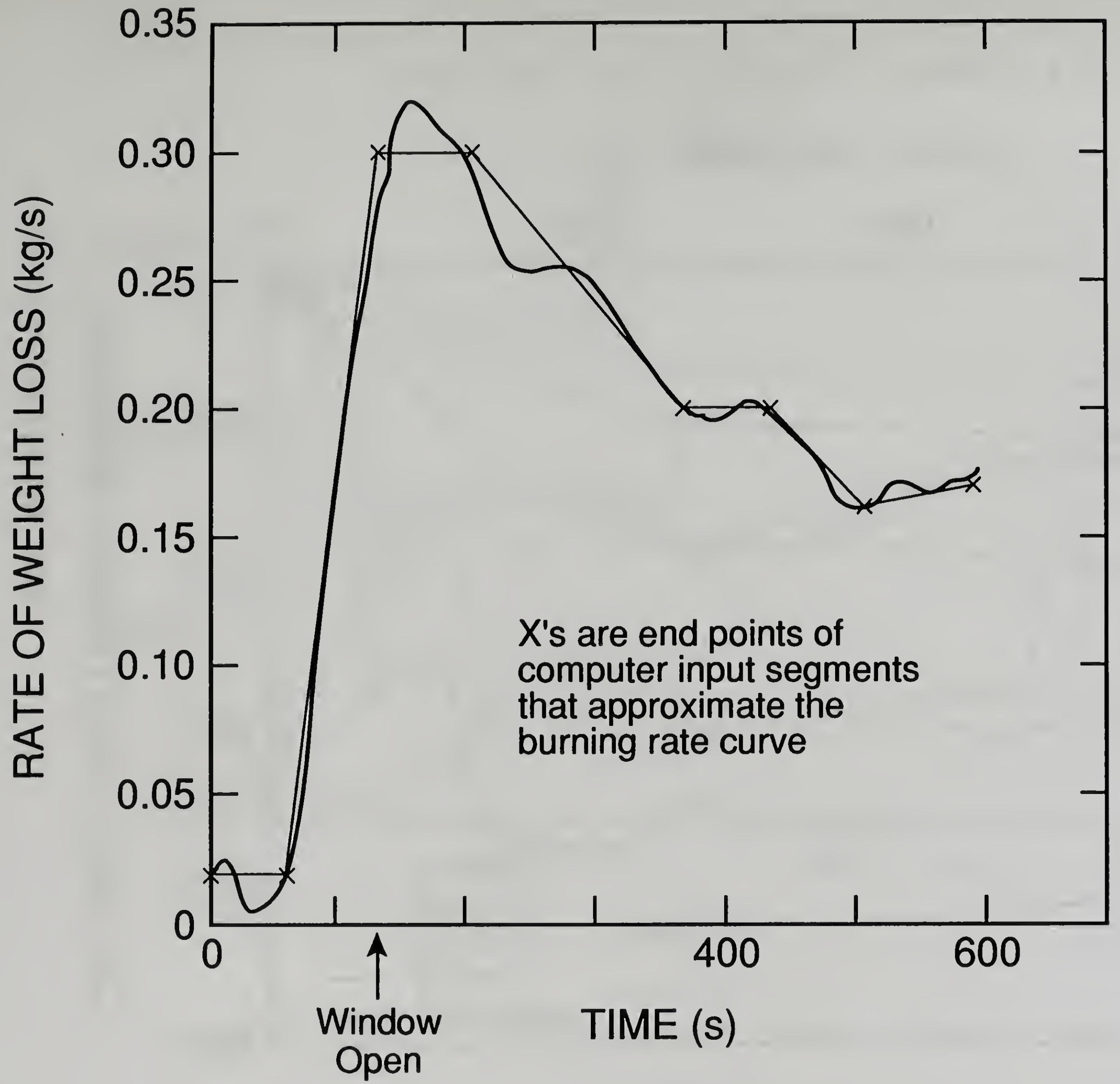


FIG II-5
Fuel Weight Loss Rate - SHARON 2 Test

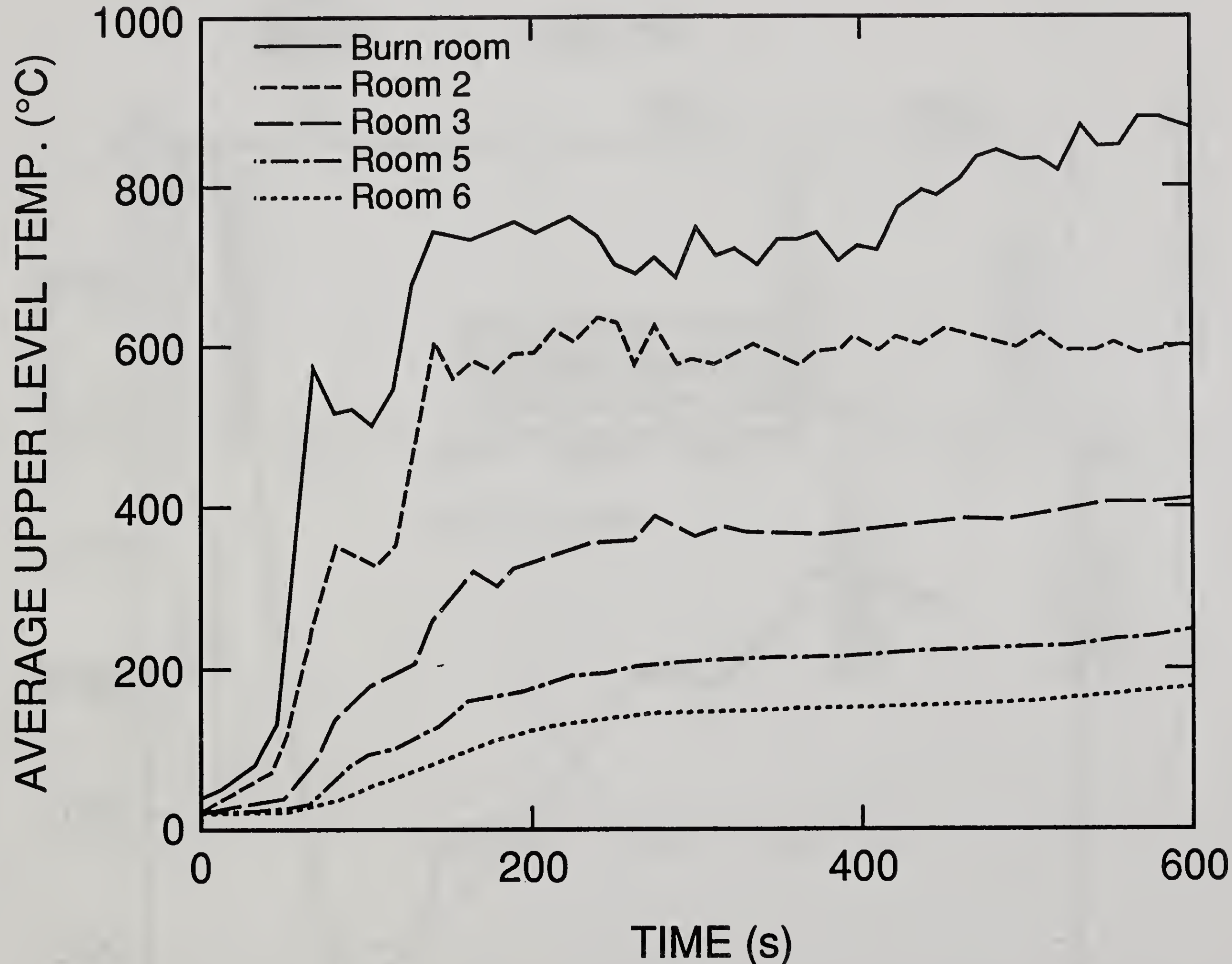


FIG II-6
Average Upper Layer Temperatures - SHARON 2 Test

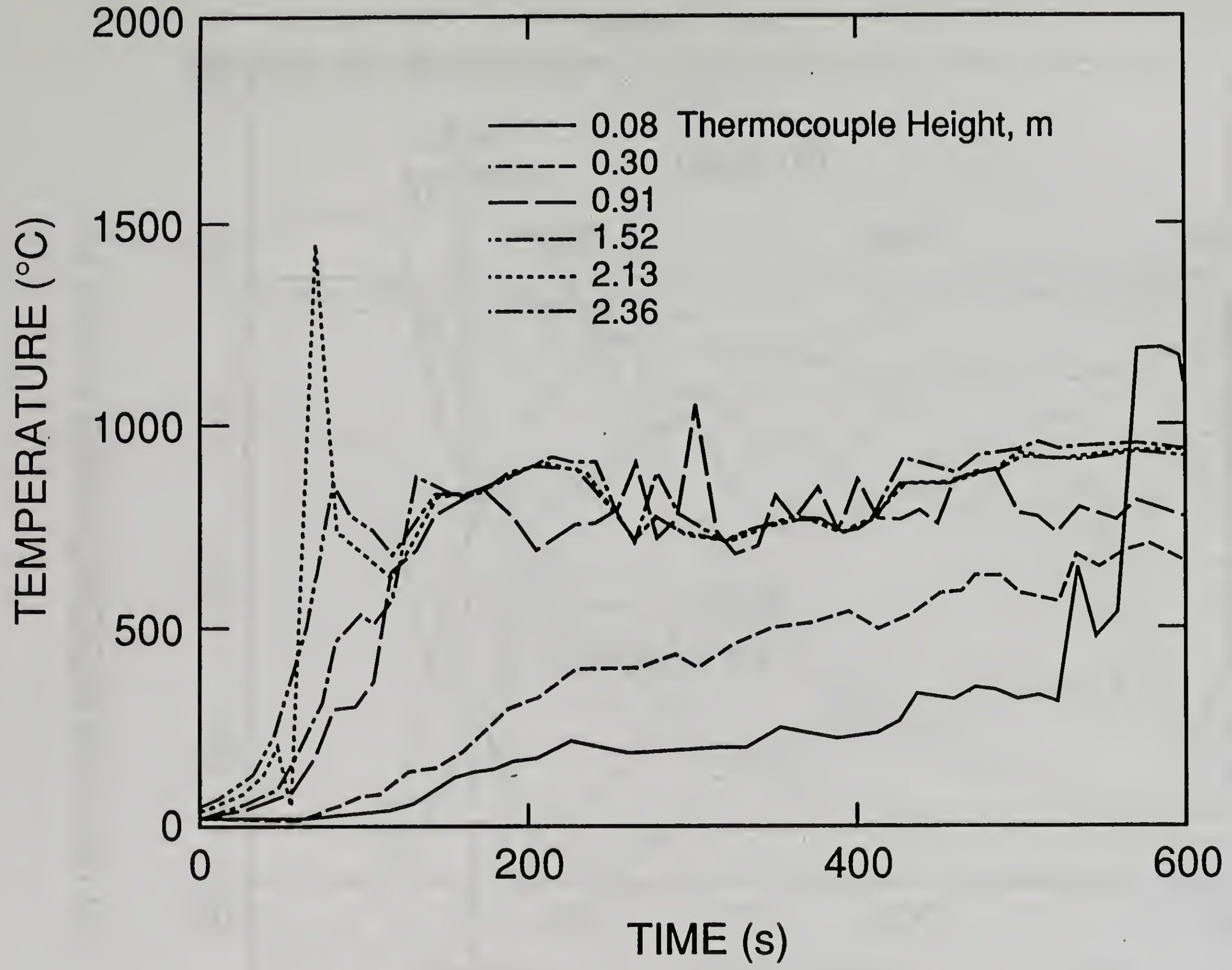


FIG II-7
Burn Room Temperatures at Various Heights - SHARON 2 Test

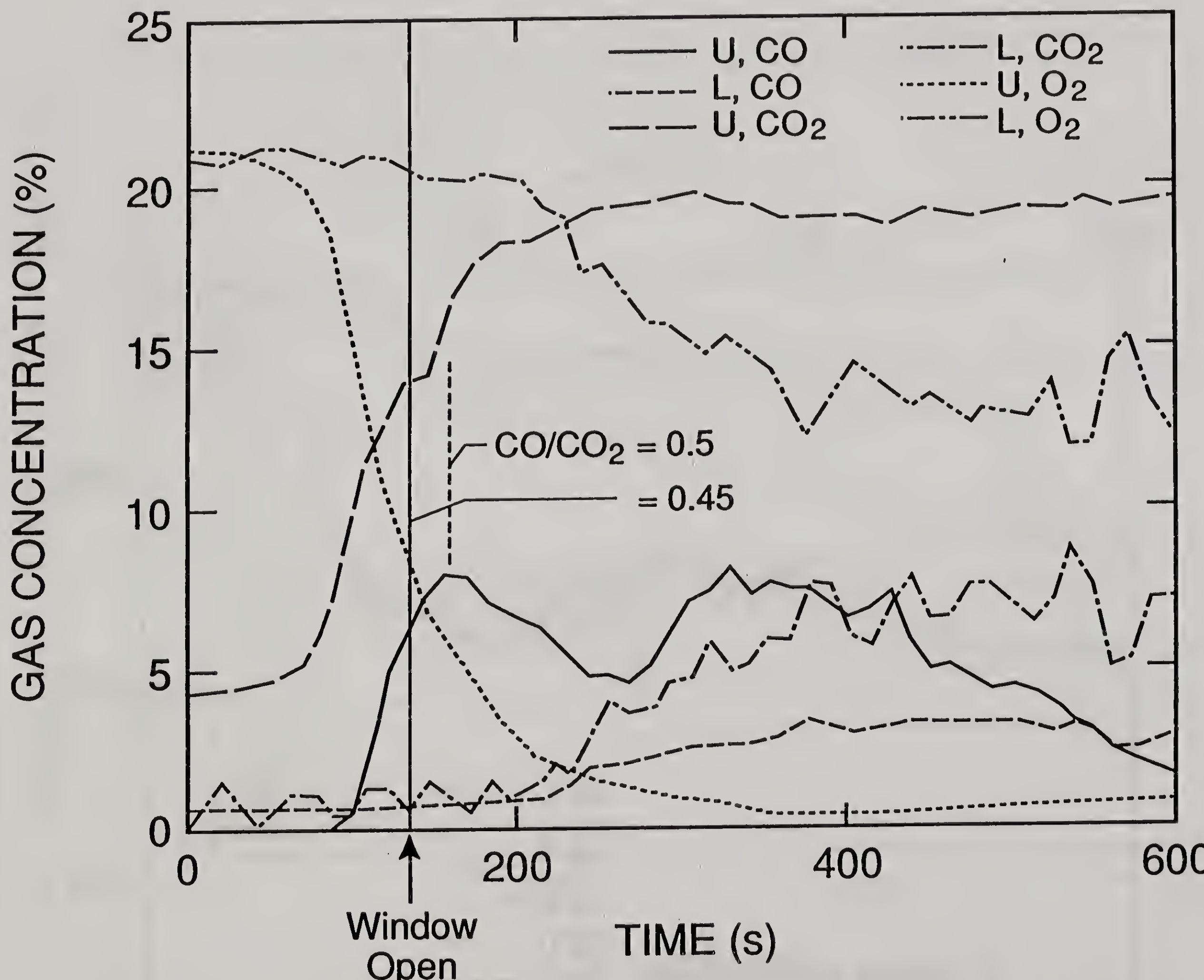


FIG II-8
Measured Gas Concentrations at the Soffit (near Burn Room Exit)
SHARON 2 Test

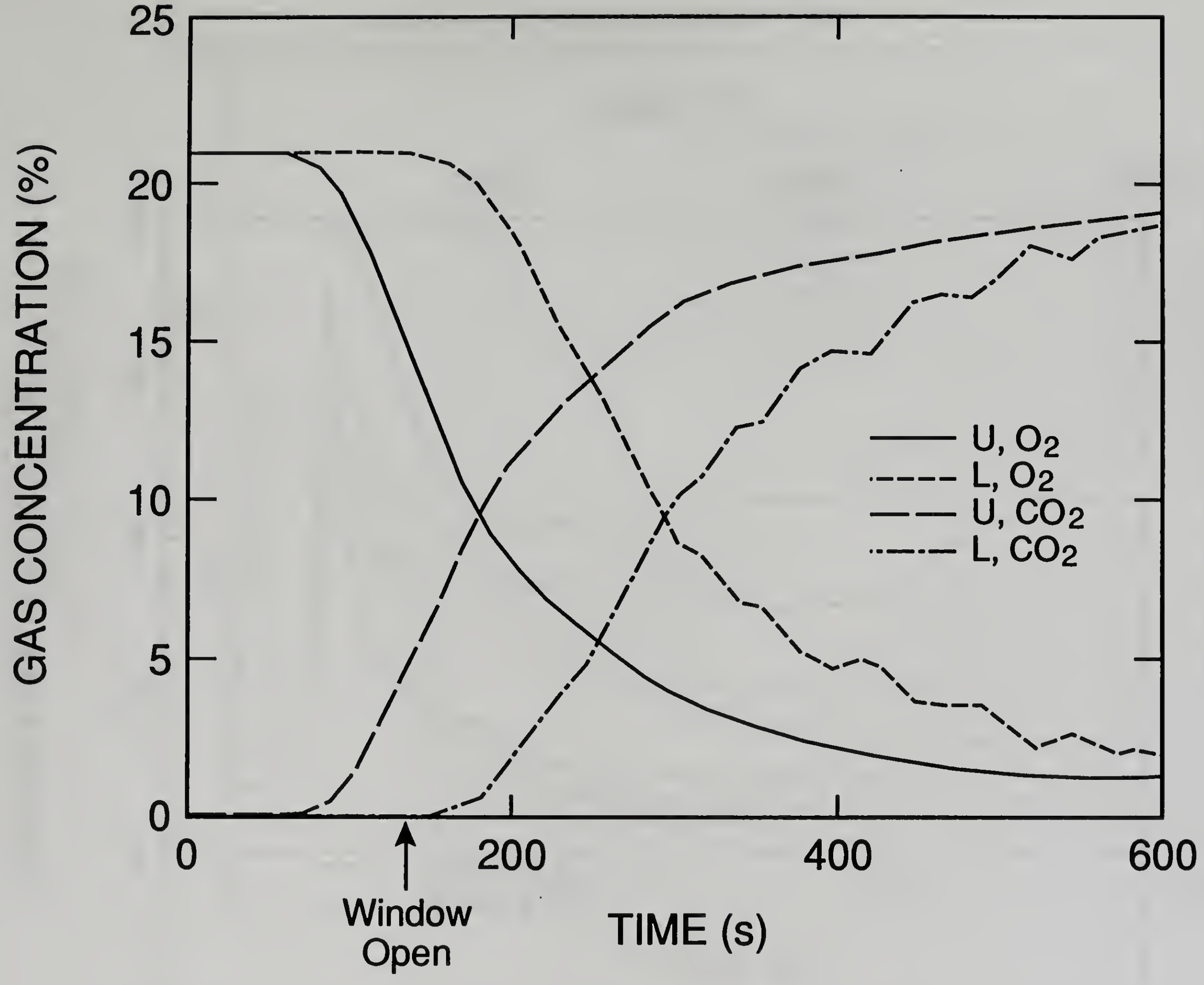


FIG II-9
Measured Gas Concentrations - Room 6
SHARON 2 Fire Test

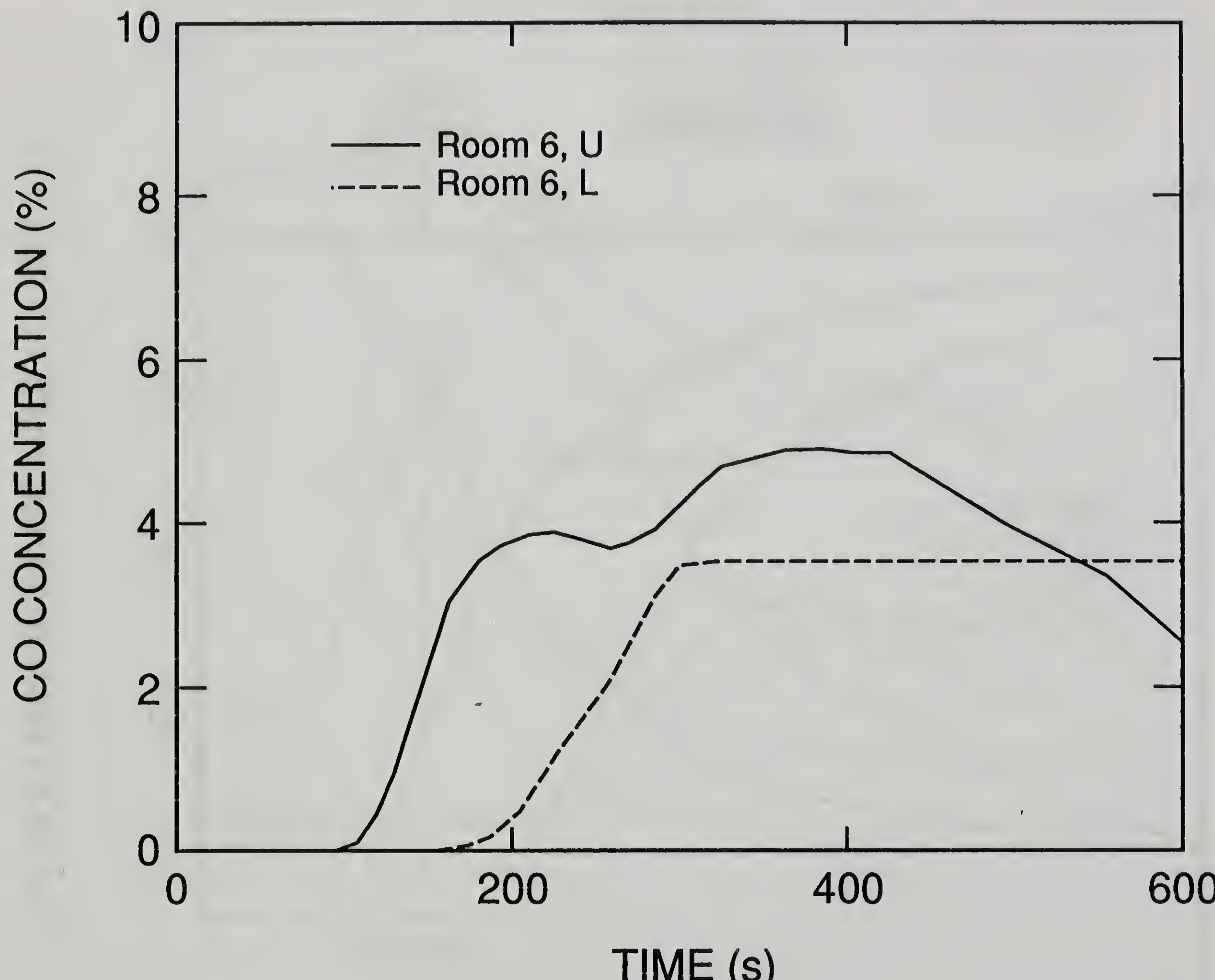


FIG II-10
Measured CO Concentrations, Room 6

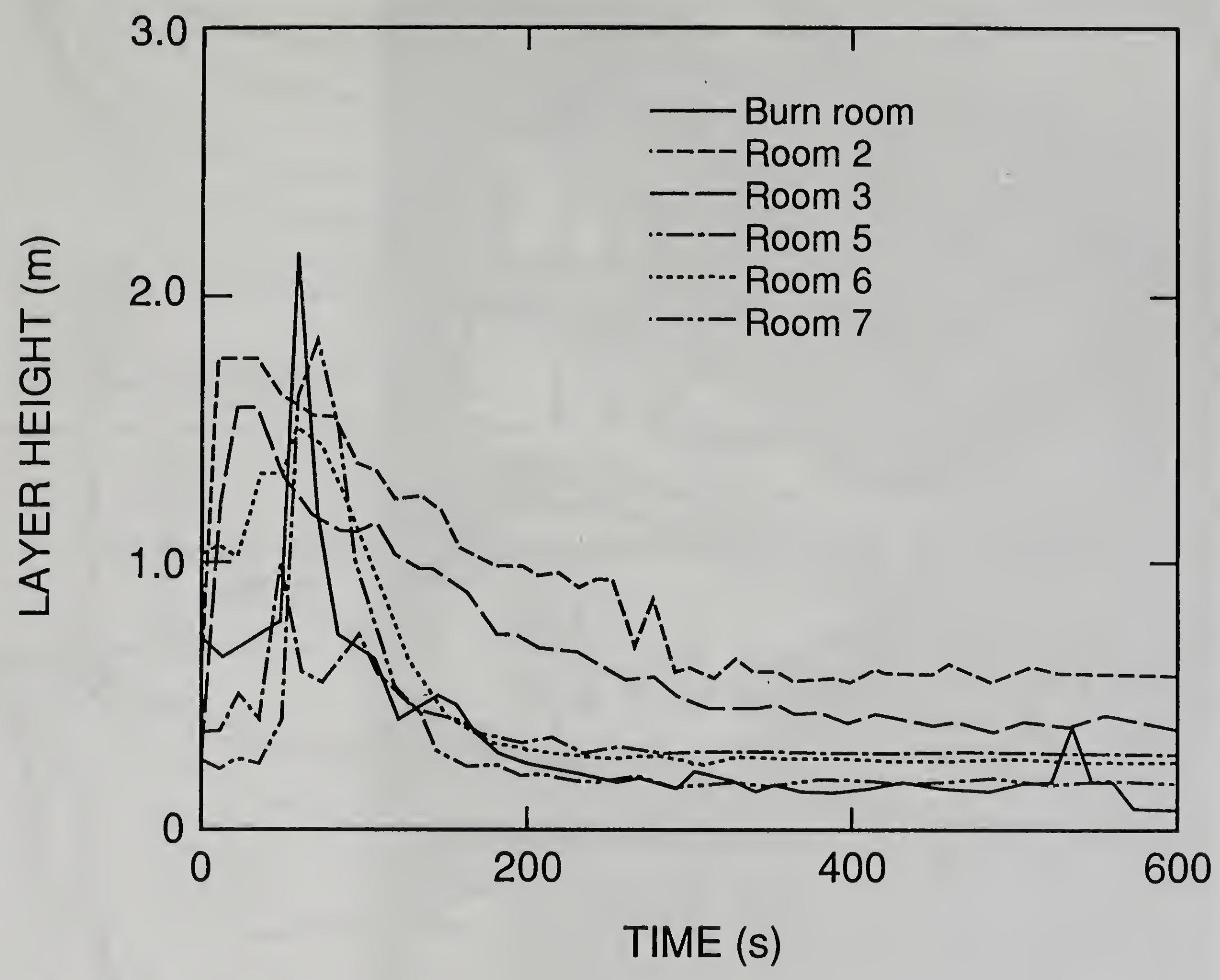


FIG II-11

Derived Ceiling Layer Heights - SHARON 2 Test

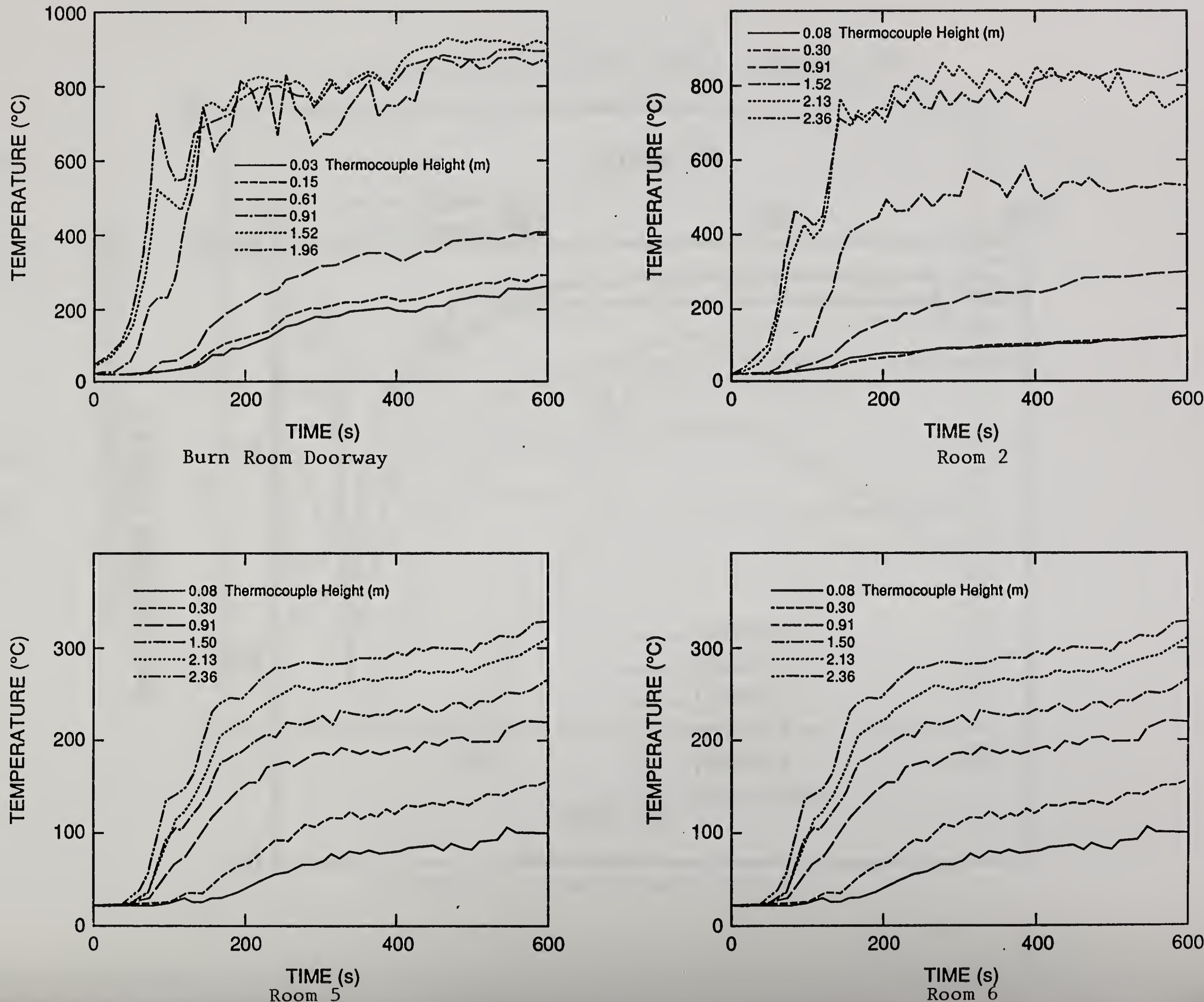


FIG II-12
Measured Temperatures at Various Heights - SHARON 2 Test

2-12

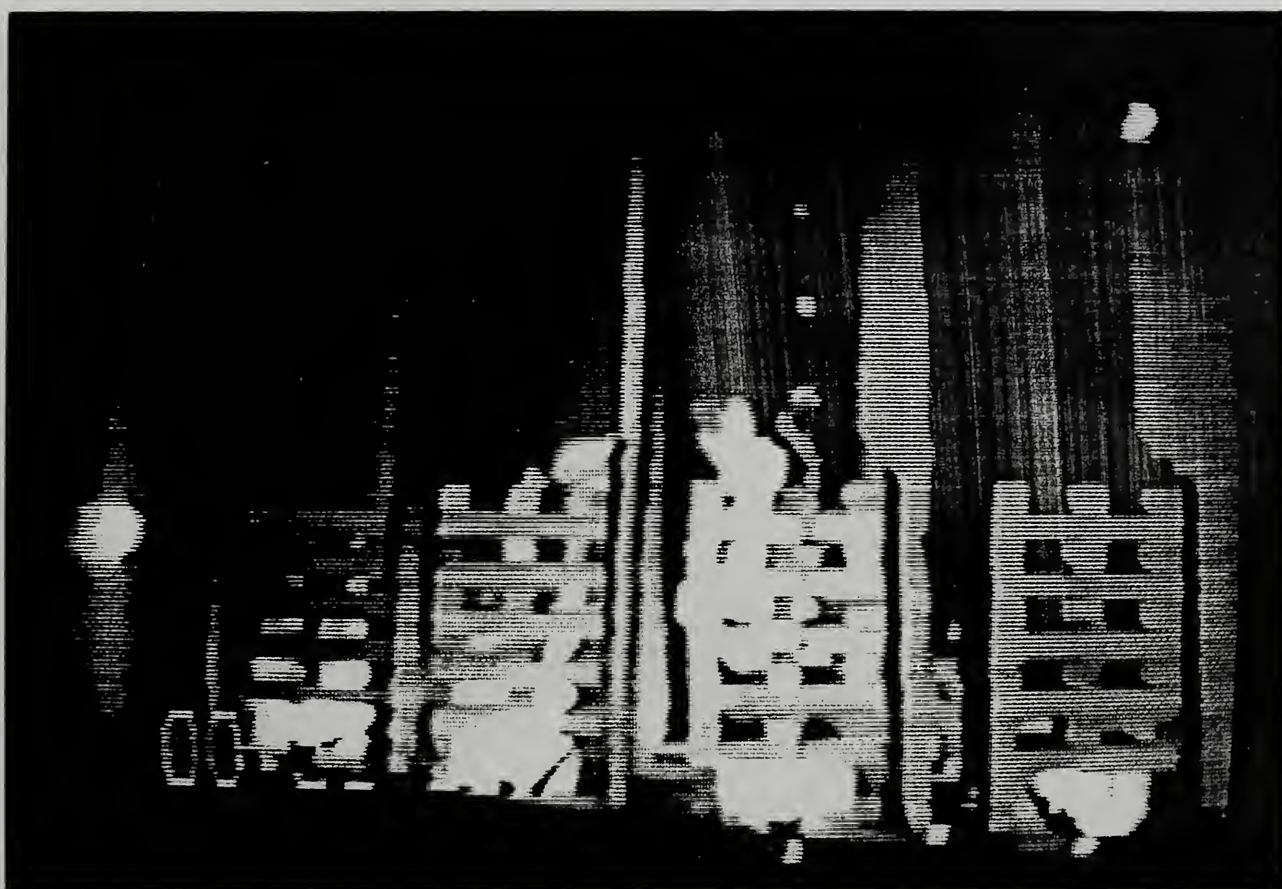


Figure II-13

Cribs 31 seconds after ignition

Figure II-14

Cribs 1 minute after ignition

Figure II-15

Dense smoke immediately after opening "window"

Figure II-16 A

"Window" about 2 minutes after opening, flame out the top, air entering at bottom, smoke circulating at interface

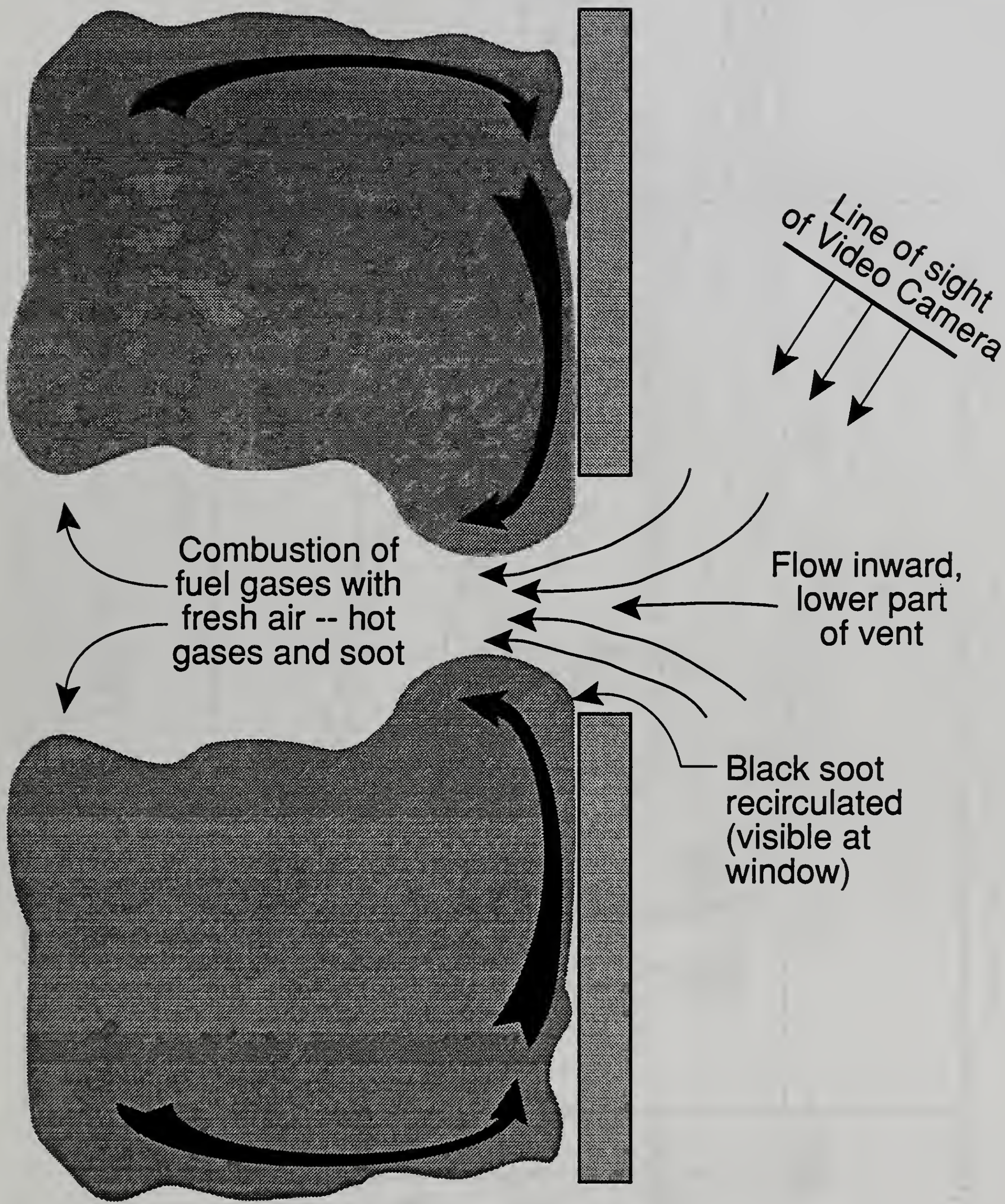


FIG II-16B
Postulated Horizontal Circulation
in Burn Room

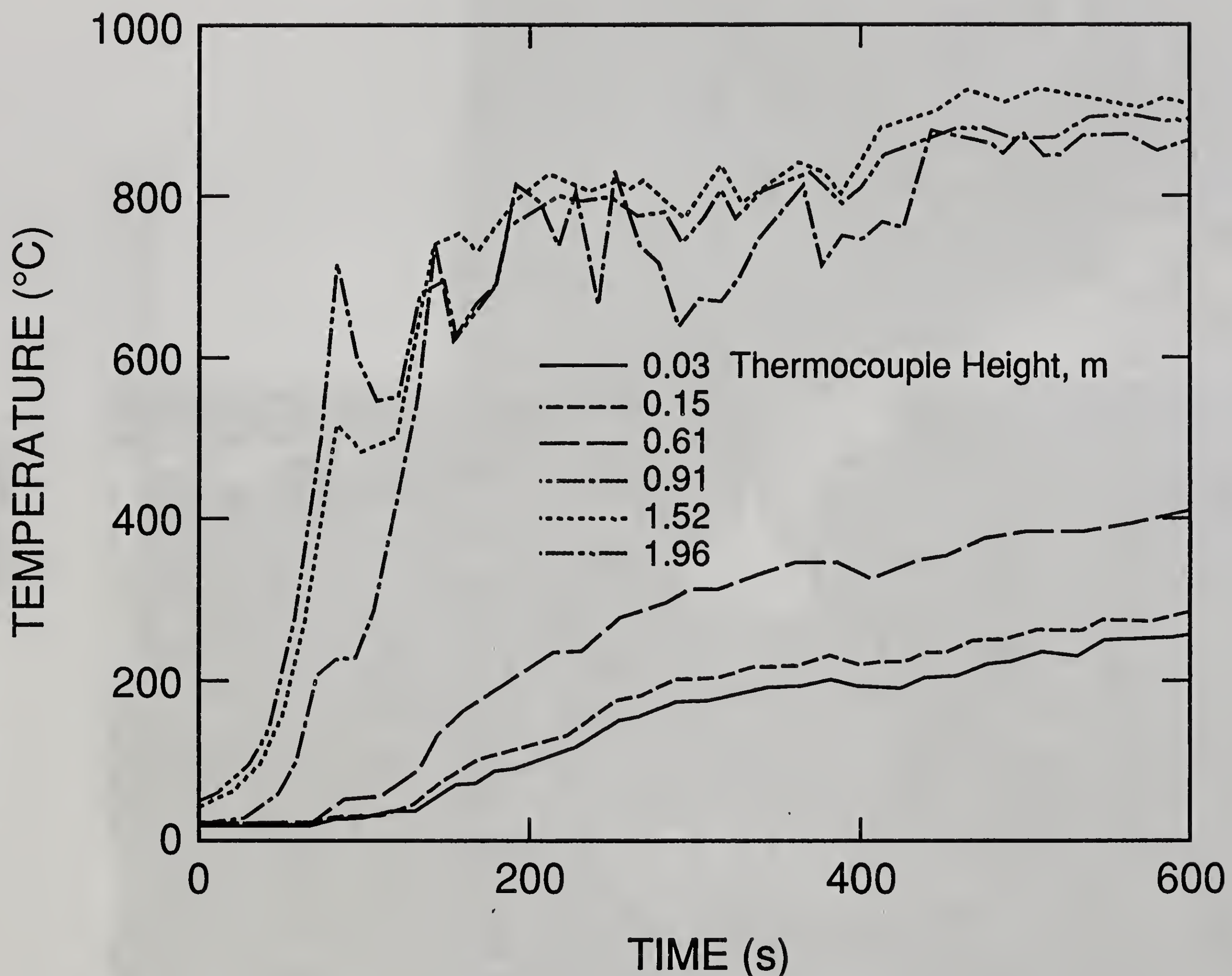


FIG II-17
Measured Temperatures at Burn Room Doorway - SHARON 2 Test

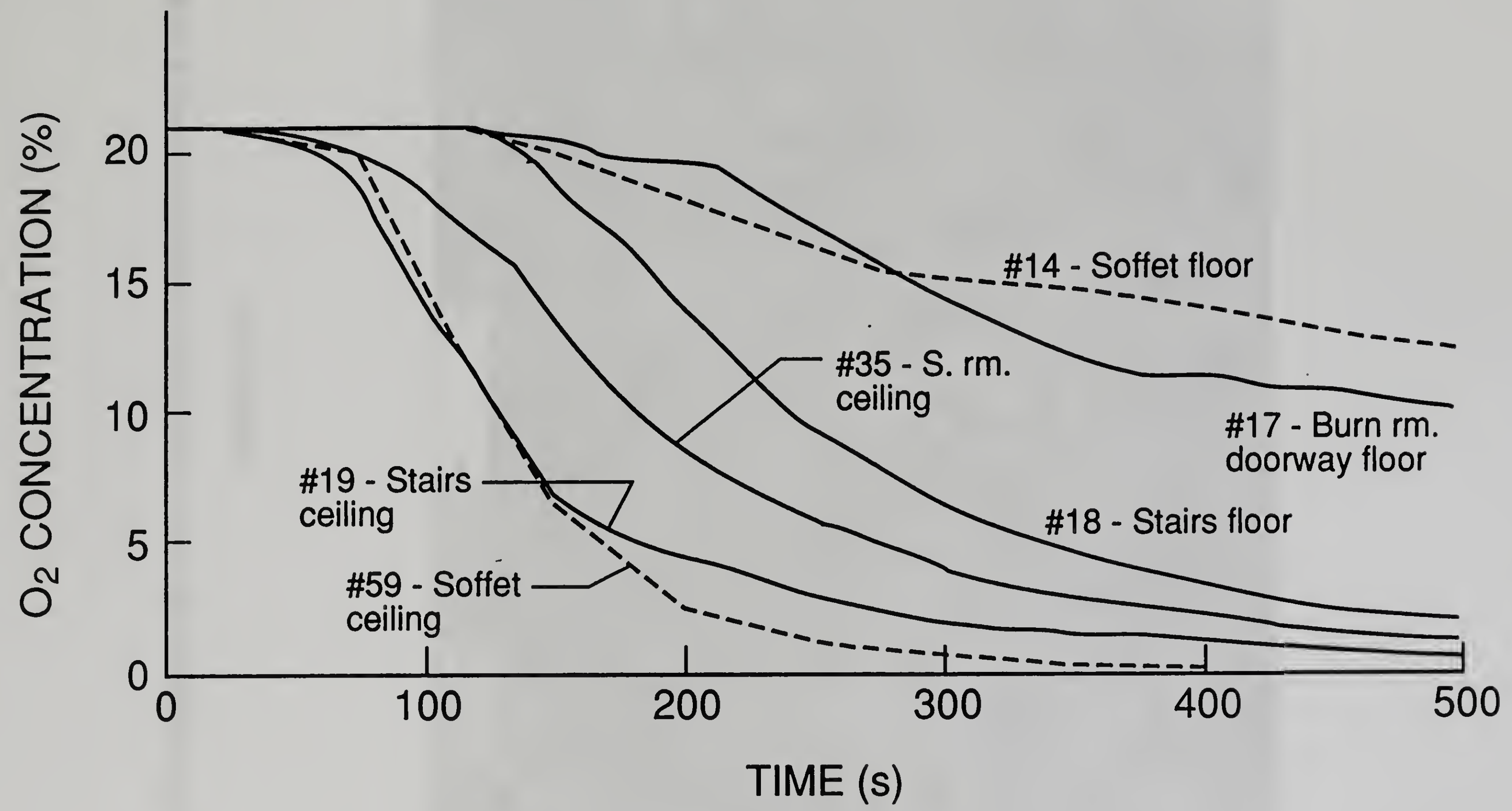


FIG II-18

Oxygen Concentrations at Various Sites - SHARON 2 Test

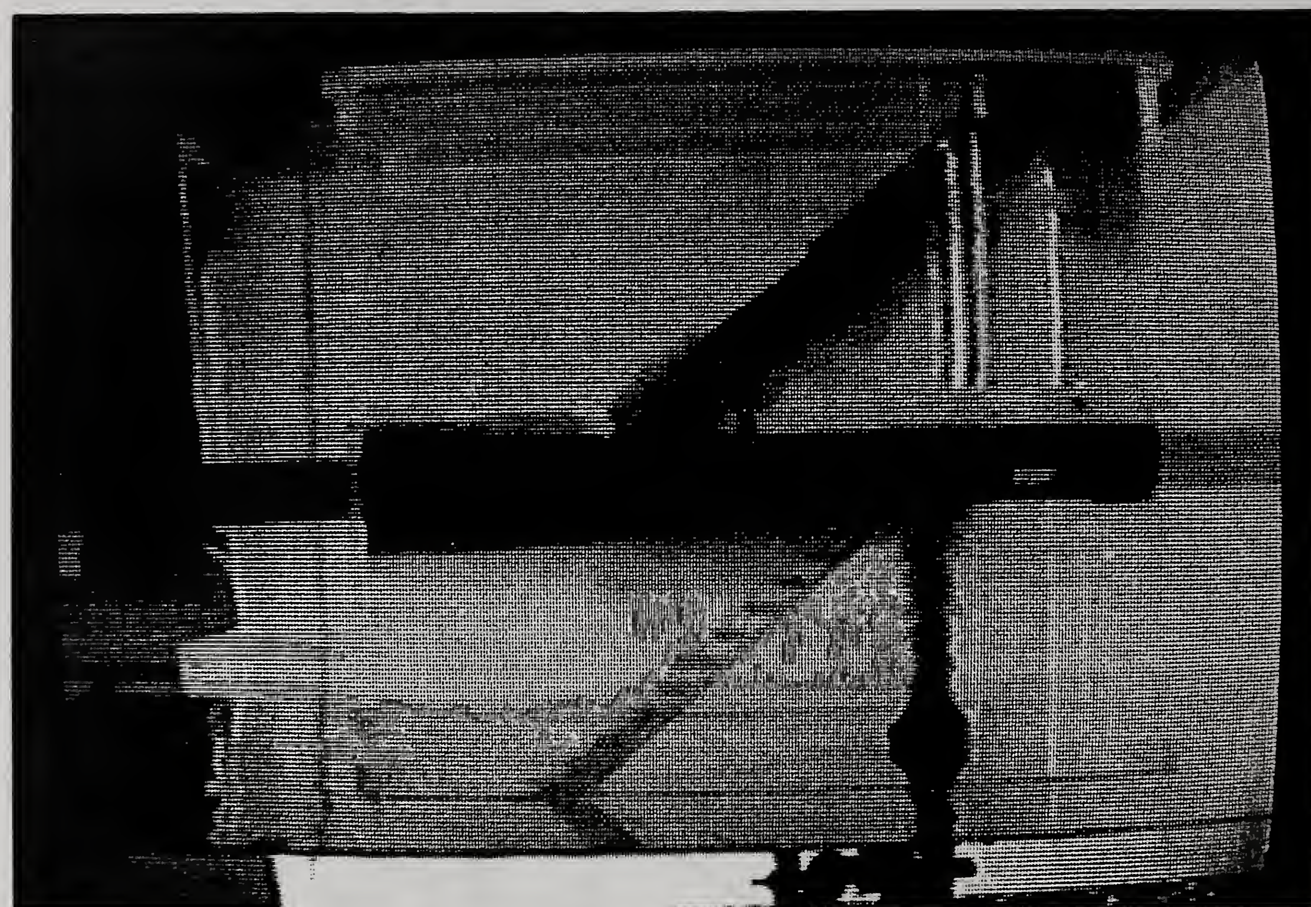


Figure II-19

Dyed salt water flow in fresh water - ceiling layer jet flowing up sloping roof of stairway

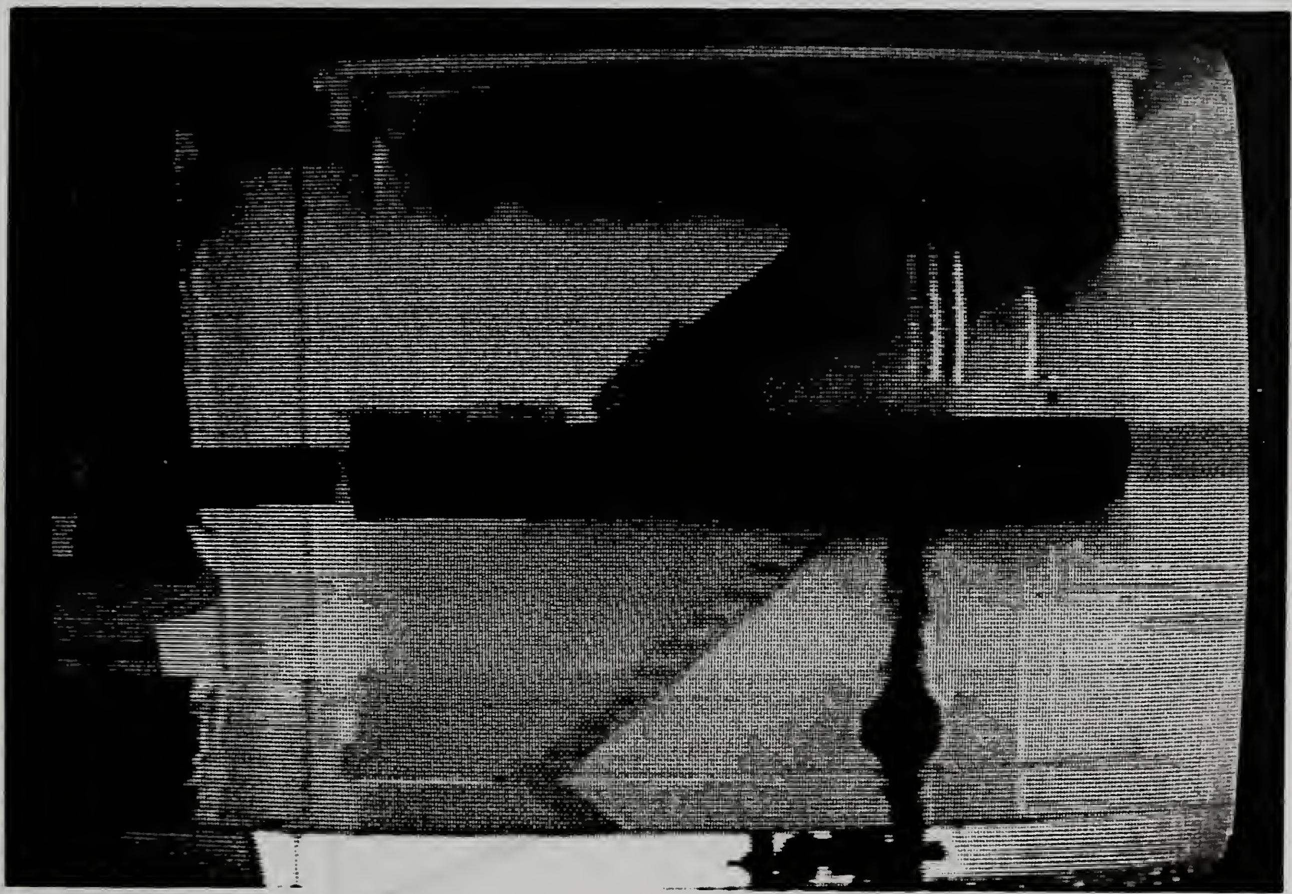


Figure II-19A

Somewhat later than Figure II-19, hallway upper layer well developed and flowing into Room 6

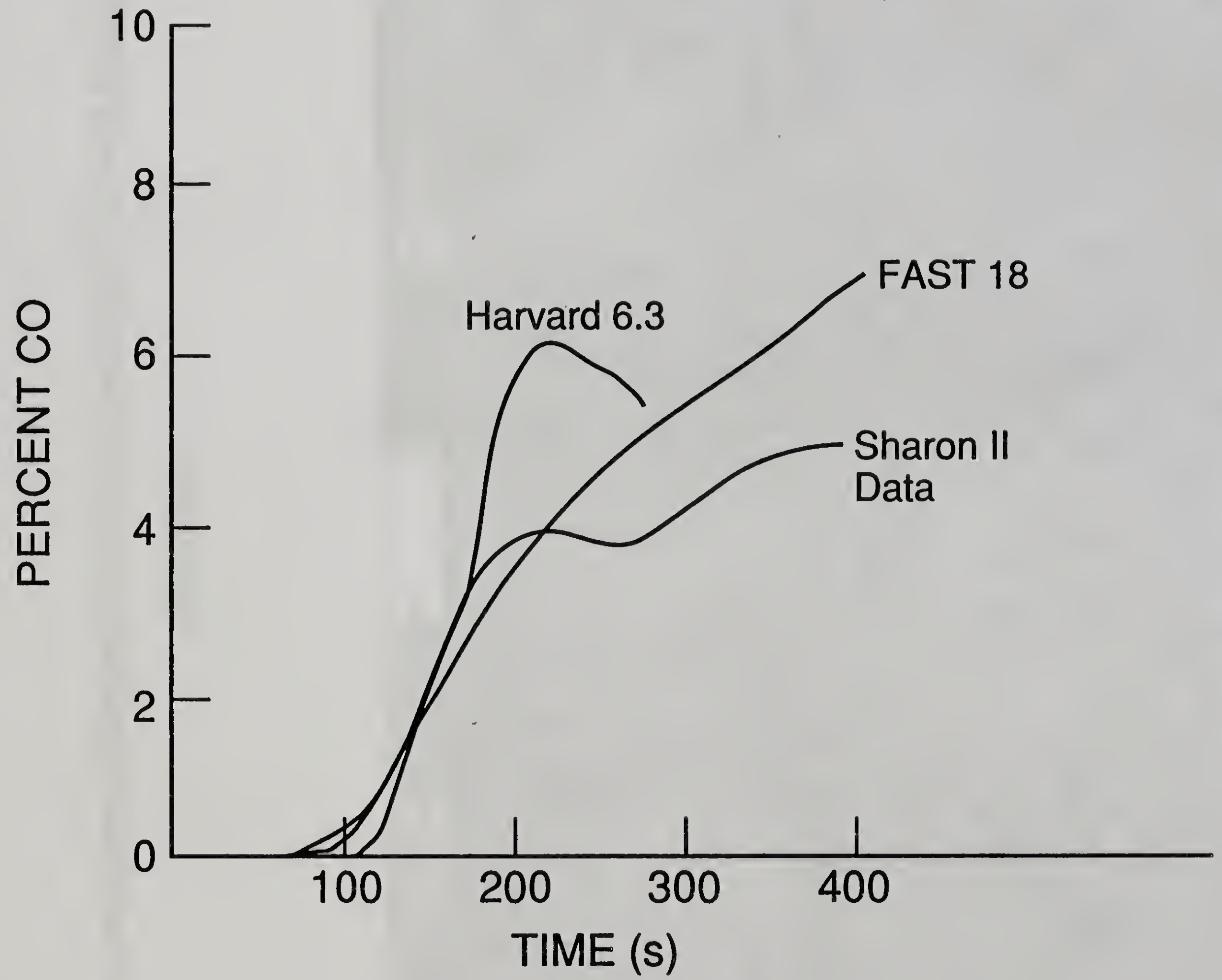


FIG III-1
CO Concentrations vs Time, Data, and Calculated by Two Models

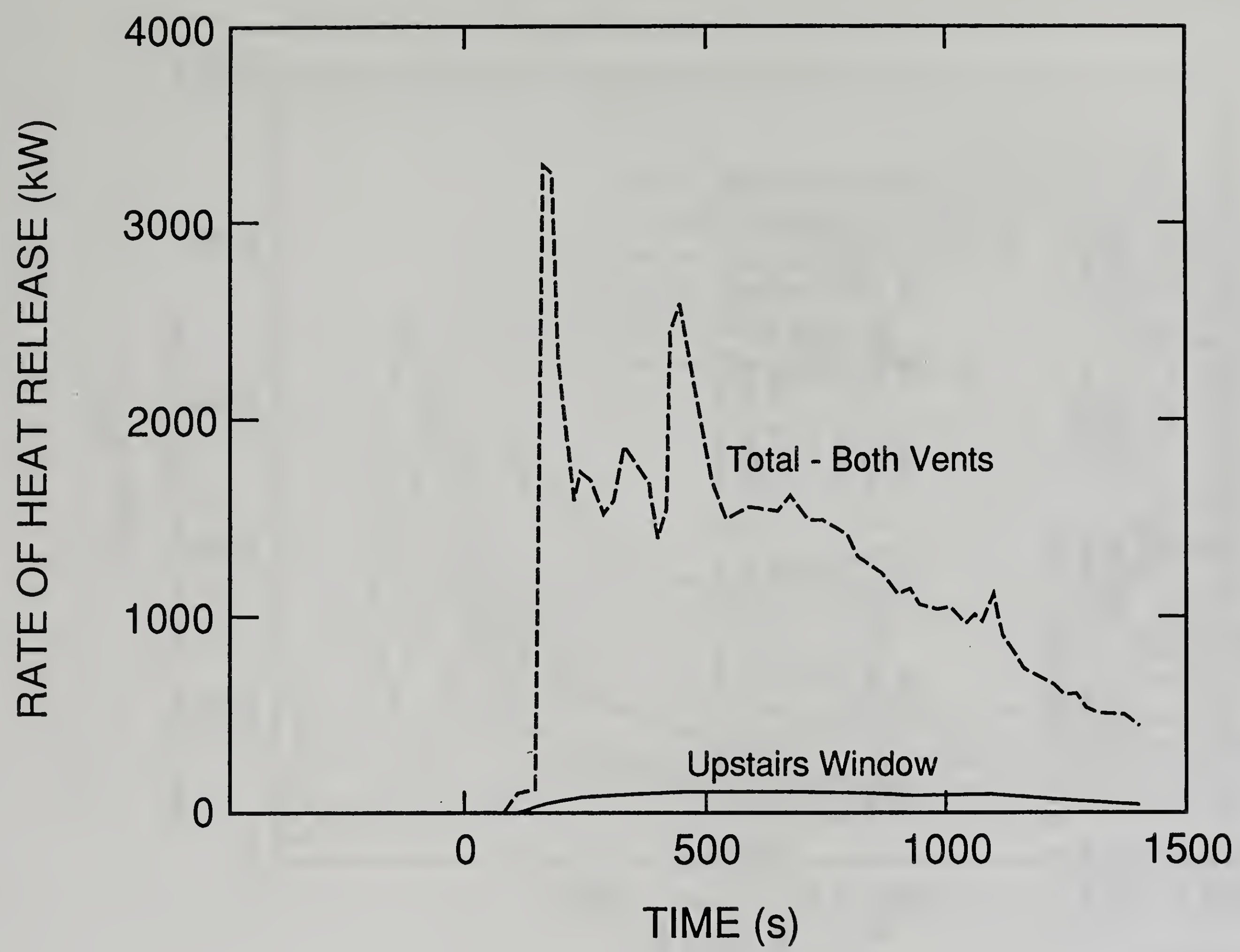


FIG III-2
Heat Release Rate Derived by Oxygen Depletion Calorimetry - SHARON 2 Test

```
VERSN   18      MODEL BLDG 205 SIMULATION OF SHARON PA FIRE
TIMES    600  30  20   0   0
TAMB   300.  101300.      0.
EAMB   300.  101300.      0.
HI/F     0.00   0.00   0.00   0.00   3.35   3.35
WIDTH    2.44   1.83   1.80   0.76   1.20   4.90
DEPTH    3.65   2.40   4.90   3.6    3.30   5.20
HEIGH    2.40   2.90   2.90   5.60   2.40   2.40
HVENT   1  2  1   0.76   2.15   0.15
HVENT   1  7  1   0.77   1.50   0.25   0.00
HVENT   2  3  1   1.50   2.60   0.00
HVENT   3  4  1   1.00   2.90   0.00
HVENT   4  5  1   0.76   5.25   3.35
HVENT   5  6  1   0.76   1.97   0.00
HVENT   6  7  1   1.00   1.31   1.16   0.00
CEILI GYPSUM    GYPSUM    GYSSUM    GYPSUM    GYPSUM    GYPSUM
WALLS GYPSUM    GYPSUM    GYPSUM    GYPSUM    GYPSUM    GYPSUM
CHEMI     0.     0.   6.0    20000000.  300.
LFBO    1
LFBT    2
LFPOS   1
LFMAX   7
FTIME     60.     74.    76.    170.     60.     70.     90.
FMASS  0.015  0.015  0.3000 0.3000 0.2000 0.2000 0.1600 0.1700
FHIGH    0.10   0.10   0.10   0.10   0.10   0.10   0.10   0.10
FAREA    0.50   0.50   0.50   0.50   0.50   0.50   0.50   0.50
HCR   0.150 0.150 0.150 0.150 0.150 0.150 0.150 0.150
CO    0.010 0.030 0.500 0.500 0.500 0.500 0.500 0.500
OD    0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
CVENT 1 7 1 0.0 0.0 1. 1. 1. 1. 1. 1.
DUMPR SHARON5.DMP
```

FIG III-3
Data File Used to Run FAST Program

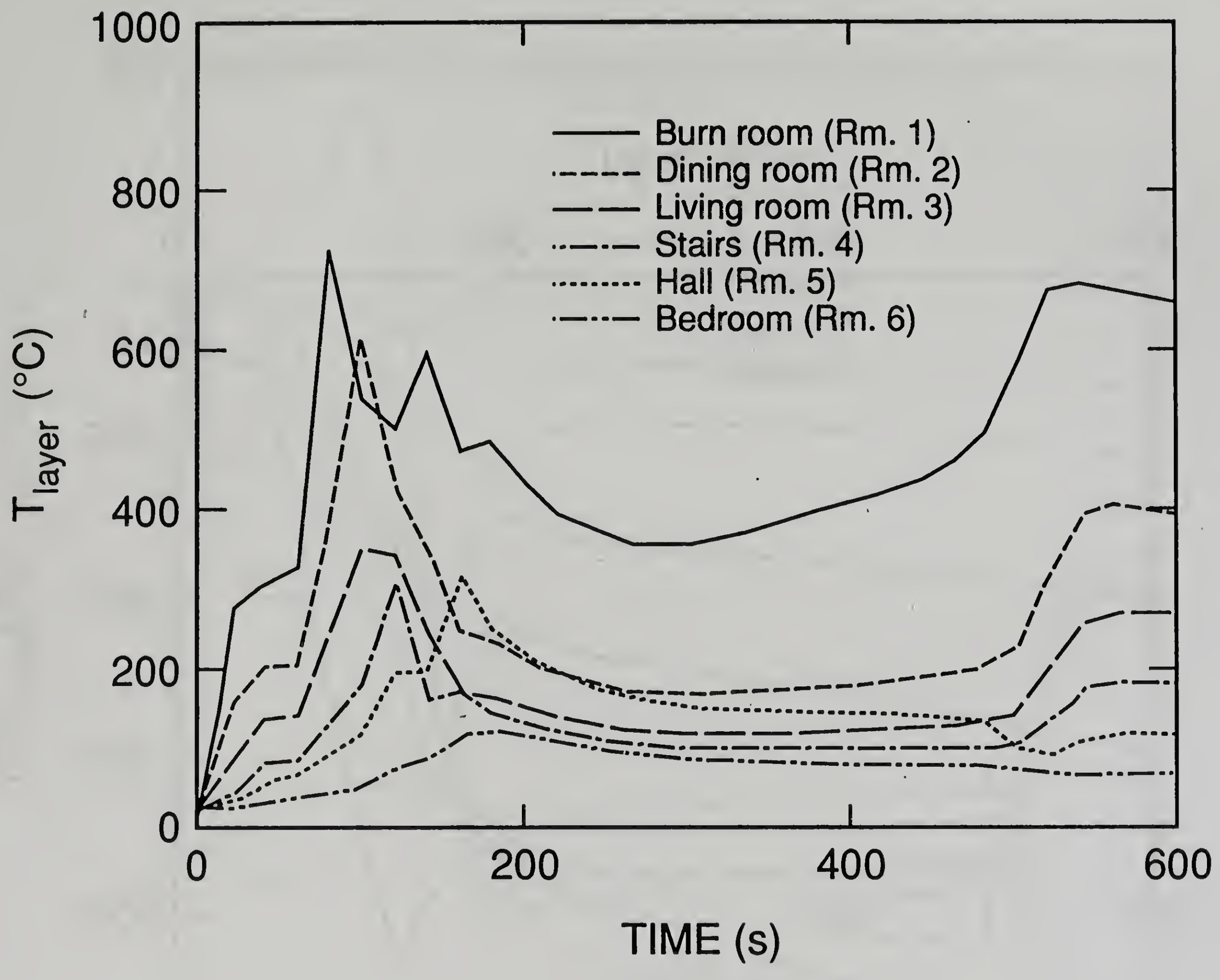


FIG III-4
Calculated Ceiling Layer Temperatures Using FAST with 6% "Oxygen Index"

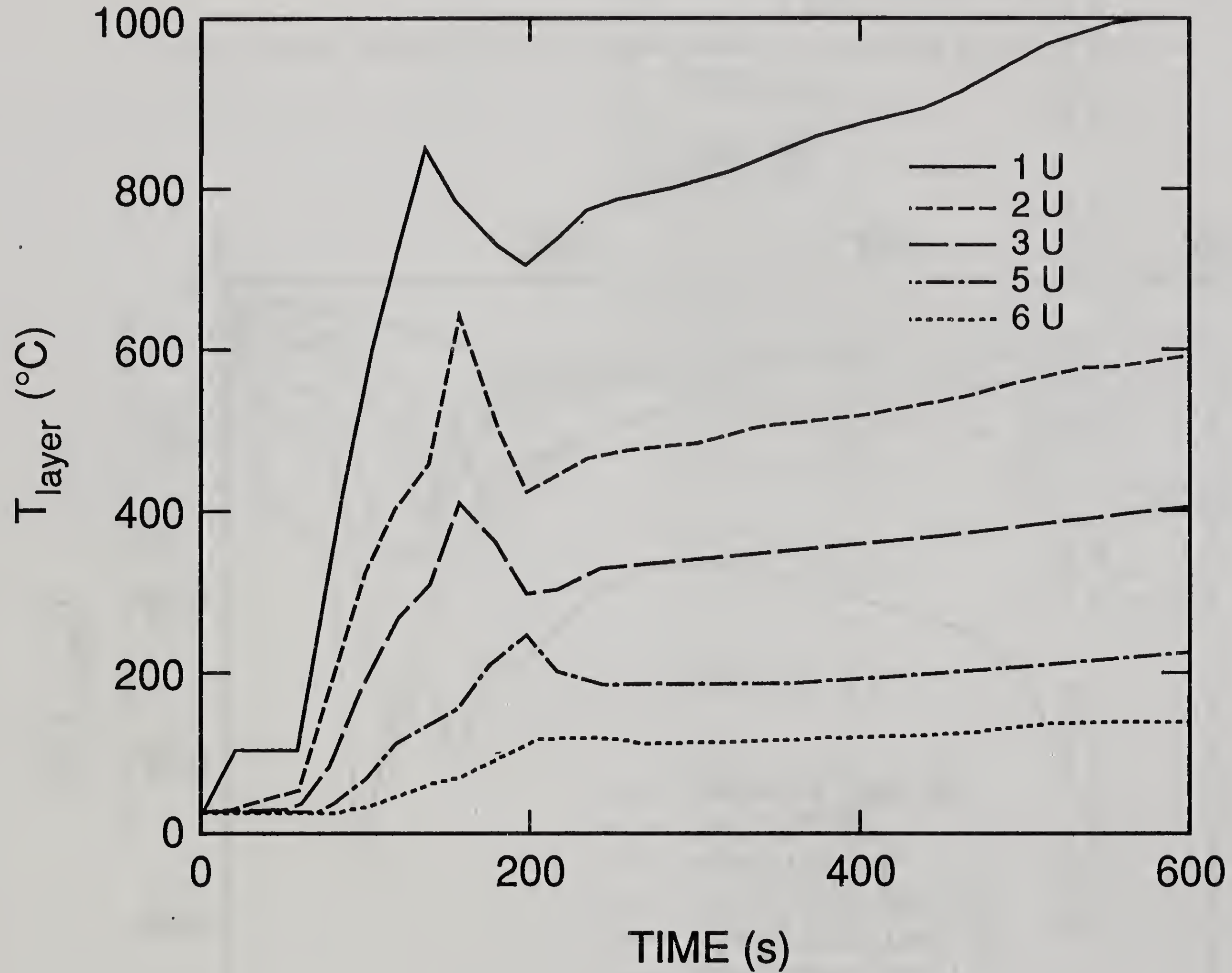


FIG III-5
Calculated Ceiling Layer Temperatures Using FAST with 2% Oxygen Index

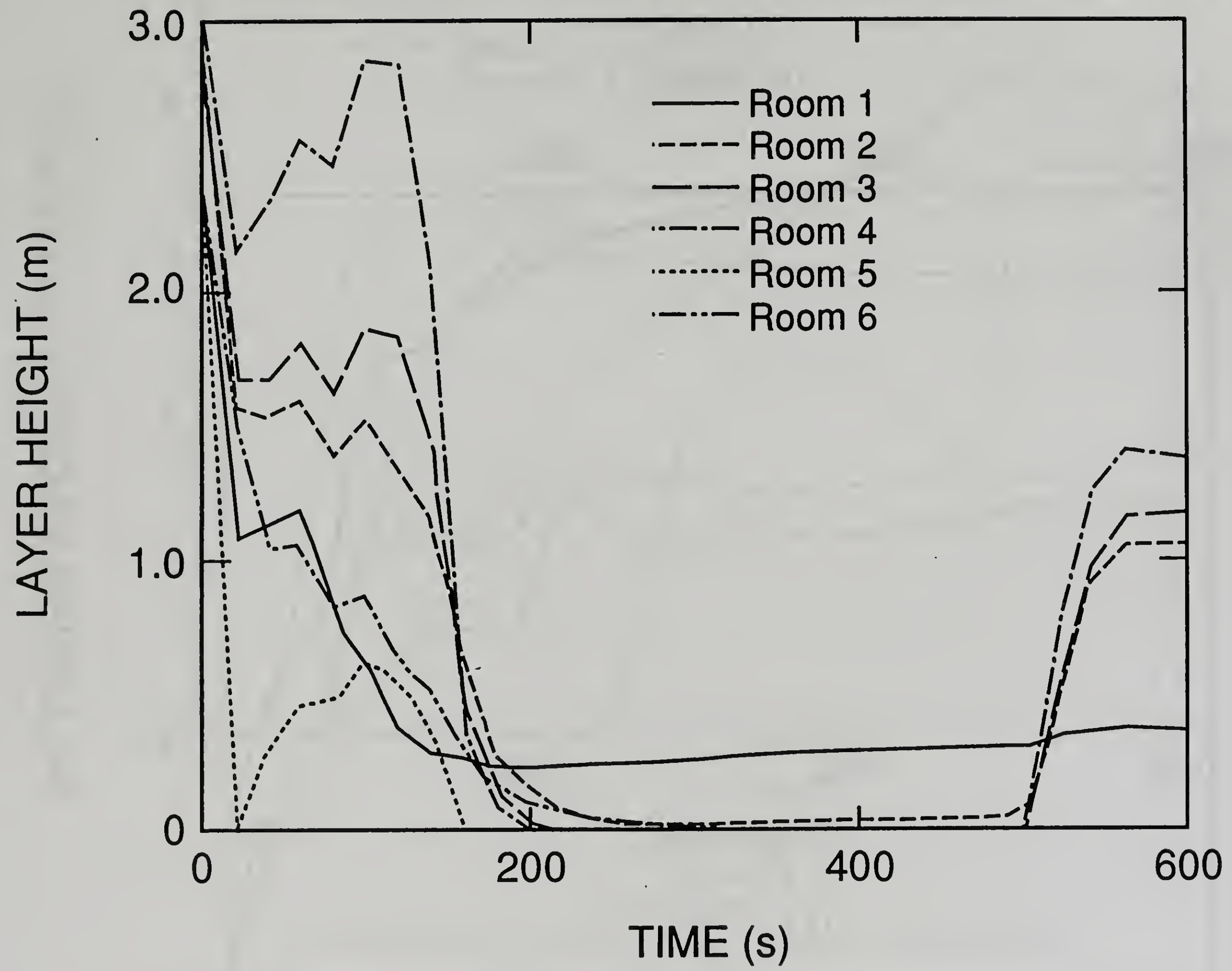


FIG III-6
Calculated Layer Heights Using FAST with Oxygen Index = 6%

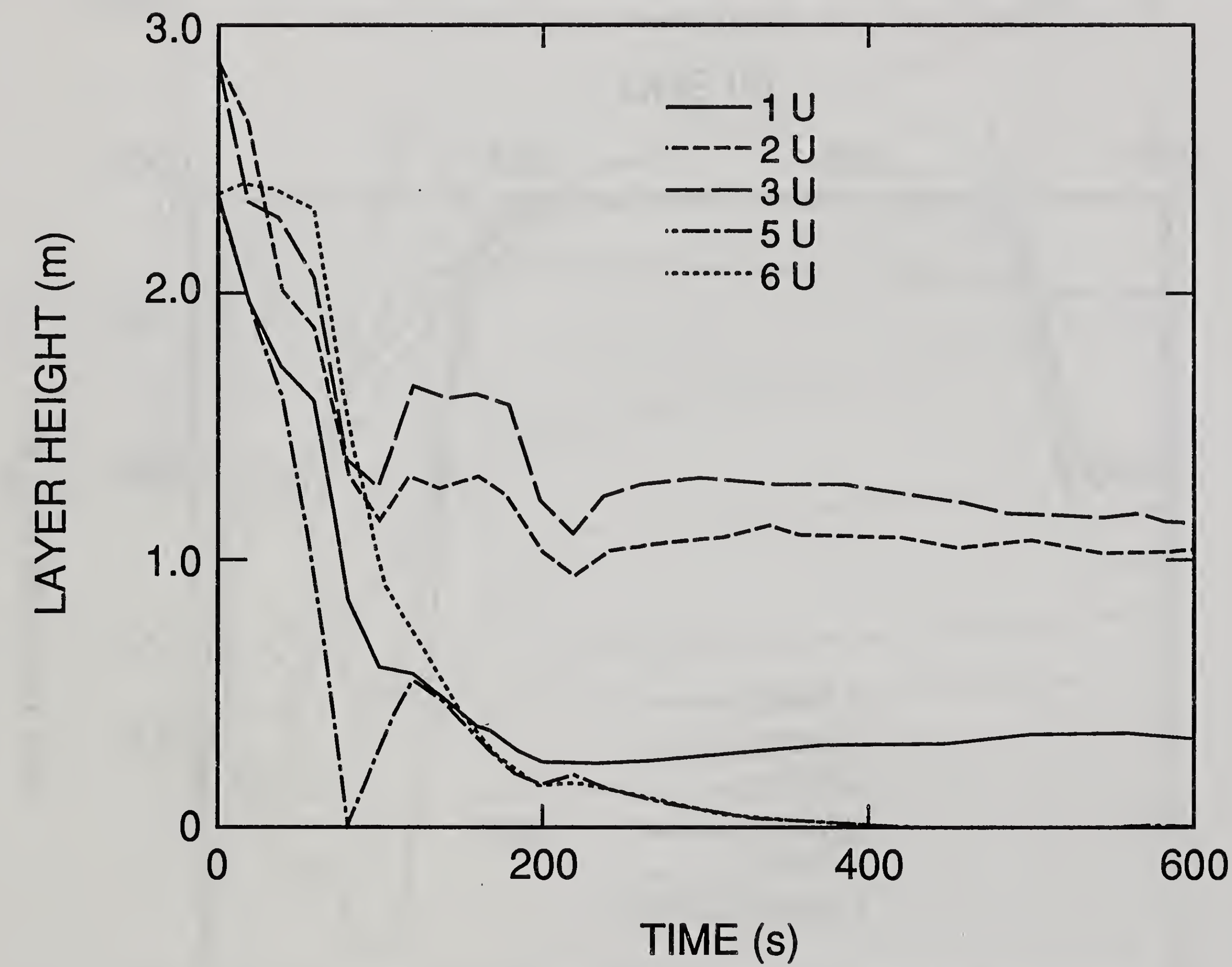


FIG III-7
Calculated Layer Heights Using FAST with Oxygen Index of 2%

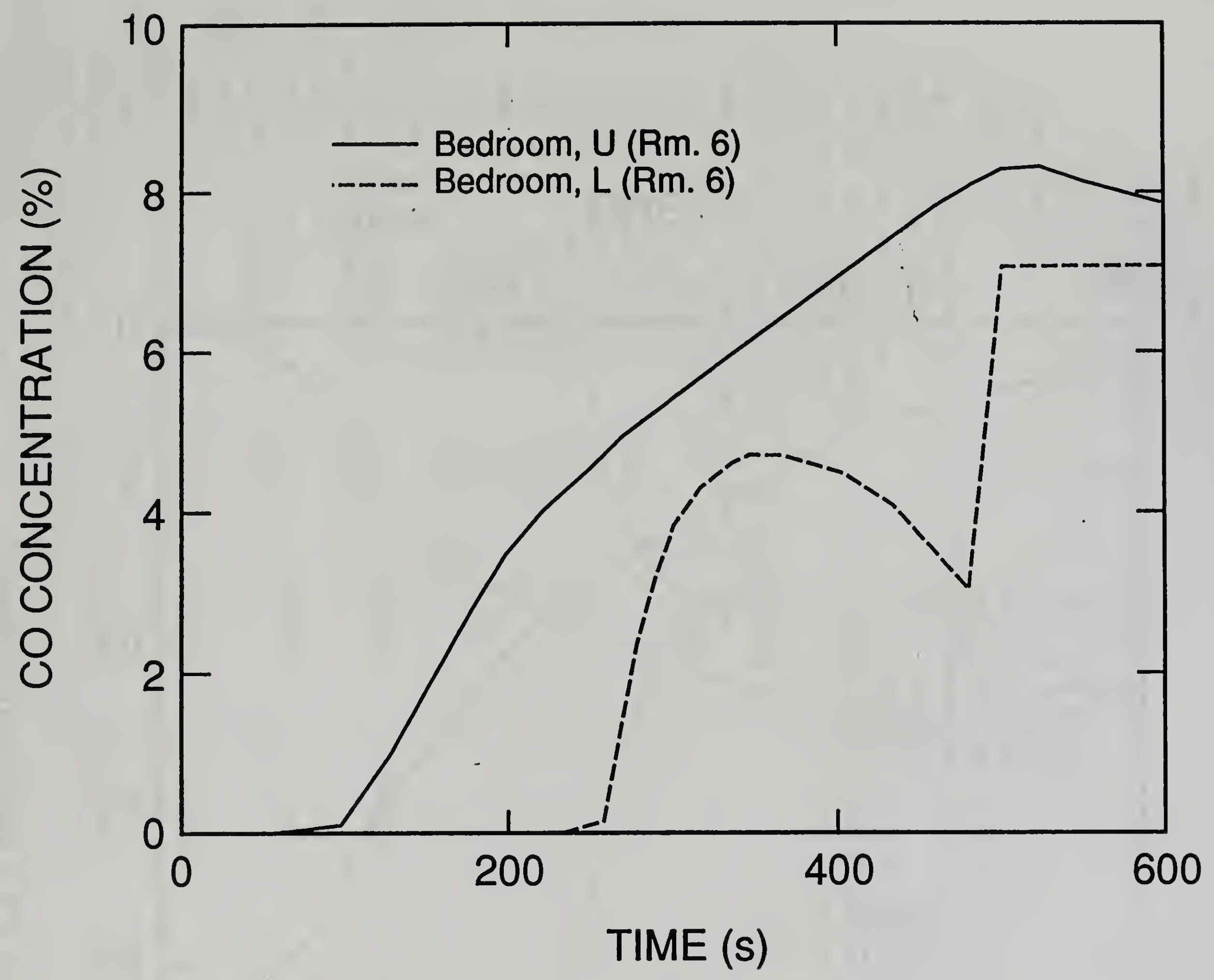


FIG III-8
Calculated CO Concentrations in Room 6 Using FAST

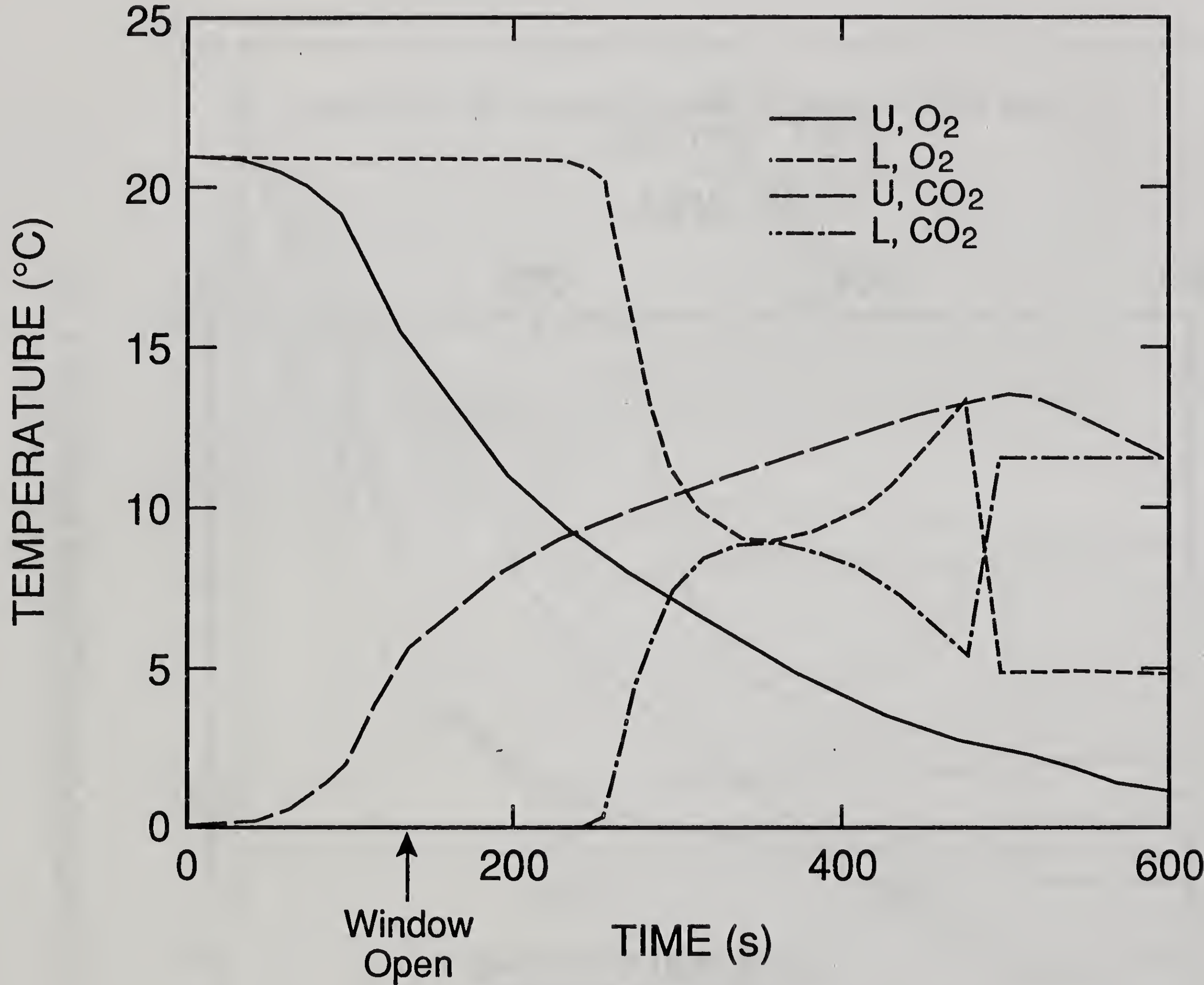


FIG III-9
Calculated Gas Concentrations in Room 6 Using FAST

```
  HARVARD 63 MODEL OF BLDG 205 SIMULATION OF SHARON PA FIRE
  THIS IS RUN 7, NOMINAL CASE, BURNER DIAM 1.0 M, A\F=2
  THIS DIFFERS FROM RUN 1 IN THAT THE SOOT.CONCENTRATION HAS BEEN REDUCED FROM
0.2
  THE HEAT TRANSFER COEFFS HAVE BEEN REDUCED X10,AND THE CEILING GAS CONCN
REDUCED
  ROOM 6 HAS BEEN INCREASED TO 5.9 M HIGH TO LET VENT 8 ACT AS A STACK
  ROOM NUMBER 1:
      DIMENSIONS(X,Y,Z)  =     (       2.4000      3.6000      2.4000)
      AMBIENT TEMPERATURE=    300.0
    OBJECT NUMBER 1 (ID= 1) :
      COORDINATES(X,Y,Z) =     (       1.2000      1.8000      0.1000)
      ANGLE WITH HORIZONTAL=     0.00   ANGLE WITH XZ-PLANE=              0.00
      THICKNESS=                 0.1000 DENSITY=                         48.00
      INITIAL MASS=            200.0000 INITIAL RADIUS=                  1.0000
      MAXIMUM RADIUS=            1.0000 OBJECT RADIUS=                   1.0000
      SPECIFICHHEAT=          1900.     THERMAL CONDUCTIVITY=            0.0540
      EMISSIVITY=                0.98   CHI(FRACTION OF HEAT RELEASED)= 0.80
      HEAT OF COMBUSTION=   2.000E+07   HEAT OF VAPORIZATION=       2.054E+06
      PYROLIZATION TEMP=       600.0    IGNITION TEMP=                727.0
      AIR/FUEL MASS RATIO=       2.00   STOICHIOMETRIC MASS RATIO=       2.00
      FCO2(CO2 MASS/FUEL MASS)= 0.400   FCO(CO MASS/FUEL MASS)=          0.310
      FS(SMOKE MASS/FUEL MASS)= 0.020   FH2O(H2O MASS/FUEL MASS)=        0.240
      A(FIRE SPREAD PARAMETER)=0.0109
      NUMBER OF SEGMENTS FOR GAS BURNER CURVE =   7
        Gas Burner Flow Curve Segments are
        Time   Flow (KG/SEC) QDOT Nominal (KW)
          0.0  0.1296E-03        3.
         60.0  0.1500E-01      300.
        134.0  0.3000E+00     6000.
        210.0  0.3000E+00     6000.
        380.0  0.2000E+00     4000.
        440.0  0.2000E+00     4000.
        530.0  0.1600E+00     3200.
        600.0  0.1700E+00     3400.
  ROOM NUMBER 2:
      DIMENSIONS(X,Y,Z)  =     (       2.9000      1.8000      2.9000)
      AMBIENT TEMPERATURE=    300.0
  ROOM NUMBER 3:
      DIMENSIONS(X,Y,Z)  =     (       4.9000      1.8000      2.9000)
      AMBIENT TEMPERATURE=    300.0
  ROOM NUMBER 4:
      DIMENSIONS(X,Y,Z)  =     (       3.6000      0.8000      2.9000)
      AMBIENT TEMPERATURE=    300.0
  ROOM NUMBER 5:
      DIMENSIONS(X,Y,Z)  =     (       3.3000      1.2000      2.4000)
      AMBIENT TEMPERATURE=    300.0
  ROOM NUMBER 6:
      DIMENSIONS(X,Y,Z)  =     (       2.4000      4.7000      5.9000)
      AMBIENT TEMPERATURE=    300.0
  ROOM NUMBER 7:
      DIMENSIONS(X,Y,Z)  =     (       2.4000      5.7000      2.4000)
      AMBIENT TEMPERATURE=    300.0
```

FIG III-10
Input File for HARVARD 6

```
 VENT NUMBER 1:
     (WIDTH, HEIGHT, DEPTH) = (      0.7700       1.5000       0.6500)
     (CDI,CDO) = (      0.6913      0.6800)
 VENT NUMBER 2:
     (WIDTH, HEIGHT, DEPTH) = (      0.7620       2.1500       0.2500)
     (CDI,CDO) = (      0.6853      0.6997)
 VENT NUMBER 3:
     (WIDTH, HEIGHT, DEPTH) = (      1.5000       2.6000       0.3000)
     (CDI,CDO) = (      0.7104      0.6903)
 VENT NUMBER 4:
    ((WIDTH, HEIGHT, DEPTH) = (      1.0000       2.9000       0.0000)
     (CDI,CDO) = (      0.6850      0.6886)
 VENT NUMBER 5:
     (WIDTH, HEIGHT, DEPTH) = (      0.7620       2.0000       0.4000)
     (CDI,CDO) = (      0.6853      0.6861)
 VENT NUMBER 6:
     (WIDTH, HEIGHT, DEPTH) = (      0.7620       2.0320       0.4064)
     (CDI,CDO) = (      0.7291      0.6834)
 VENT NUMBER 7:
     (WIDTH, HEIGHT, DEPTH) = (      0.7620       2.0320       0.4064)
     (CDI,CDO) = (      0.6800      0.6800)
 VENT NUMBER 8:
     (WIDTH, HEIGHT, DEPTH) = (      1.0000       0.1500       1.0600)
     (CDI,CDO) = (      0.6853      0.6800)
 WALL NUMBER 1:
     THICKNESS=             0.0127     DENSITY=                          1700.00
     SPECIFIC HEAT=           800.     THERMAL CONDUCTIVITY=               0.8000
 WALL NUMBER 2:
     THICKNESS=             0.0127     DENSITY=                          1700.00
     SPECIFIC HEAT=           800.     THERMAL CONDUCTIVITY=               0.8000
 WALL NUMBER 3:
     THICKNESS=             0.0127     DENSITY=                          1700.00
     SPECIFIC HEAT=           800.     THERMAL CONDUCTIVITY=               0.8000
 WALL NUMBER 4:
     THICKNESS=             0.0127     DENSITY=                          1700.00
     SPECIFIC HEAT=           800.     THERMAL CONDUCTIVITY=               0.8000
 WALL NUMBER 5:
     THICKNESS=             0.0127     DENSITY=                          1700.00
     SPECIFIC HEAT=           800.     THERMAL CONDUCTIVITY=               0.8000
 WALL NUMBER 6:
     THICKNESS=             0.0127     DENSITY=                          1700.00
     SPECIFIC HEAT=           800.     THERMAL CONDUCTIVITY=               0.8000
 WALL NUMBER 7:
     THICKNESS=             0.0127     DENSITY=                          1700.00
     SPECIFIC HEAT=           800.     THERMAL CONDUCTIVITY=               0.8000
 PHYSICAL CONSTANTS:
     SPECIFIC HEAT OF AIR=  1004.      ABSORPTION COEFF OF FLAME=        1.55
   FOR AIR:
     HEAT TRANSFER COEFF=        0.50  PLUME ENTRAINMENT COEFF=          0.10
   FOR LAYER GASES:
     MAX. HEAT TRANSFER COEFF=  5.00   MIN. HEAT TRANSFER COEFF=         0.50
VERSUN(1)= 2  VERSUN(2)= 2
VENT  1: SIDE 1 IN ROOM  1 SIDE 2 IN ROOM  0
VENT  2: SIDE 1 IN ROOM  1 SIDE 2 IN ROOM  2
```

FIG III-10
Continued

```
VENT  3: SIDE 1 IN ROOM  2 SIDE 2 IN ROOM  3
VENT  4: SIDE 1 IN ROOM  3 SIDE 2 IN ROOM  4
VENT  5: SIDE 1 IN ROOM  4 SIDE 2 IN ROOM  5
VENT  6: SIDE 1 IN ROOM  5 SIDE 2 IN ROOM  6
VENT  7: SIDE 1 IN ROOM  5 SIDE 2 IN ROOM  7
VENT  8: SIDE 1 IN ROOM  6 SIDE 2 IN ROOM  0
Simulation length [sec.] = 600.00
  CRT output every 20.00 sec
  Disk output every 10.00 sec
Tolerance: .0010000     Minimum time step .0001000 sec
HMIN= 1.000E-04   HMAX= 5.000E+00   EPS= 1.000E-03   MAXODR=  4
     99 VARIABLES IN THE SYSTEM, MAX DIMENSIONED: 260
     38 LARGEST 2ND DIMENSION OF JACB, MAX ALLOWED: 130
ATTEMPTING TO GET INITIAL VALUES FOR THE RUN.
```

FIG III-10
Concluded

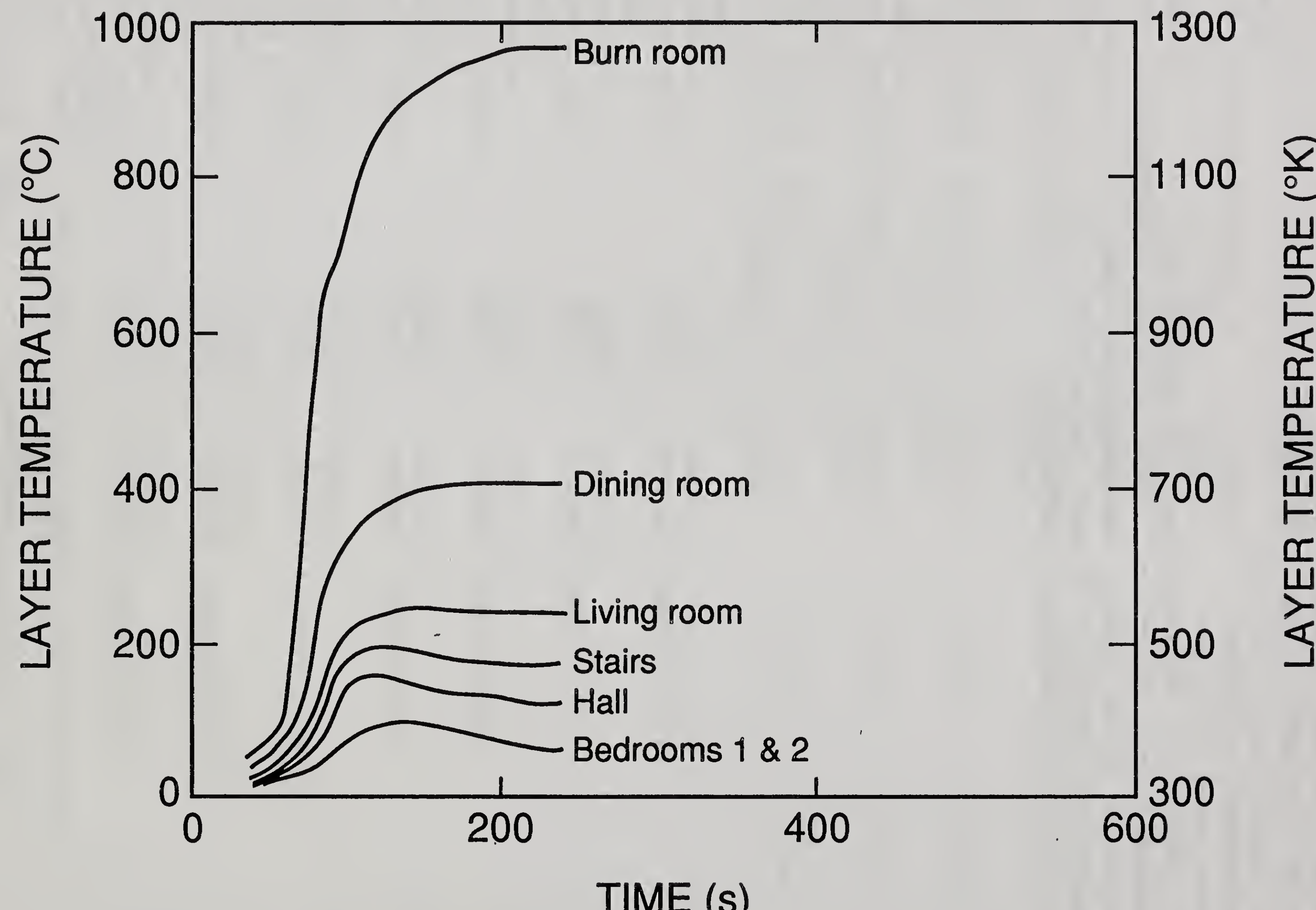


FIG III-11
Calculated Ceiling Layer Temperatures Using HARVARD 6

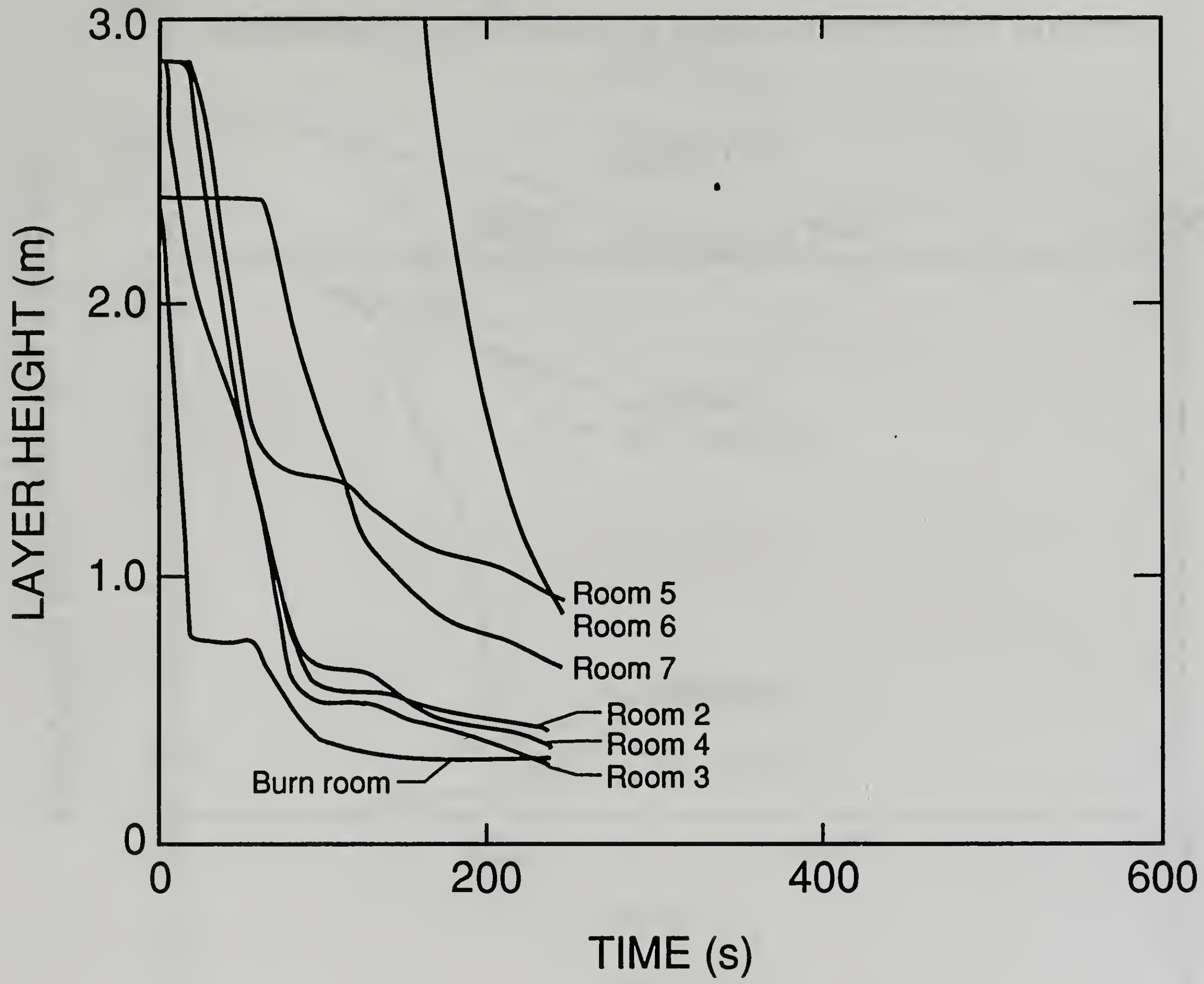


FIG III-12
Calculated Ceiling Layer Heights Using HARVARD 6

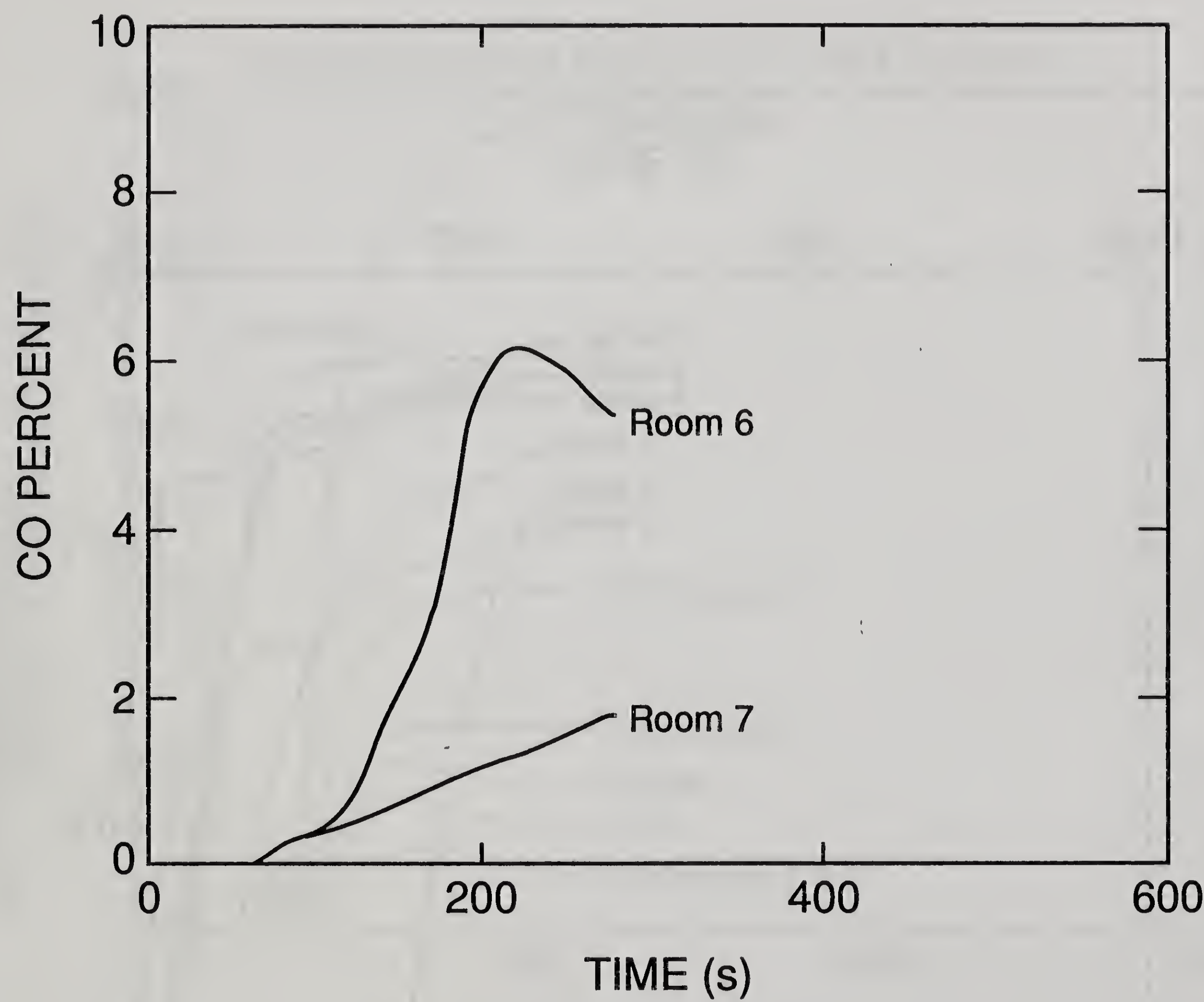


FIG III-13
Calculated Ceiling Layer CO Concentrations Using HARVARD 6

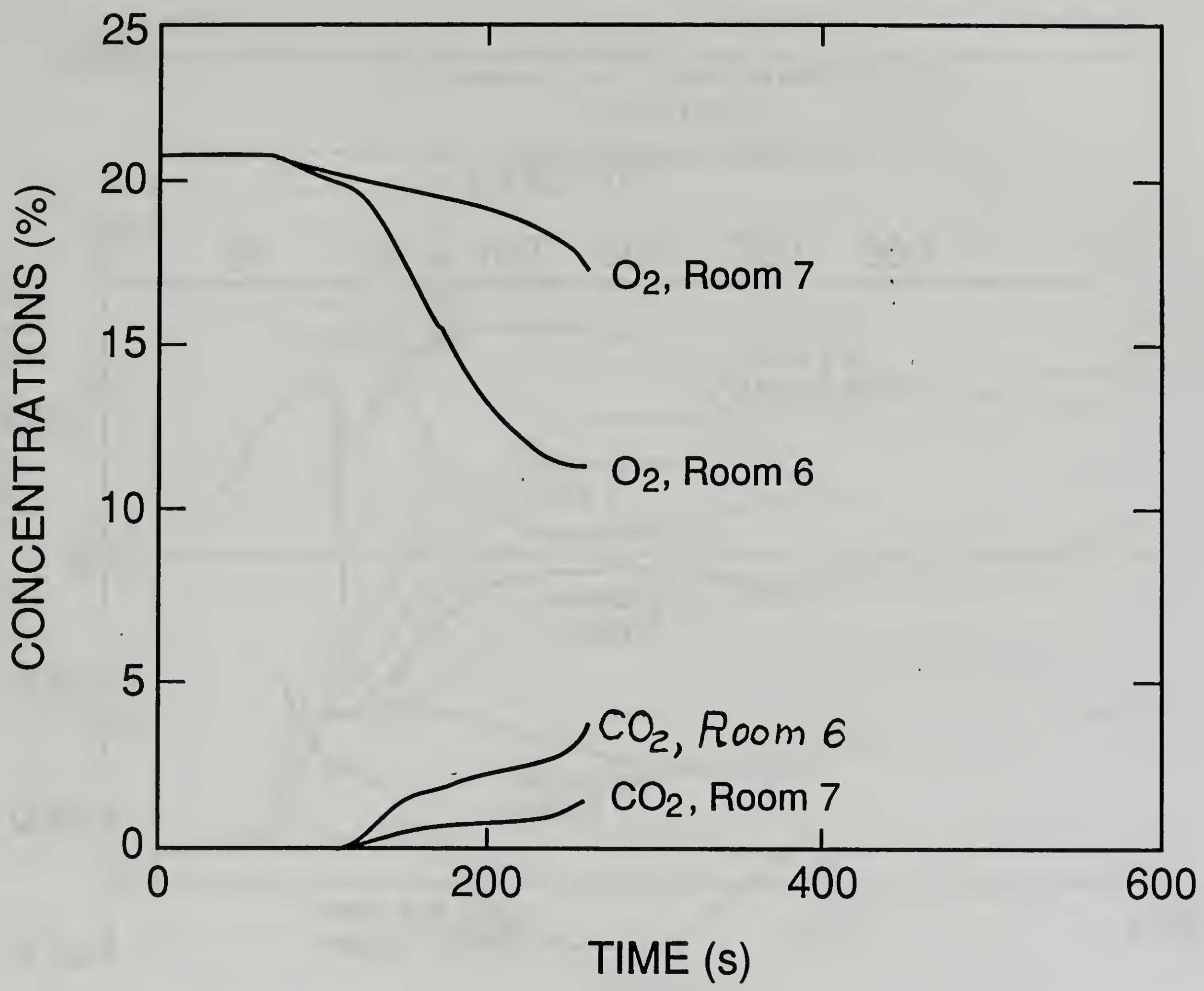


FIG III-14
Calculated Ceiling Layer Gas Concentrations Using HARVARD 6

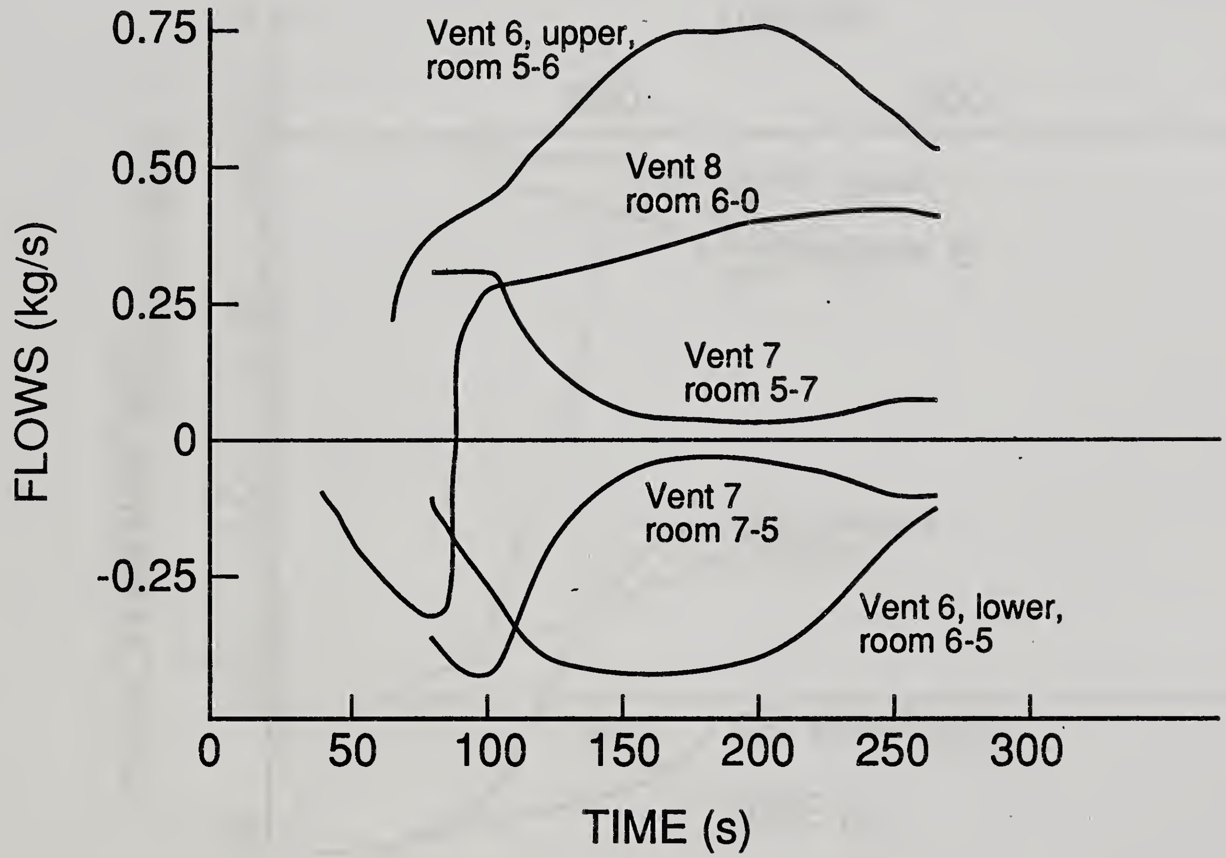


FIG III-15
Calculated Vent Flows Using HARVARD 6

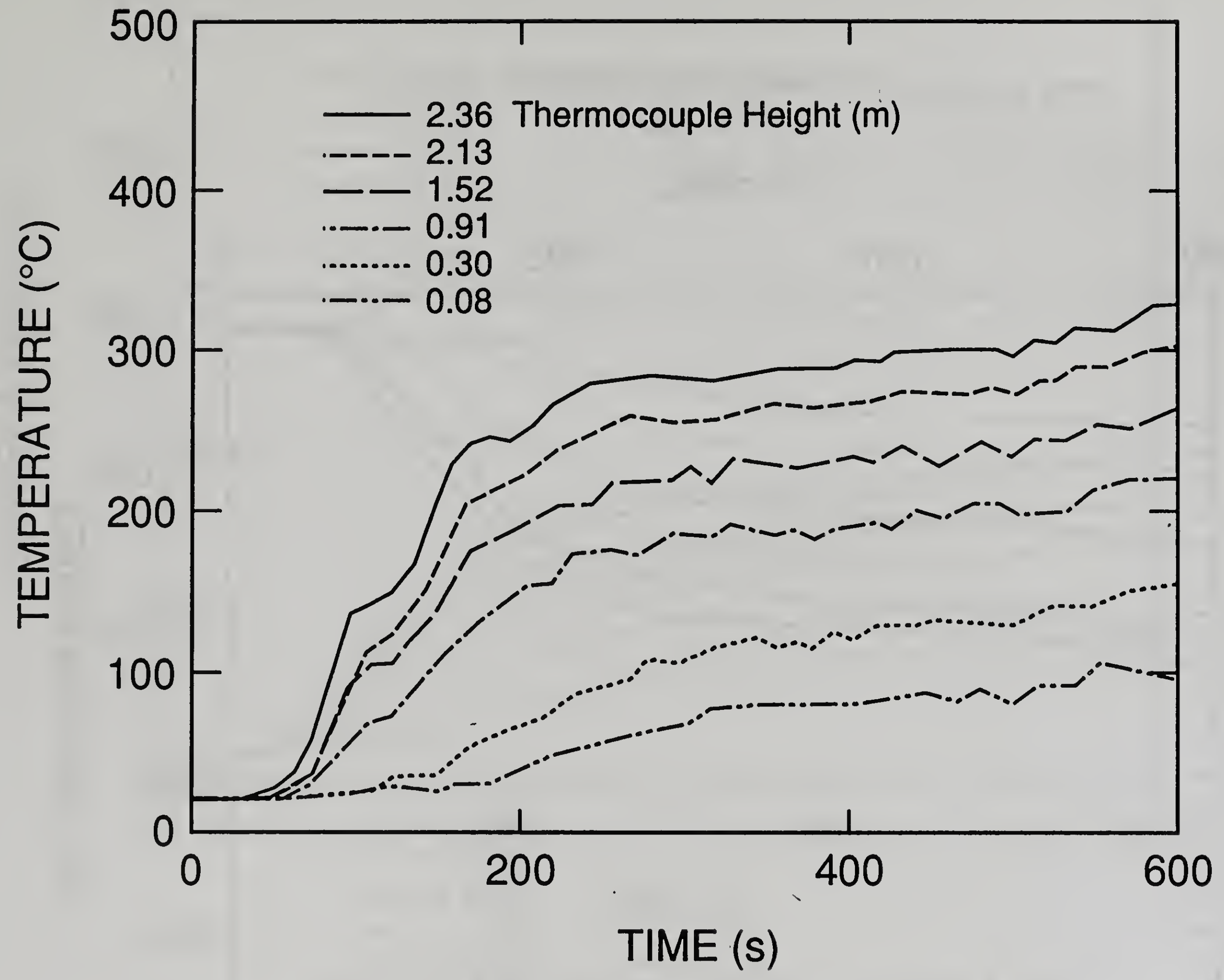


FIG III-16
Measured Temperatures in Room 5 - SHARON 2 Test

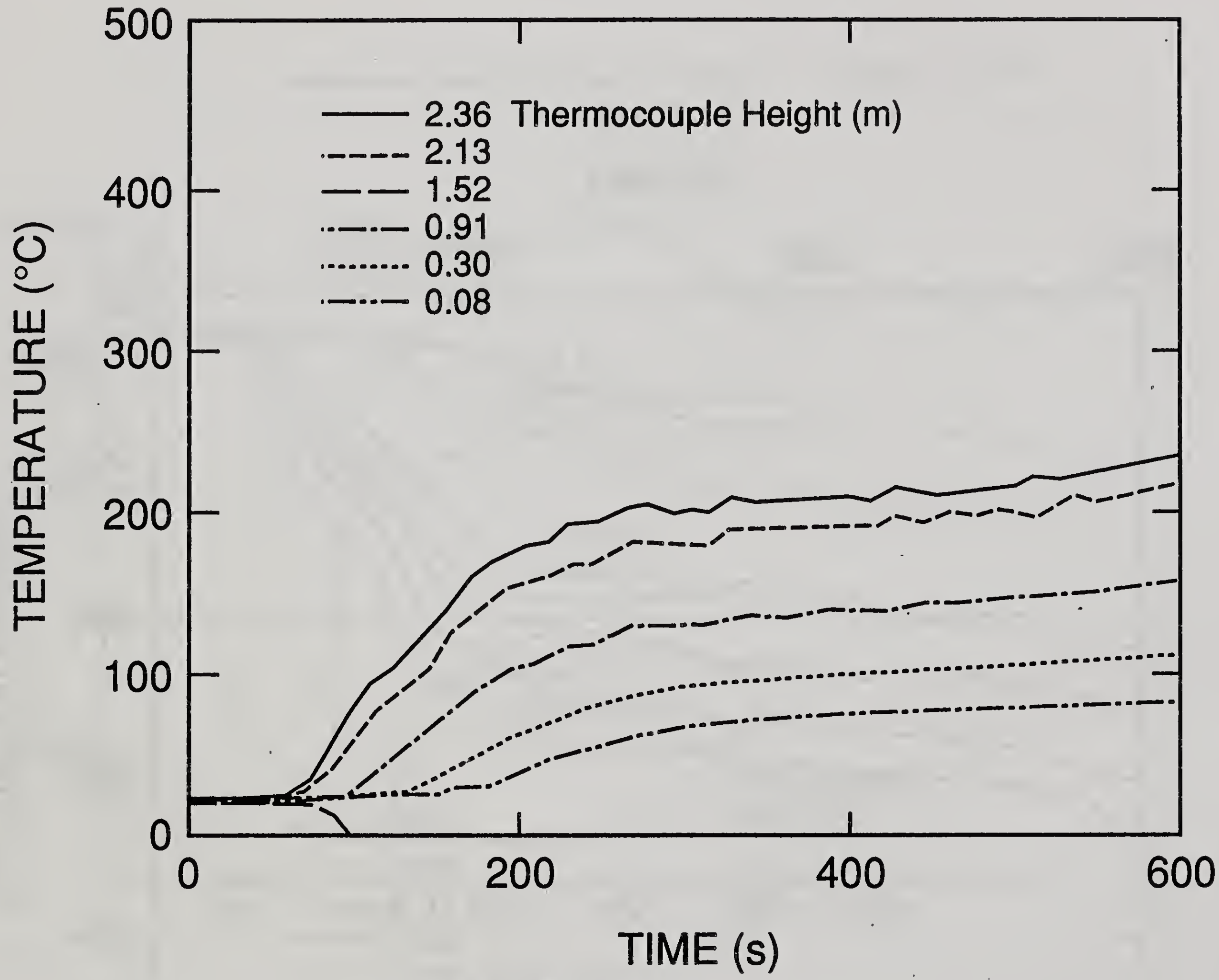


FIG III-17
Measured Temperatures in Room 6 - SHARON 2 Test

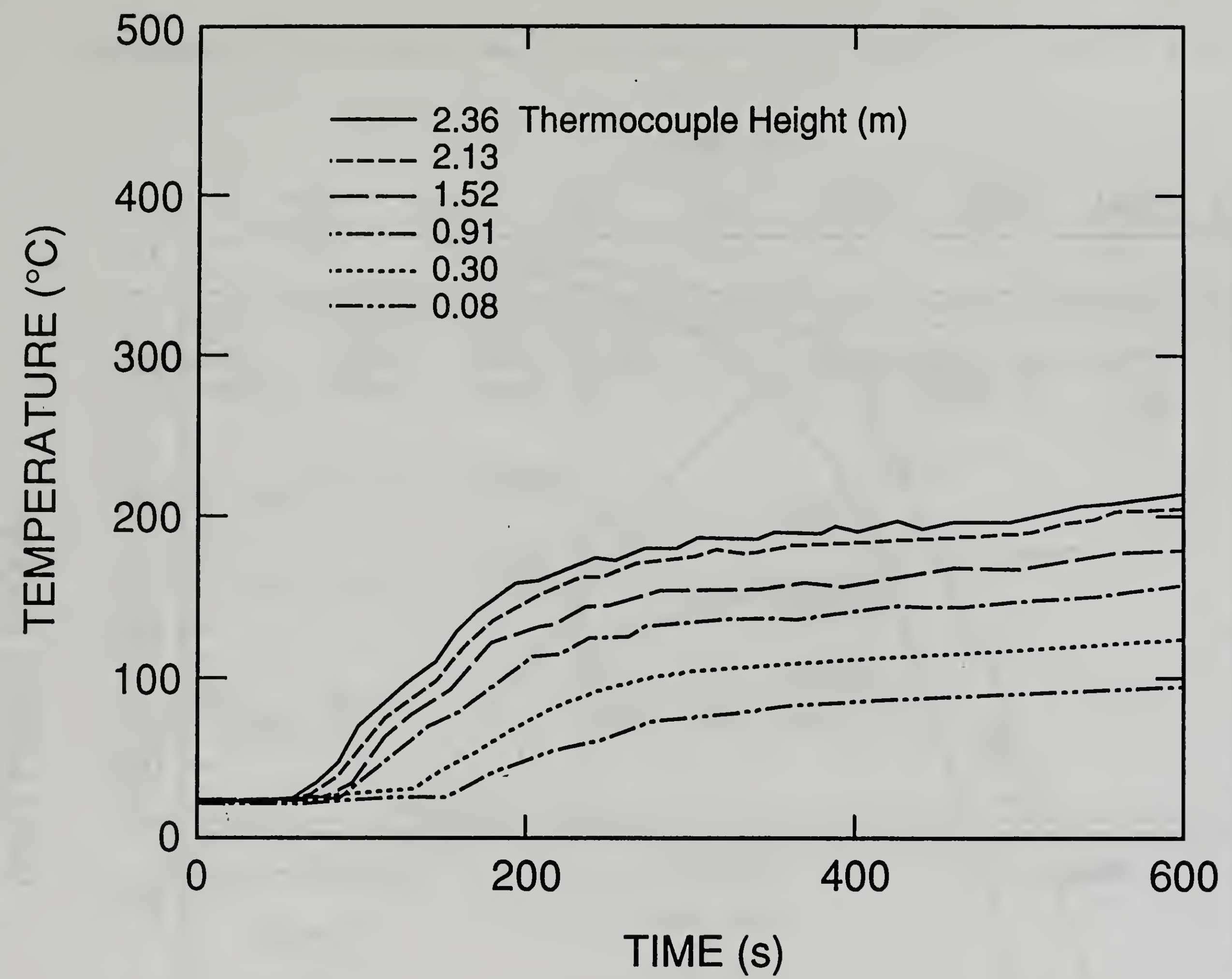


FIG III-18
Measured Temperatures in Room 7 - SHARON 2 Test

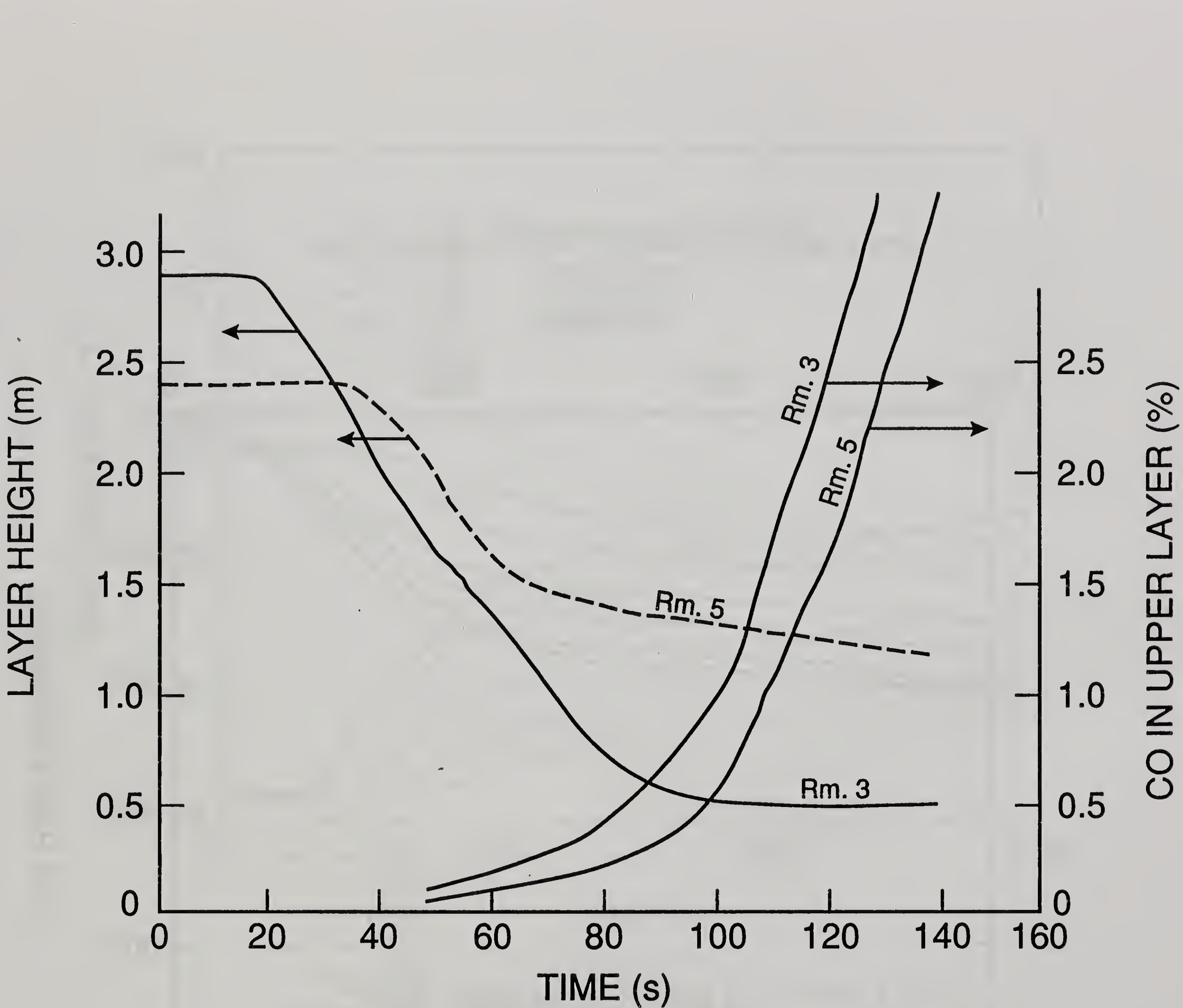


FIG III-19
Calculated Layer Heights and CO Concentrations in Room 3 and Room 5 Using HARVARD 6

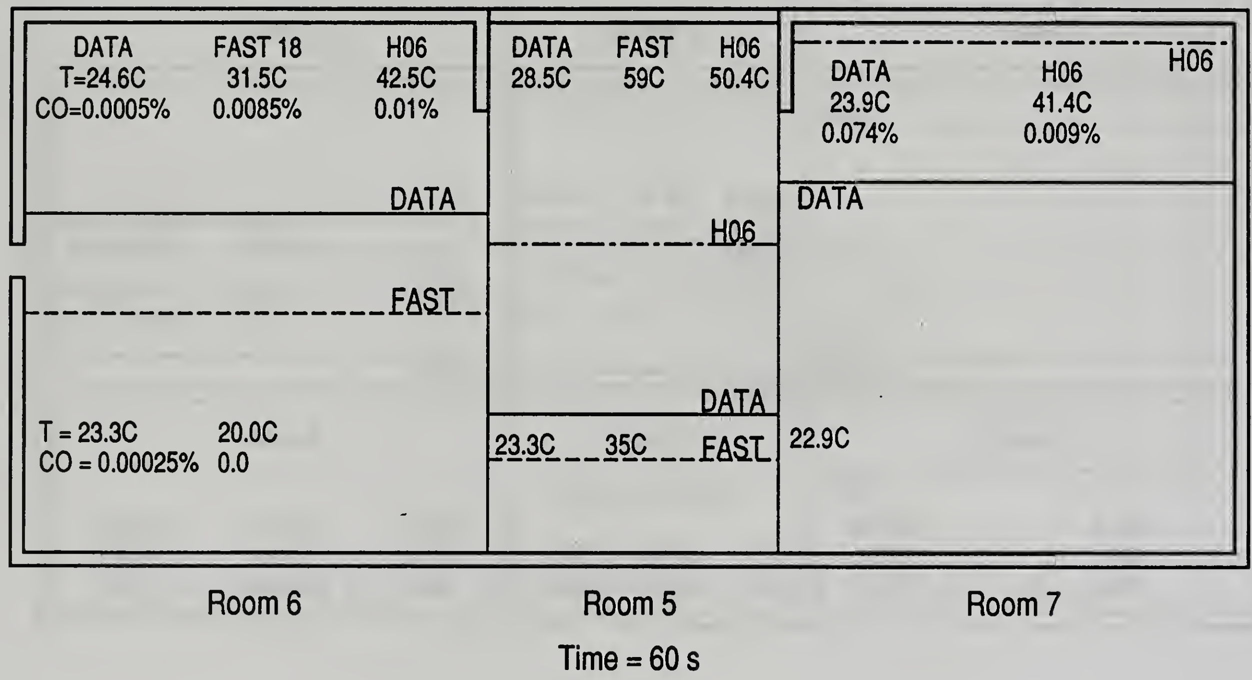


FIG IV-1
Comparisons of Data and Calculations Using FAST and HARVARD 6

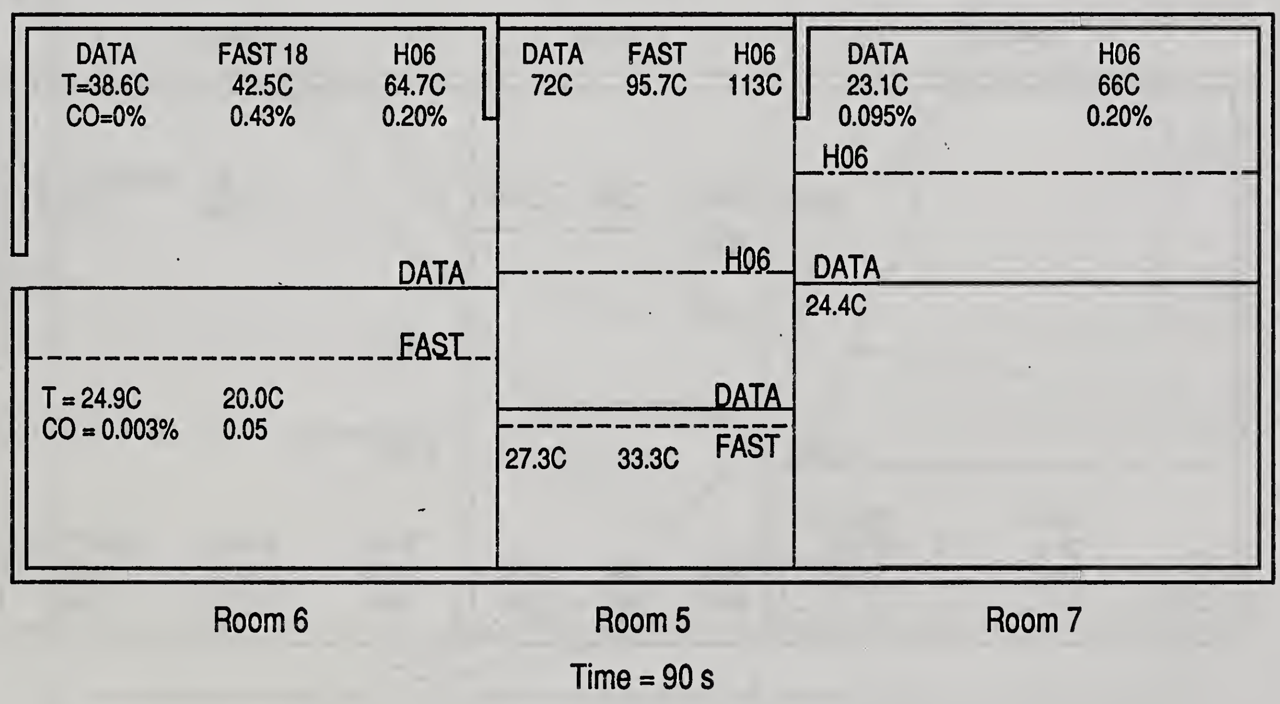


FIG IV-2
Comparisons of Data and Calculations Using FAST and HARVARD 6

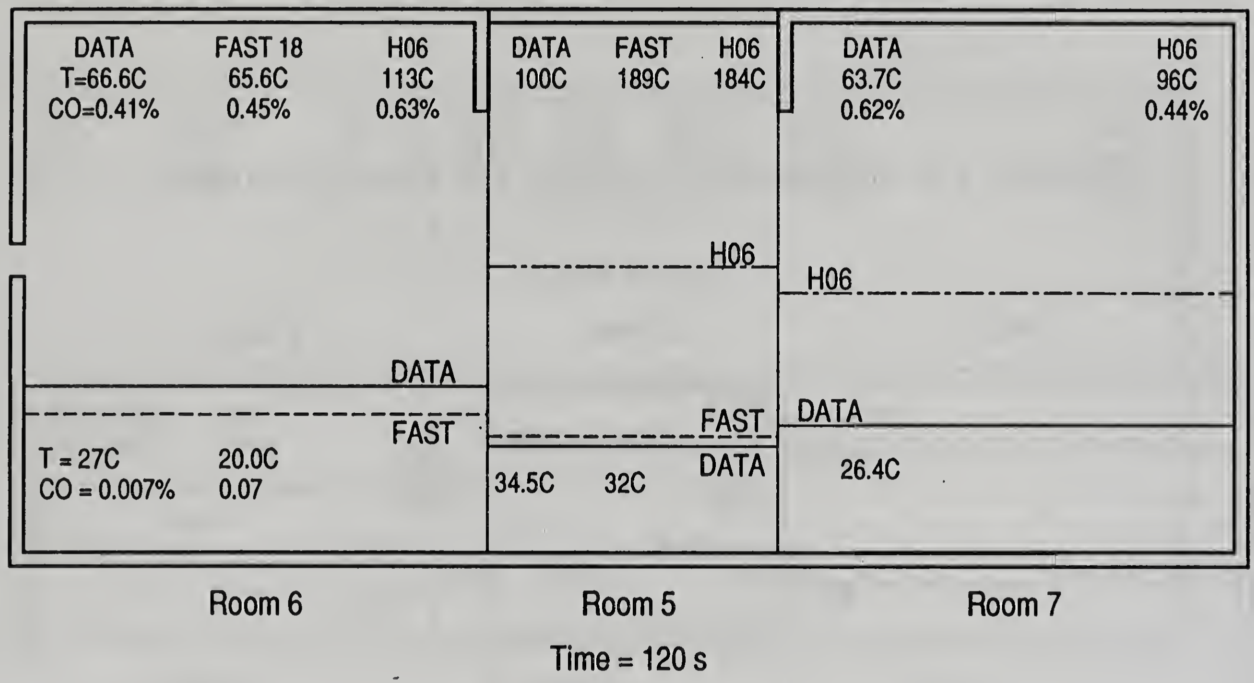


FIG IV-3
Comparisons of Data and Calculations Using FAST and HARVARD 6

4-3

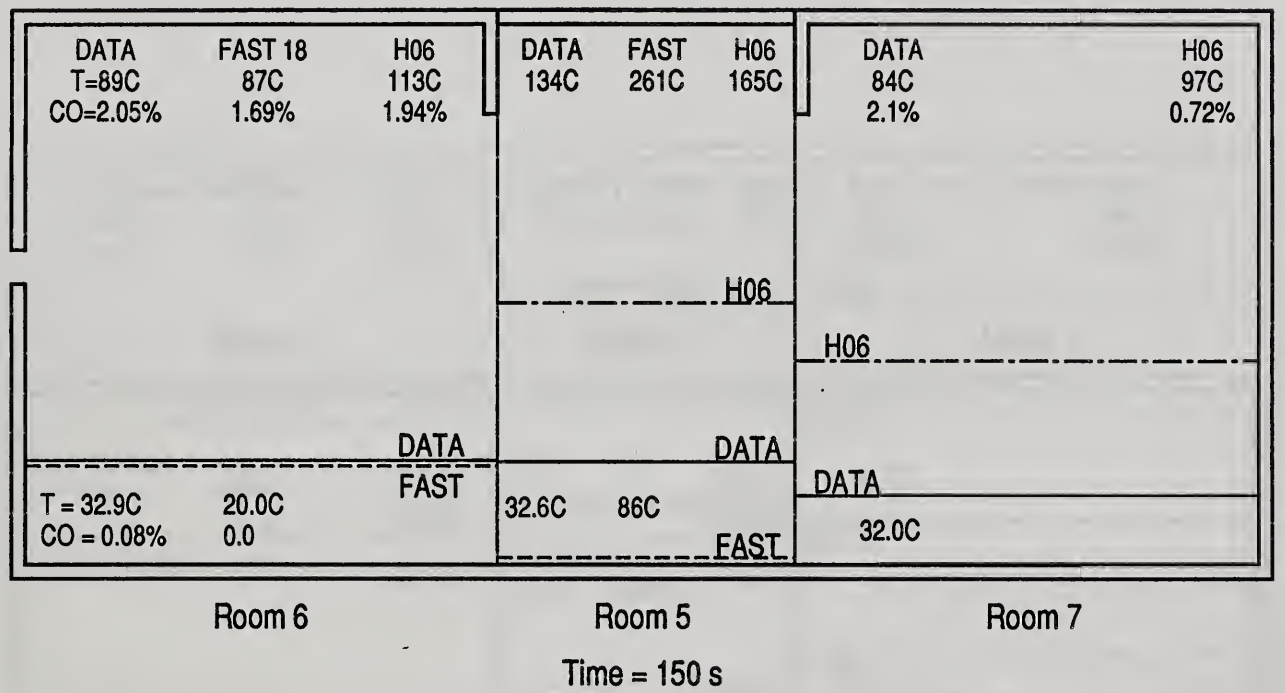


FIG IV-4
Comparisons of Data and Calculations Using FAST and HARVARD 6

4-4

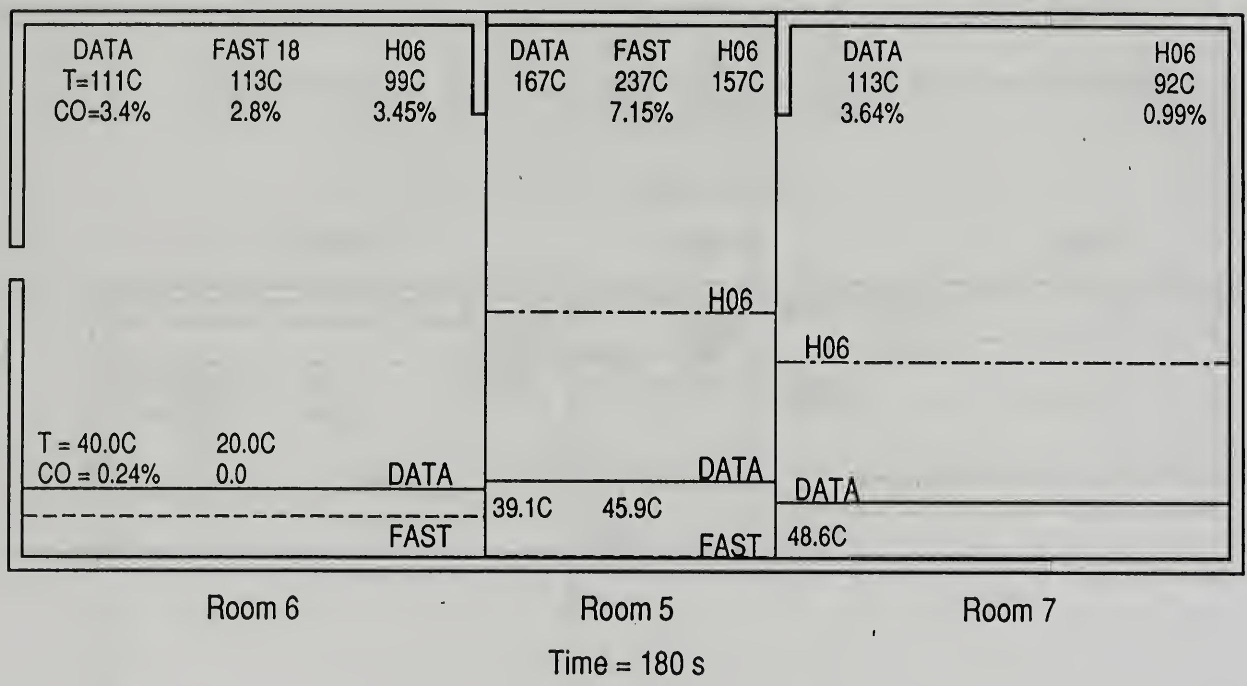


FIG IV-5
Comparisons of Data and Calculations Using FAST and HARVARD 6

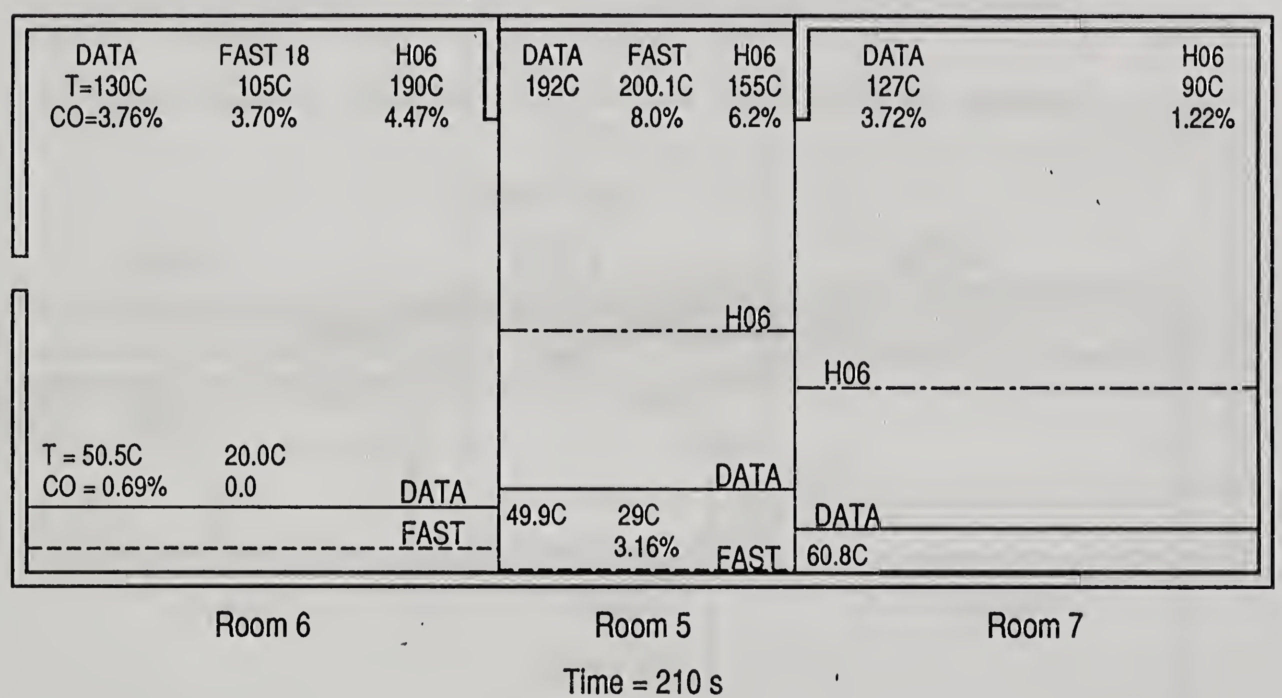


FIG IV-6
Comparisons of Data and Calculations Using FAST and HARVARD 6

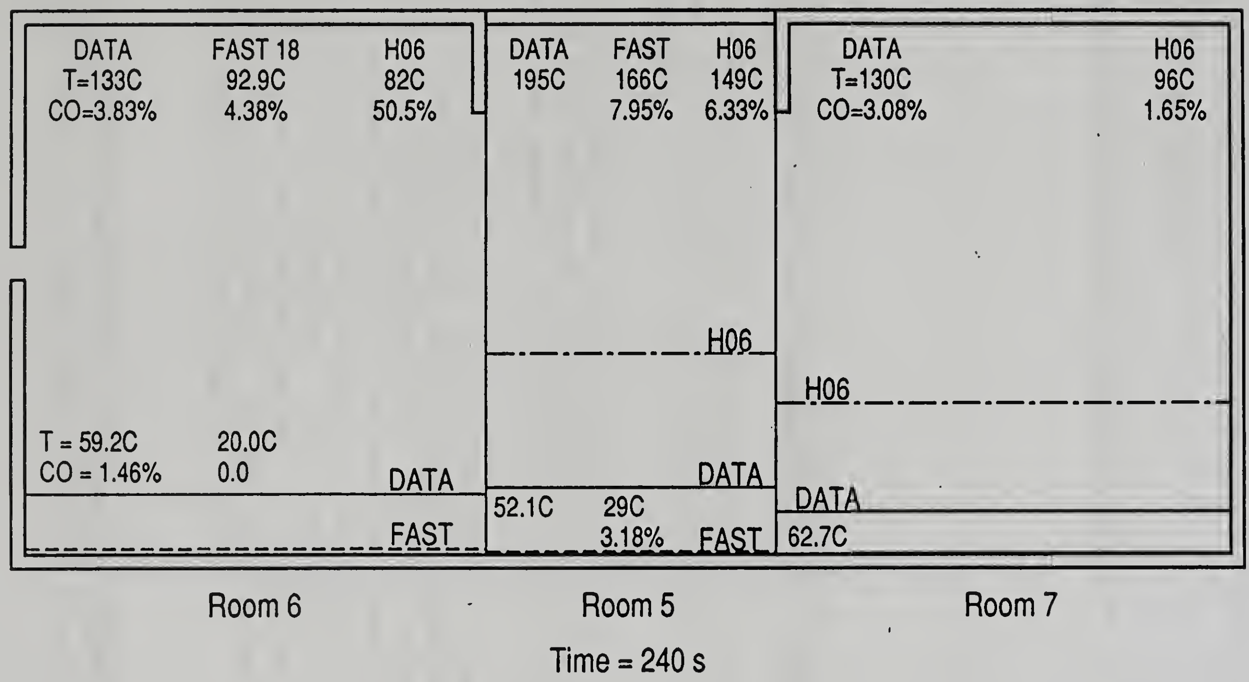


FIG IV-7
Comparisons of Data and Calculations Using FAST and HARVARD 6

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☐ DOCUMENT DESCRIBES A COMPUTER PROGRAM; SF-185, FIPS SOFTWARE SUMMARY, IS ATTACHED.

11. ABSTRACT (A 200-WORD OR LESS FACTUAL SUMMARY OF MOST SIGNIFICANT INFORMATION. IF DOCUMENT INCLUDES A SIGNIFICANT BIBLIOGRAPHY OR LITERATURE SURVEY, MENTION IT HERE.)

In 1987, a fire in a kitchen in Sharon, PA resulted in the deaths of three persons in upstairs bedrooms, one with a reported blood carboxyhemoglobin content of 91%. Considerable physical evidence remained.

The fire was successfully simulated at full scale in a fully instrumented seven room test called SHARON 2. The data collected during SHARON 2 have been used to evaluate the precision of two multiroom computer fire codes: FAST 18 and HARVARD 6.3.

A coherent ceiling layer flow occurred during the SHARON 2 simulation and quickly carried high concentrations of carbon monoxide (CO) to remote compartments. Such flow is not directly accounted for in either computer code. However, both codes predict well the carbon monoxide buildup in the sixth room (i.e., the room most remote from the fire). Prediction of the pre-flashover temperature rise was good. Prediction of temperatures after flashover of the room of origin was less successful. Other predictions of conditions throughout the seven test rooms varied from good approximations to significant deviation from test data. Hypotheses are presented as to the reasons for the differences. At least some are believed due to phenomena not considered in the computer codes.

12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)
carbon monoxide; large scale fire tests; model studies; simulation; smoke transport; toxic products

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