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Static Pressures Produced by Room Fires

J. B. Fang

Center for Fire Research
National Engineering Laboratory
National Bureau of Standards
U.S. Department of Commerce
Washington, D.C. 20234

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STATIC PRESSURES PRODUCED BY ROOM FIRES

J. B. Fang

Abstract

The distributions and time-varying nature of the static pressures developed due to fires in residential recreation rooms were determined for a range of combustible load densities and different types of interior lining materials. The vertical pressure differentials with respect to the ambient static pressure for various fire sizes are satisfactorily correlated by a hydrostatic perfect gas model based on temperature measurements in enclosures and an orifice flow model, and the calculated doorway inflow and outflow gas velocities are in good agreement with the measured values. The pressure differentials are found to reflect the locations of the neutral plane at the doorway and the thermal discontinuity within the fire room reasonably well, and their magnitudes depend on the average upper gas temperature. Rates of mass flow in and out of the room calculated from the ceiling and the floor pressure differentials agree fairly well with those derived from the doorway gas velocity data.

Key words: Building fires; fire tests; flow measurement; furniture; interior finishes; residential buildings; room fires; static pressure.

1. INTRODUCTION

Induced flows of cold air in and hot gas out of a fire compartment occur due to pressure differentials between the compartment and its adjacent area. This mechanism is caused by buoyancy due to the increase in gas temperature, and thermal expansion of the gases in the compartment. It has been found that a temperature distribution described as a step function provides a reasonable first approximation to the vertical temperature profile in the compartment. Within the compartment, there is an upward flow from the cold layer below the thermal discontinuity interface to the hot layer as air entrained into the fire plume and combustion products is carried upward.

Mathematical analysis of the flow through an opening using a hydraulics-orifice flow analogy has been reasonably successful for calculation of fire induced flow in enclosures [1-4][1]. Recently, McCaffrey and Rockett [5] have presented some results of static pressures developed in full-scale and reduced size enclosures with various heat input rates of gas burners and a comparison of experimental observations with the hydraulics-orifice enclosure model [1,3]. However, no extensive static pressure data are available in published reports relating to the burning of furniture in a room and extended fire durations including both growth and decay periods.

The fire resistance of building construction has generally been evaluated by directly exposing the structural elements to fire conditions in a test furnace according to the ASTM E 119 test method [6]. The level of the static pressure to be maintained in the furnace, although not rigorously prescribed, is one of the important factors affecting the fire endurance rating of the test specimen involved, especially doors and floor/ceiling constructions. This is because the convective heat transfer at the test assembly due to outflow of hot furnace gas or inflow of cool air and through openings and porous materials is dependent on the pressure

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[1] Numbers in brackets refer to the literature references listed at the end of this report.

difference across the assembly. Information on the static pressures developed within a building compartment is needed as a basis for devising rational procedures for testing the fire response of building materials and structures.

The current basement recreation room fire study program at NBS is aimed at developing a meaningful test procedure for evaluating the structural fire performance of floor assemblies in residential occupancies and to suggest improved performance criteria and design procedures for the proper selection and use of unprotected and fire protective, load bearing structural elements. The immediate objectives of this phase of the room fire program are to characterize basement fires based on a range of typical fire load densities, room sizes, interior finishes and ventilation conditions and to develop a rational fire exposure curve applicable to residential constructions.

This paper is a report of part of the work in progress. Presented here are some measurements of static pressures and temperature levels obtained from fires in rooms lined with selected interior finish materials and furnished with combustible contents commonly found in residential recreation rooms. The data include the time history of the pressure differentials at different locations in the fire room, the vertical distributions of pressure difference for various fire sizes, and the relationships with the upper gas temperature inside the room and the exhaust gas and incoming air velocities at the door opening.

2. EXPERIMENTAL DETAILS

2.1 Test Compartment

All room burnout tests were conducted in a 3.2 x 3.2 m (10.5 x 10.5 ft) burn room with 2.4 m (8 ft) ceiling height. A doorway opening measuring 0.8 m (32 in) wide by 2 m (80 in) high located symmetrically in the front wall was the single source of ventilation for the room. The room had one heat resistant glass window, 0.41 m (16 in) wide by 0.2 m (8 in) high, in one of the side walls for observation purposes. The basic construction of the room was 0.2 m (8 in) thick standard lightweight aggregate concrete block walls, concrete floor, and 1.3 cm (1/2 in) mineral board covered with 1.6 cm (5/8 in) Type X gypsum wallboard ceiling mounted to W6 x 12 steel I-beams resting on the top of the block walls. The entire burn room was built within a large test facility building in which the indoor air was conditioned within the human comfort range (air temperature 21 ± 4°C and relative humidity 42 ± 8%).

2.2 Instrumentation

Static pressures at various locations in the fire room were measured by means of 0.64 cm (1/4 in) steel pipes installed horizontally through one of the side walls with the open end flush with the exposed surface of the wall lining panels. These pressure taps were placed at two stations--one near the door-wall corner at a horizontal distance of 0.3 m (12 in) from the front block wall and at heights of 0.18, 0.99, 1.55, 2.01 and 2.21 m (7, 39, 60, 79, and 87 in) above the floor, and the other station near the rear corner at a spacing of 0.3 m (12 in) from the back block wall at heights of 0.18 and 2.21 m (7 and 87 in) above the floor. A plan view of the test room showing the locations of pressure probes, thermocouple "trees" and bidirectional velocity probes, and arrangements of furniture and interior finishes is given in figure 1. The pipes were connected by copper and tygon tubing through a 12 position fluid wafer selector switch to a variable capacitance pressure transducer, except for the top pressure tap in the front corner which was continuously monitored by a separate pressure transducer. This pressure meter in conjunction with the fluid switch converted the multiple differential pressures to electrical signals by time sharing at a rate of 2 seconds per probe. Each of the two pressure transducers had one pressure tap positioned at floor level and opened to draft-free ambient air for a common reference. Two potentiometric strip chart recorders were used to monitor the outputs of these transducers.

The temperature levels of the room gas were measured by bare beaded thermocouples having a spherical junction diameter of approximately 1.5 mm

(0.06 in) and made from 0.5 mm (0.020 in) diameter Type K wire. A total of 47 thermocouples were distributed within nine evenly spaced thermocouple "trees" inside the test room, and 12 thermocouples were positioned along the vertical center line of the doorway opening. The vertical distribution of the gas velocities at the doorway was measured by six bidirectional flow probes [7] along with variable reluctance pressure transducers. A digital data acquisition system was employed to record, every 8 seconds, the output signals from the thermocouples and the velocity probes directly on a magnetic tape. The data were processed, tabulated and plotted by the computer.

2.3 Interior Furnishings and Finish Materials

For most of the room burnout tests, the interior furnishings included a sofa, an upholstered chair and ottoman, an end table, a coffee table and a bookcase. Included among the furnishings were old record files placed in the bookcase and distributed randomly on the tops of the ottoman and the coffee and end tables. The loading density of the combustible contents, excluding carpeting, ranged from 15 to 37 kg/m^2 (3.1 to 7.6 lb/ft^2) with a mean value of 23 kg/m^2 (4.7 lb/ft^2) of the floor area, which is an average value for an occupied recreation room in the basement of a single family home in the Washington, D.C. metropolitan area [8].

The interior surfaces of the block walls were either painted or covered by nailing plywood panel, or gypsum board to wood furring strips anchored to the block walls. The following table lists the wall materials and fire load density, which is defined as the weight of combustible materials per unit floor area:

Test no.	Wall materials	Fire load density (kg/m^2)			
		Interior finish	Combustible contents	Carpet	Total
2	Painted concrete block	0	23	2.0	25
4	4 mm lauan plywood	12	15	2.0	39
5	4 mm lauan plywood	12	37	2.1	51.1
6	12.7 mm painted gypsum board	6	23	2.1	31.1
8	4 mm lauan plywood	12	23	2.2	37.2

It may be noted that the test numbers are not in sequence as there were other fire tests with forced ventilation or closed door which are not included in this comparison. Except for test 8, which had suspended 12.7 mm fiberboard base acoustic tile on the ceiling, the ceiling lining used was 16 mm thick Type X gypsum wallboard over the concrete floor.

2.4 Test Procedure

A section of a daily newspaper weighing 400 g placed along the backrest and the seat cushions in the middle of the sofa was used as the ignition source. The paper was conditioned to equilibrium at an ambient temperature of 23 ± 3°C and a relative humidity of 50 ± 5% prior to the fire test. The test was started by igniting the newspaper with an electrically heated book of paper matches. Visual observations, video tape and photographic records of the progress of the room fires were made during the course of the tests. Data were generally collected for a period of an hour, although the durations for tests 2 and 4 were shortened to avoid damage to the surrounding structures.

3. RESULTS AND DISCUSSION

The histories of fire development in these five tests were found to be similar in many respects, based on visual observation and data from temperature measurements: newspaper ignited, sofa ignited in 0.8 to 1.2 min, flames extending to the ceiling in 1.2 to 1.9 min; other furniture items and all combustible interior finishes ignited (flashover) in 2.3 to 2.8 min and flames emerging from the doorway in 2.4 to 2.7 min. Typical time variations of differential static pressures measured at various heights in the front corner of the fire room for test 5 are given in figure 2. The experimental points shown were the mean values obtained from averaging the readings of pressure transducers in a finite time interval. The differential pressure at each height is the pressure difference between the room and the ambient pressures at that height. As shown in the figure, the pressure differential at the top of the room increased rapidly to its peak level soon after room flashover and then decreased gradually with time in the later stages of the fire. The maximum pressure differentials at the lower elevations were attained more slowly.

In order to determine any variation due to the location of the measuring station, a comparison plot of the pressure differentials as a function of time for measurements taken at the identical heights in both the front and the rear corners is shown in figure 3. It can be seen that there is little difference between the static pressures measured at these two locations.

Figure 4 shows the static pressures developed within the fire room as a function of time for four test runs. The pressure measurements were made at two locations, 0.18 and 2.21 m above the floor and 0.305 m out from the back wall. As shown in the figure, all of the room fires have similar static pressure-time curves, especially in the lower cold air region. The pressure difference developed in the hot and cold gas zones depend upon the upper gas temperature.

On the basis of the two-fluid zone model in which the gas in a compartment is assumed to be ideal and stably stratified with a region of hot gas above and cool ambient air below, the pressure difference with respect to ambient static pressure at a given height Z in the upper portion of the room can be expressed by

$$\Delta P = \rho_o g \left(1 - \frac{T_o}{T}\right) (Z - Z_N) \quad , \qquad Z_D \leq Z \leq H \qquad (1)$$

where ρ_o and T_o are the density and absolute temperature of ambient air, g is acceleration of gravity, T is absolute temperature of the gas in the upper part of the room, Z_N is the height of the neutral plane and H is the room height. The height of the neutral plane can be experimentally determined when the pressure differentials are plotted as a function of height, or predicted with the use of equation (1) along with the data on the upper gas temperature and static pressure measured at a certain height. The latter method was used for calculating some of the data points shown in figures 9 and 10.

The pressure differential with respect to ambient pressure in the lower cold fluid zone is given by the hydrostatic relation

$$-\Delta P = \rho_o g \left(1 - \frac{T_o}{T}\right) (Z_N - Z_D) \quad , \quad 0 \leq Z \leq Z_D \qquad (2)$$

where Z_D is the height of thermal discontinuity.

Figure 5 shows vertical distributions of the pressure difference with respect to the ambient pressure at that height for various times in test 5. The figure indicates that the pressure differential in the upper part of the fire room varies linearly with the height, and the pressure points fall along the best-fit line as indicated in equation (1). The upper room gas temperature calculated using equation (1) along with the measured value for the slope of the fitted line at times of 6.2, 31 and 42 minutes after the start of the test was found to be 751°C, 584°C and 553°C respectively, which were comparable to the measured values of 749°C, 634°C, and 510°C derived from averaging the readings of 36 equally spaced thermocouples in the upper half of the room. For this test run, the ambient air was at 21°C. As illustrated in the pressure plot, the slope of the line fitted through the upper pressure points tends to increase slightly with a decrease in the average upper gas temperature.

In figure 6, vertical temperature traverses of air within the room and in the doorway are shown at the same times as those given in figure 5. No radiation correction was made for thermocouple readings. It can be noted that, due to turbulent mixing of both the hot gas with the cool air entering through the doorway and mass injection from the decomposing plywood walls and burning of debris on the floor, and radiant heating from the hot gas layer, the temperature of the air in the lower space was significantly higher than that of ambient air and the interface of the hot and cold layers had an increased thickness. The heights of the neutral plane for various fire intensities shown in figure 5 were found to be 0.74, 0.93 and 1.03 m respectively, or approximately 15 percent higher than those interpolated from the doorway temperature data. The intercept of the upper hydrostatic line and the vertical line through the lower pressure point in figure 5 or the use of equation (2) together with the value for the neutral plane yielded an estimate of the thermal discontinuity height. The interface of these hot and cold layers was estimated to be situated at 0.3, 0.4 and 0.45 m above the floor, respectively, at 6.2, 31 and 42 minutes. Except for an intense fire at 6.2 minutes when the hot smoky gas layer was observed to descend to the floor level, the heights of the thermal discontinuity estimated from pressure data were generally lower than those derived from the vertical gas temperature profiles.

In order to determine the relationship between the vertical distribution of static pressure developed in the fire room and the flow pattern of air interchange at the doorway, air velocities calculated from the pressure data shown in figure 5 were plotted in comparison with the measured center line velocities in figure 7. The velocity for a given height was defined as $C_D\sqrt{2\ (\Delta p)/\rho}$, in which C_D is an equivalent orifice coefficient [1,4], and the gas density was evaluated using air at a temperature equal to the average of the local temperatures of air in the doorway and within the room at the same height. The average air temperature was used in order to account for change in both gas density and velocity along the flow path within the room and discharging through the doorway opening. An orifice coefficient equal to unity was employed for calculating doorway air velocities shown in figure 7. It can be seen that the calculated velocities are in good agreement with the measured ones in the magnitude and flow direction. The neutral plane height estimated from the measured velocity reversal for the fire at 6.2, 31 and 42 minutes was 0.66, 0.88 and 0.98 m, which were found to range from 5 percent to 11 percent lower than those interpolated by the pressure differentials as illustrated in figure 5.

The mass flow rates of the outgoing gases and the incoming air were determined using both the measured and the pressure calculated velocities along with the local gas density and cross-sectional area of the doorway opening with an assumption of uniform flow across the door width. A comparison of the measured mass flow rates based on doorway velocity measurements shown in figure 7, and the calculated mass flow for fire intensities at 6.2, 31 and 42 minutes after initiation of test 5, is presented in table 1. The discrepancy between the mass flow rates by room static pressure measurements and those obtained from velocity data was found to vary from 3 percent high to 20 percent low with a mean of approximately 9 percent. For ventilation controlled compartment fires, the steady-state burning rate of wood fuel is determined by the air supply and can be related to the size of the opening by the approximate relation [9,10]: $\dot{m} = k A_o\sqrt{H_o}$ where A_o and H_o are the area and the height of the opening, respectively, and k is a constant about 0.092 to 0.1 $kgs^{-1}m^{-5/2}$. For conditions employed, and assuming a negligible rate of mass accumulation within the fire room compared with the inflows and outflows, the rate of burning was estimated to be the order of $\dot{m} = 0.092 \times 1.55 \times\sqrt{2.03} =$ 0.2 kg/s. From the measured inflow rates given in the table, the burning rate of ventilation controlled fires at times of 6.2, 31 and 42 minutes was approximately equal to 0.10, 0.20 and 0.24 kg/s using a stoichiometric air-fuel mass ratio of 5.1 kg air/kg fuel. The mass balance results also suggest that a significant amount of fuel volatiles leaving the fire room remained unburned, and its outflow rate decreased with increasing time.

Figure 8 shows a plot of the normalized pressure differentials with respect to ambient density and doorway height, at the ceiling and the floor levels in the rear corner throughout the test duration for tests 5 and 6 as a function of a dimensionless temperature (the ratio of the temperature difference between the upper gas and the ambient air to the average upper gas). The absolute ambient temperatures for tests 5 and 6 were 294 K and 295 K, respectively. It can be seen from the figure that the pressure differentials increased with an increase in the upper gas temperature. Inspection of equations (1) and (2) would lead to the conclusion that the slopes of the best-fit lines drawn separately through the upper and the lower pressure points on the plot of the normalized pressure differentials versus the term (1 - T_o/T) were constant for the fixed heights of the neutral plane and thermal discontinuity. As shown in figure 8, the departure from linearity demonstrates a significant variation of the neutral plane and thermal discontinuity heights throughout the test duration since these heights are indeed a function of room gas temperature. However, some aspect of the data points in figure 8 are a result of the two layer thermal approximation.

The thermal discontinuity and neutral plane heights both calculated with the use of equations (1) and (2), respectively, and normalized to the doorway height are displayed as a function of average upper gas temperature for tests 5 and 6 in figure 9. The neutral plane heights interpolated from the intersection plane between the two measured horizontal velocity profiles of the inflows and outflows at the doorway opening for test 3 are also plotted on the same figure for comparison. It can be seen that there is considerable dispersion of data points probably caused by the turbulent and fluctuating nature of room fires. Yet, a general trend can be derived from these data such that the majority of data points fall somewhere around their best-fit lines, and suggests that positions of both neutral plane and thermal discontinuity drop with an increase in the spatially averaged temperature of the hot gas in the upper portion of the fire room. Also, the calculated neutral plane heights are in reasonably good agreement with those determined from the measured velocity reversal. Extrapolation of the thermal discontinuity curve to allow its height to approach zero results in an upper gas temperature of about 1030°C and at this same time, it was observed for these tests that the entire rooms were fully involved in flames. The corresponding room gas temperature at this time for tests 5 and 6 were 937°C and 965°C, respectively.

The hydraulic-orifice approach has been used with reasonable success in determining the gross features of the transport phenomena of hot-cold fluids at the opening of an enclosure. From reference [1], the mass flow rates of gases in and out of the fire room can be expressed in terms of the neutral plane and thermal discontinuity heights, and the average upper gas temperature, as follows:

$$\frac{\dot{m}_i}{\rho_o A_o \sqrt{gH_o}} = \frac{2}{3} \quad C_D \sqrt{2 \frac{T_o}{T} \left(1 - \frac{T_o}{T}\right)} \left(1 - \frac{Z_N}{H_o}\right)^{3/2} \tag{3}$$

$$\frac{\dot{m}_o}{\rho_o A_o \sqrt{gH_o}} = \frac{2}{3} \quad C_D \sqrt{2 \left(1 - \frac{T_o}{T}\right)} \left(\frac{Z_N}{H_o} - \frac{Z_D}{H_o}\right)^{1/2} \left(\frac{Z_N}{H_o} + \frac{Z_D}{2H_o}\right) \tag{4}$$

where $\dot{m}_i$ and $\dot{m}_o$ are the mass flow rates of gases entering and leaving the room, respectively. Figure 10 shows a plot of the rates of mass flow in and out, which were calculated using equations (3) and (4) along with the derived neutral plane and thermal discontinuity heights from simultaneous measurements of the ceiling and the floor pressure differentials and normalized by the ventilation parameter $\rho_o A_o \sqrt{gH_o}$, as a function of the term $(1 - T_o/T)$. The flow rates obtained from the doorway gas velocity and temperature measurements were also plotted in the same figure for comparison. The values of the equivalent orifice coefficient used for taking account of constriction energy loss were equal to 0.51 for air inflow and unity for gas outflow, which provided the least deviation from the experimental values on mass flow rates. Both sets of data indicate that the rates of gas outflow are significantly greater than those of air inflow especially at higher temperatures. The measured values of $\dot{m}/(\rho_o A_o \sqrt{gH_o})$ for the incoming air and the exiting gas averaged over a period from room flashover to test termination were found to be 0.112 and 0.185, respectively, or $\dot{m}_i = 0.93$ and $\dot{m}_o = 1.53$ kg/s. In general, the deviation of mass flow rates computed from the ceiling and the floor pressure results from those derived from the doorway gas velocity data was estimated to be within approximately 18 percent and 14 percent for the inflow and outflow, respectively.

4. CONCLUSIONS

Vertical profiles of the pressure differentials with respect to ambient static pressure are found to follow the hydrostatic distribution described by a two-layer hot and cold fluid model. Both neutral plane and thermal discontinuity heights computed from pressure measurements at the ceiling and the floor levels agree fairly well with those derived from gas velocity and temperature data.

Static pressure differentials increase with an increase in the temperature of the hot gas in the upper part of the fire room (or severity of room fires involved). The calculated rates of mass inflow and outflow based on the ceiling and the floor static pressure differentials appear to be reasonably consistent with the experimental observations of the doorway flow.

The highest pressure difference obtained in these fire tests was 15.5 Pa (0.062 in of water) which occurred near the ceiling shortly after room flashover was found to be a factor of 2 greater than the differential pressures developed in a room with a 450 kW gas burner [5]. This difference decreased slowly during the course of the tests due to the reduction in burning rate within the room.

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Table 1. Mass flow rates for test 5

Time (min)	Inflow (kg/s)			Outflow (kg/s)		
	Measured	Calculated	% Difference	Measured	Calculated	% Difference
6.2	0.53	0.55	3.2	1.78	1.98	11
31	1.04	0.84	-19	1.53	1.51	-1.3
42	1.24	1.23	-0.3	1.49	1.19	-20

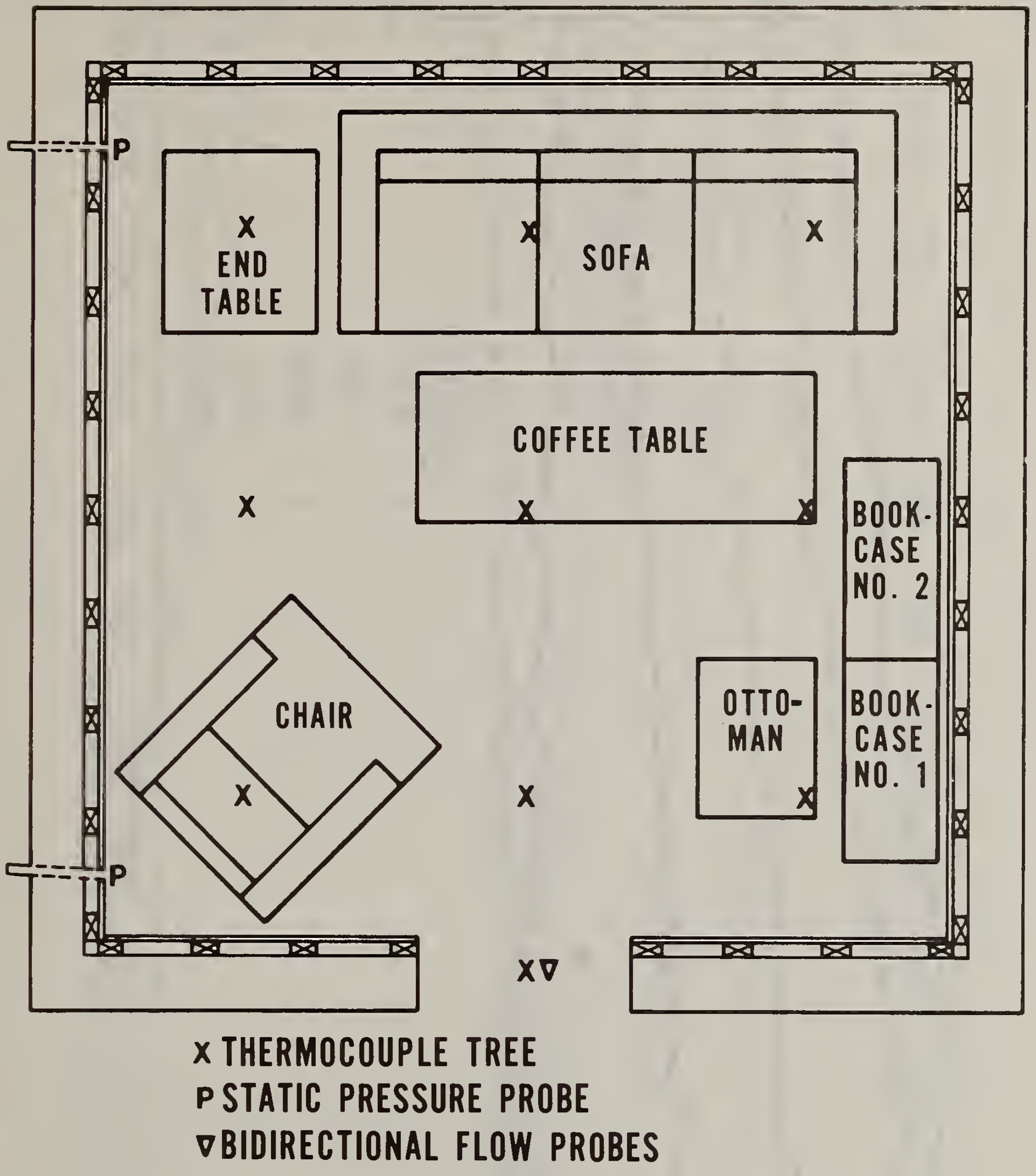

Figure 1. Plan view of the test room showing locations of furniture and wall linings, and arrangement of instrumentation

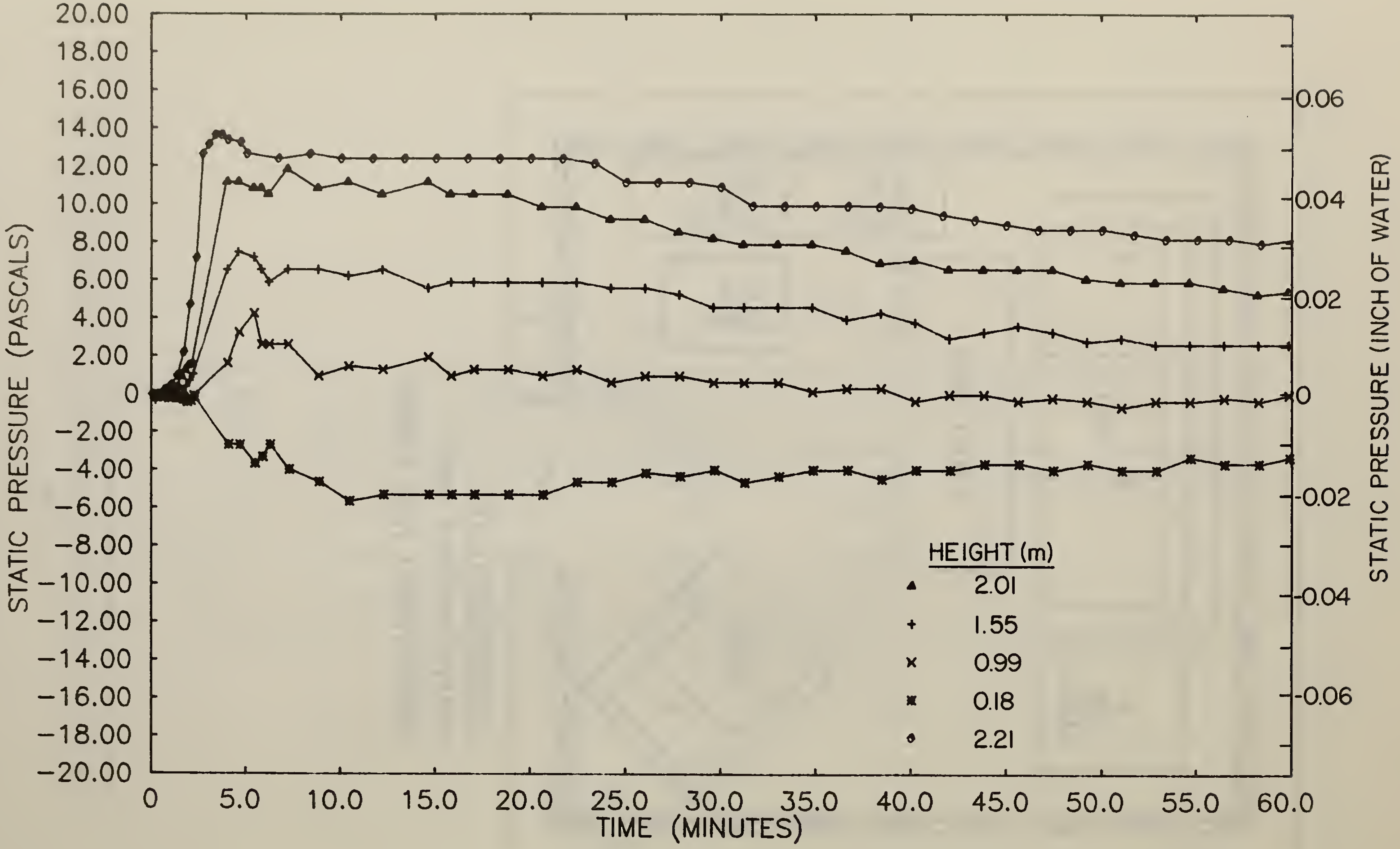

Figure 2. Time history of the differential static pressures measured at various heights in the front corner during test 5

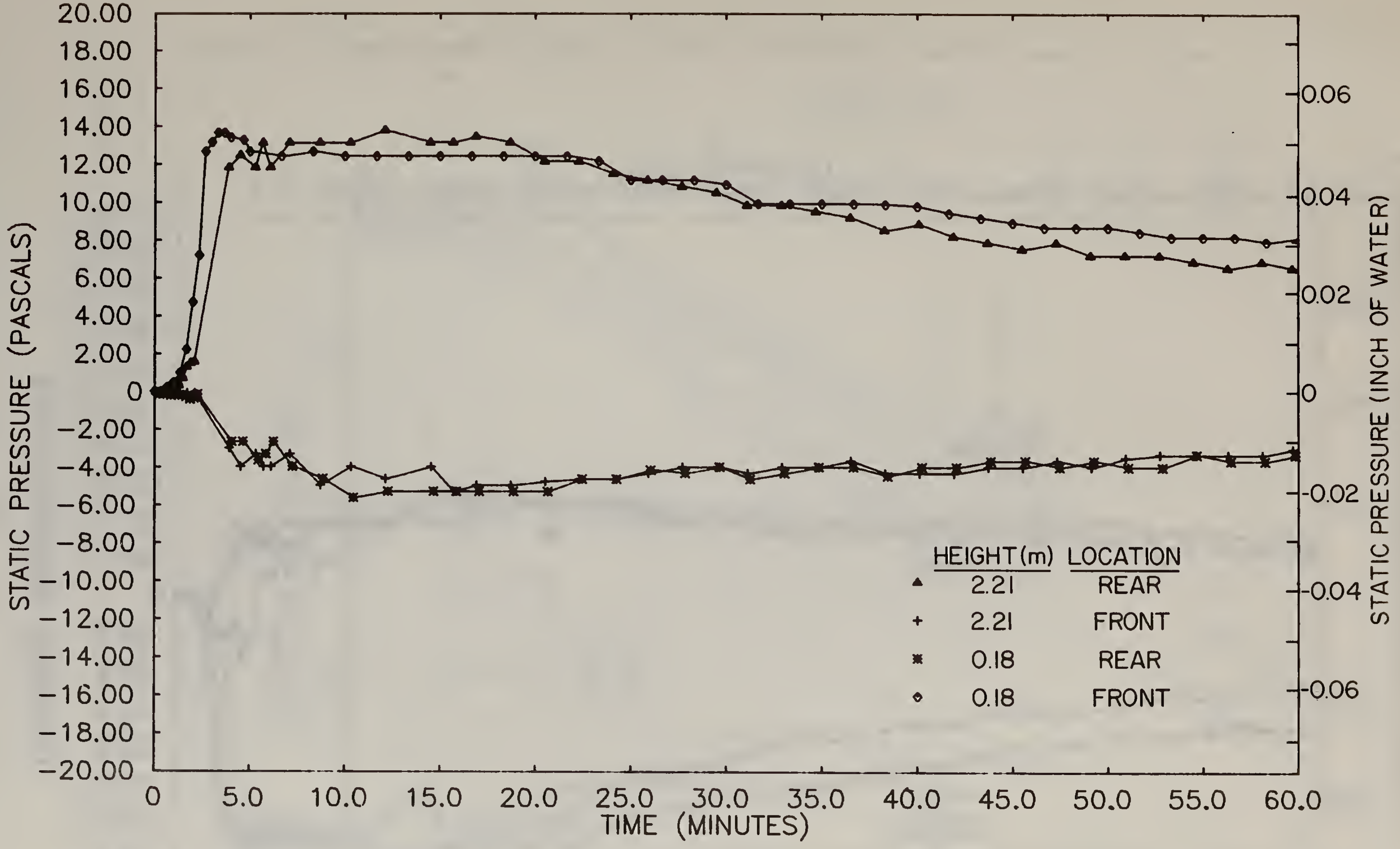

Figure 3. Comparison plot of the time variations of the pressure differentials measured at the same heights in the front and the rear corners during test 5

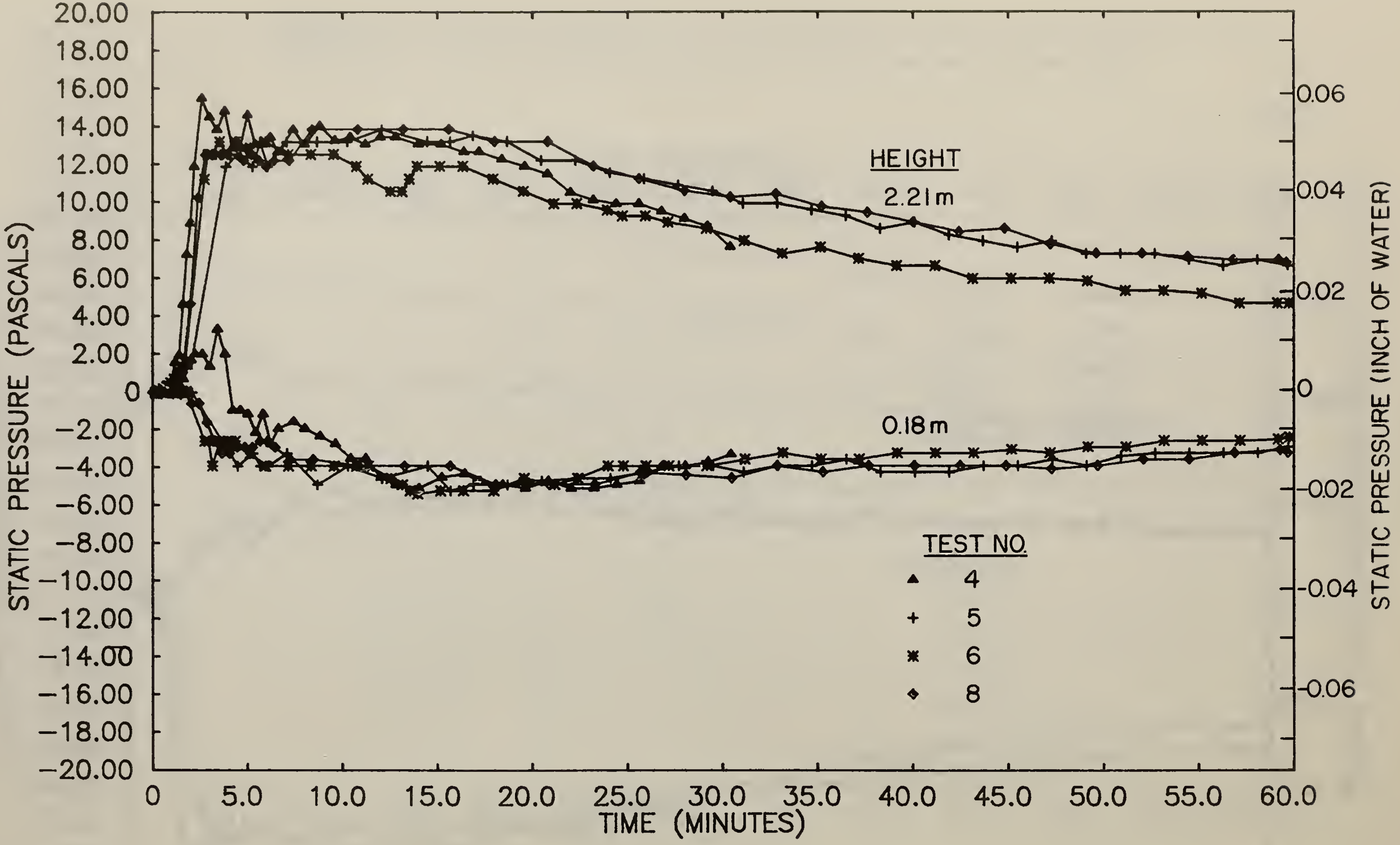

Figure 4. Time history of static pressures developed in various room fire tests

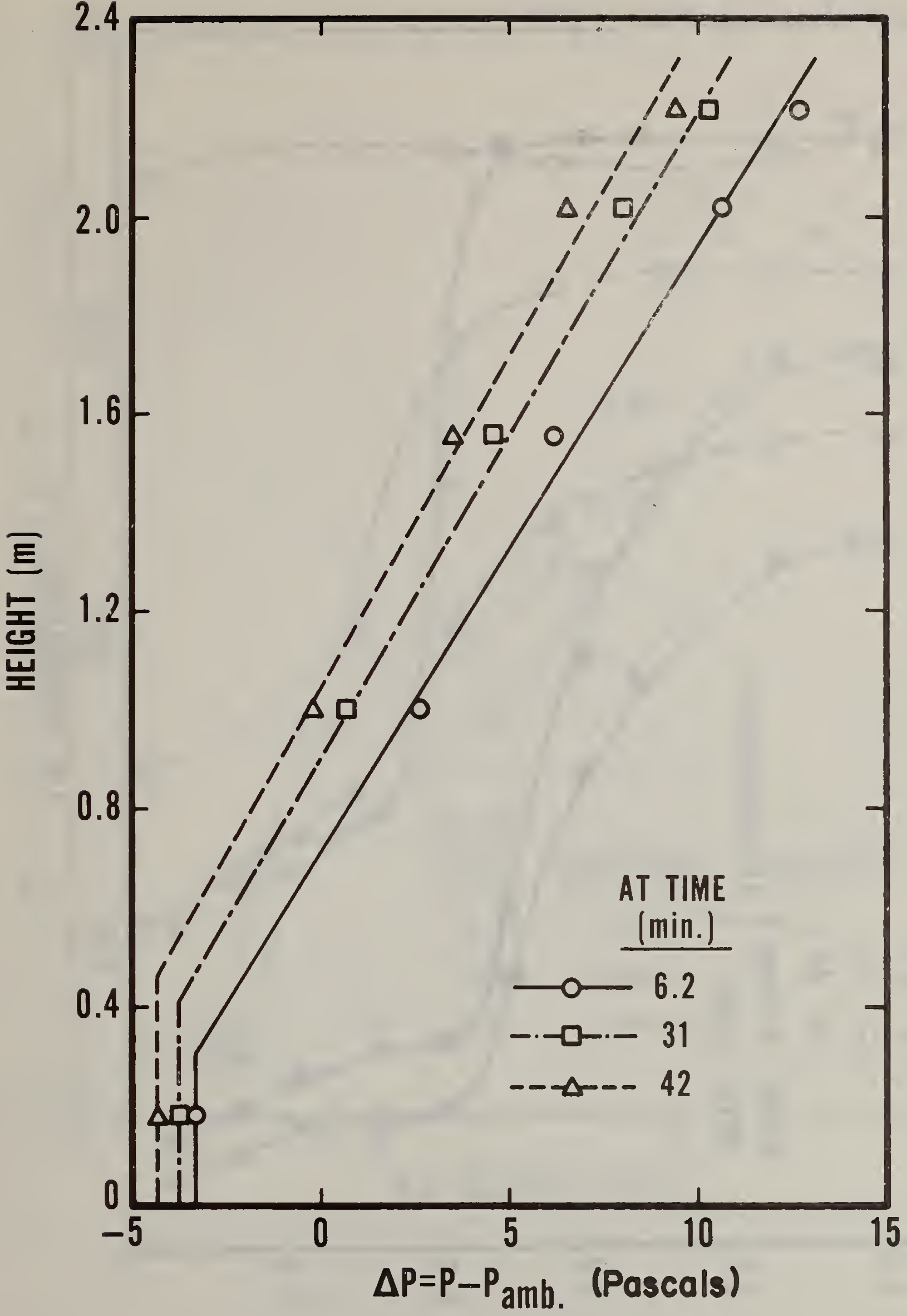

Figure 5. Vertical distributions of the pressure differential at various times for test 5

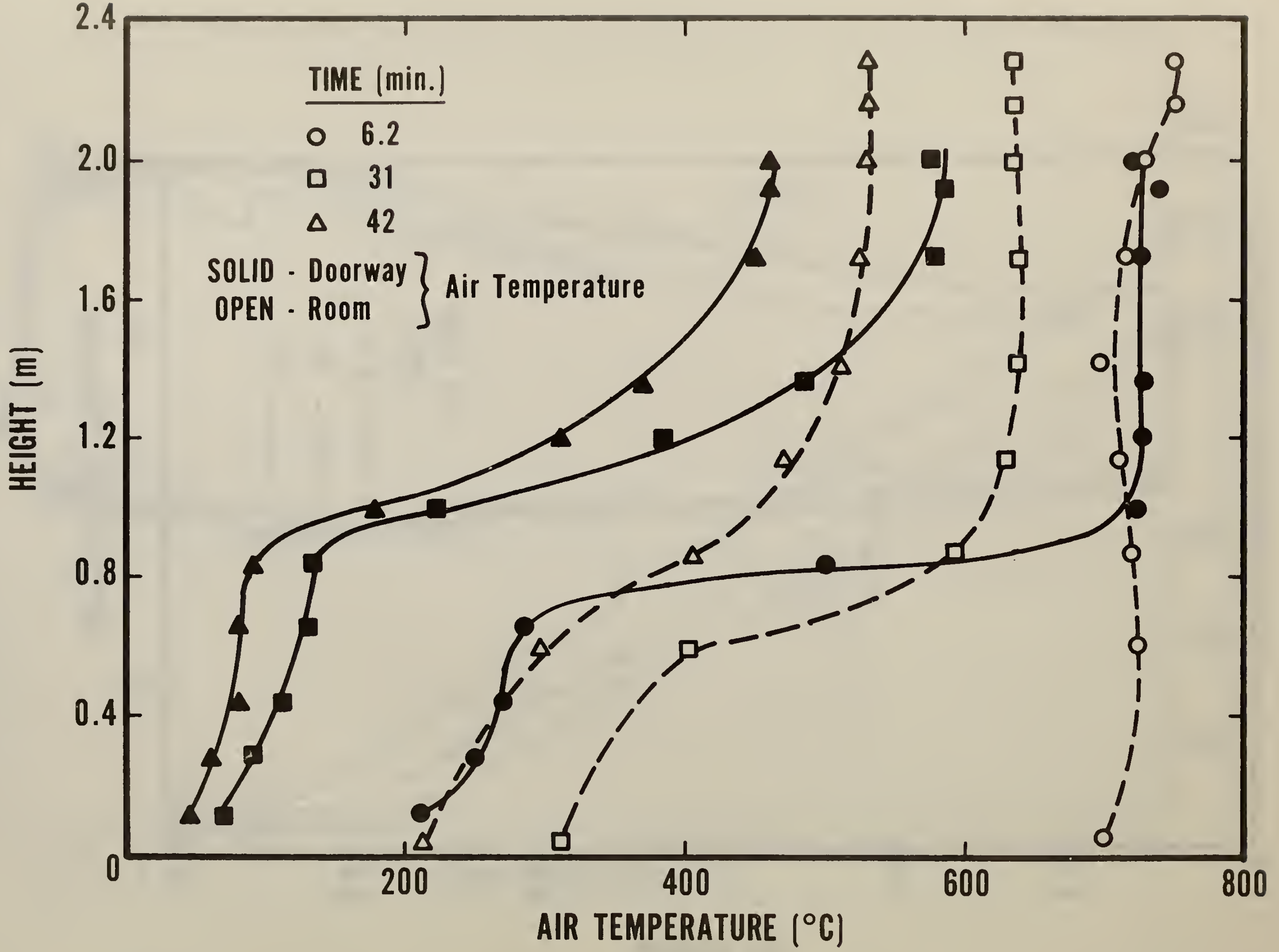

Figure 6. Vertical temperature profiles of air in the room and in the doorway at various times for test 5

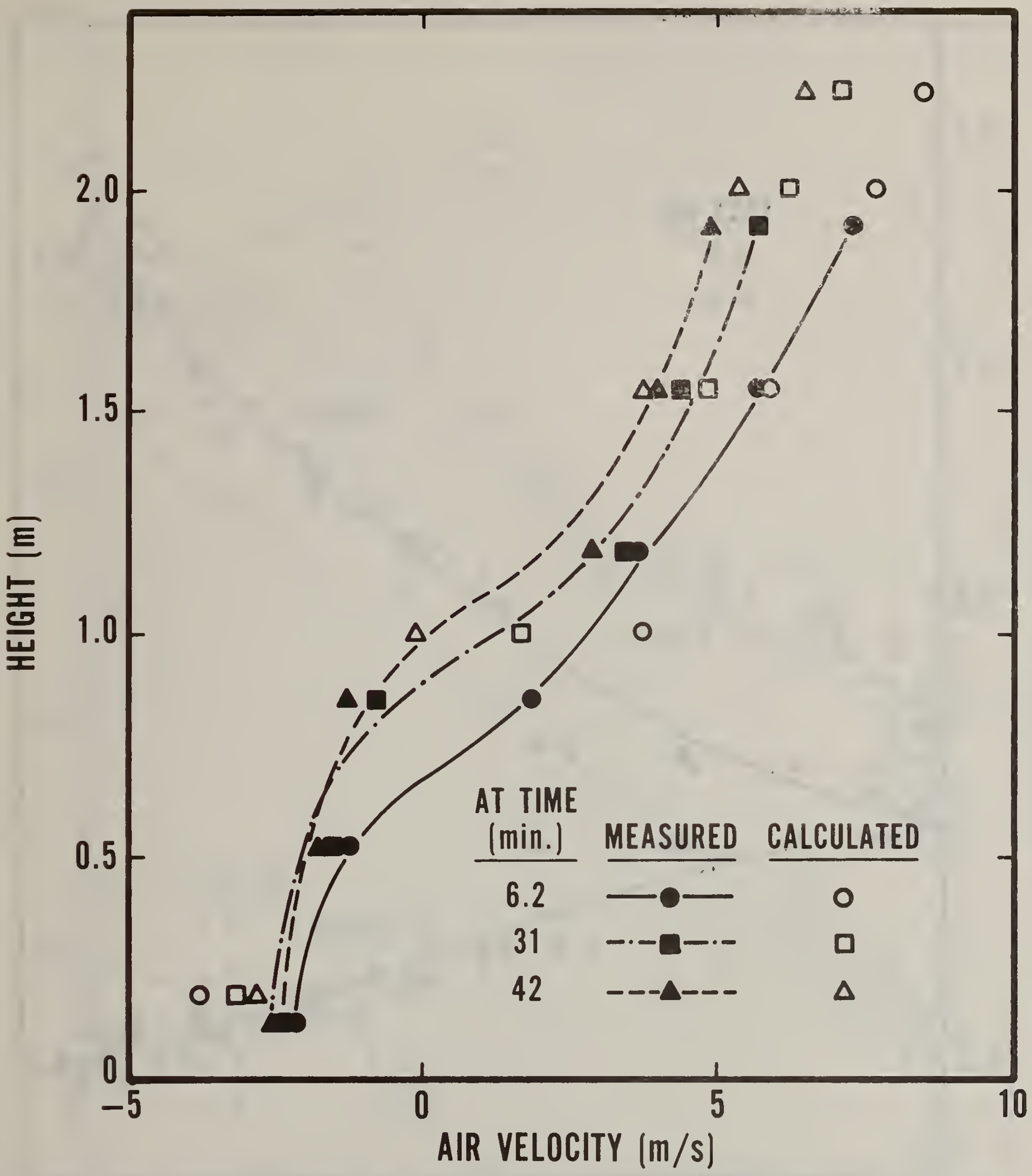

Figure 7. Comparison of measured and calculated air velocities at the doorway in test 5

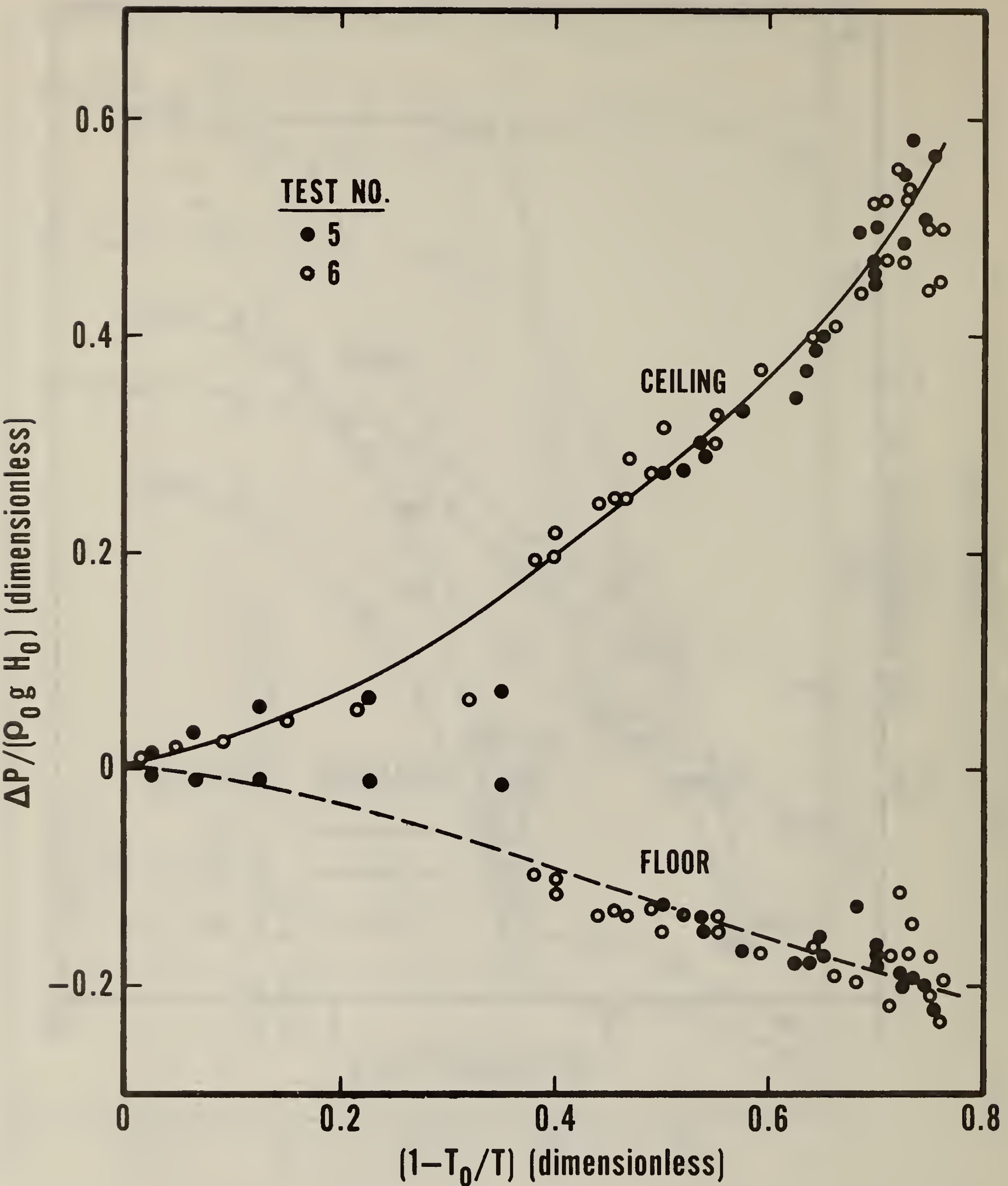

Figure 8. Relationship between the normalized pressure differentials and average upper gas temperature

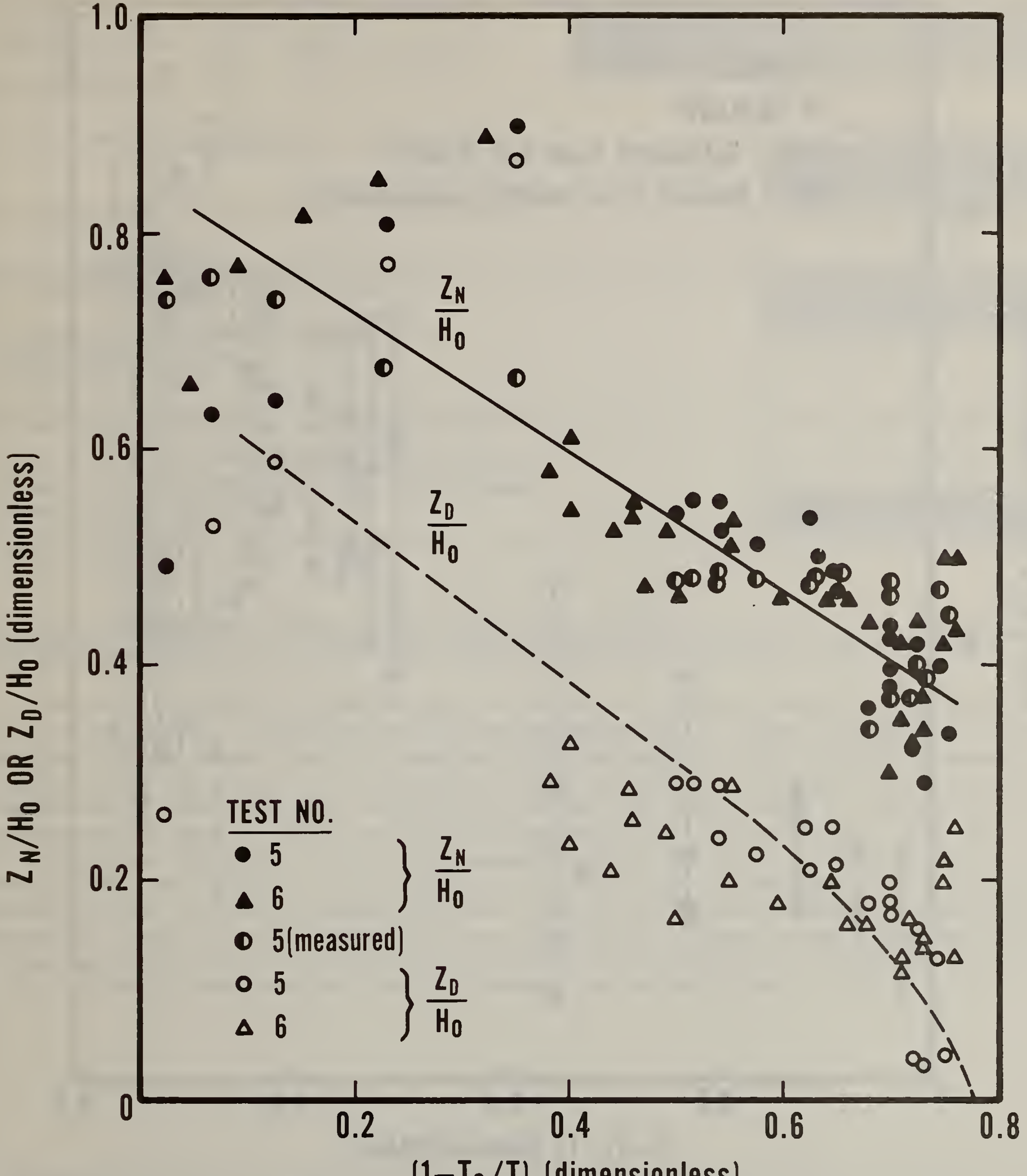

Figure 9. The normalized neutral plane and thermal discontinuity heights as a function of average upper gas temperature

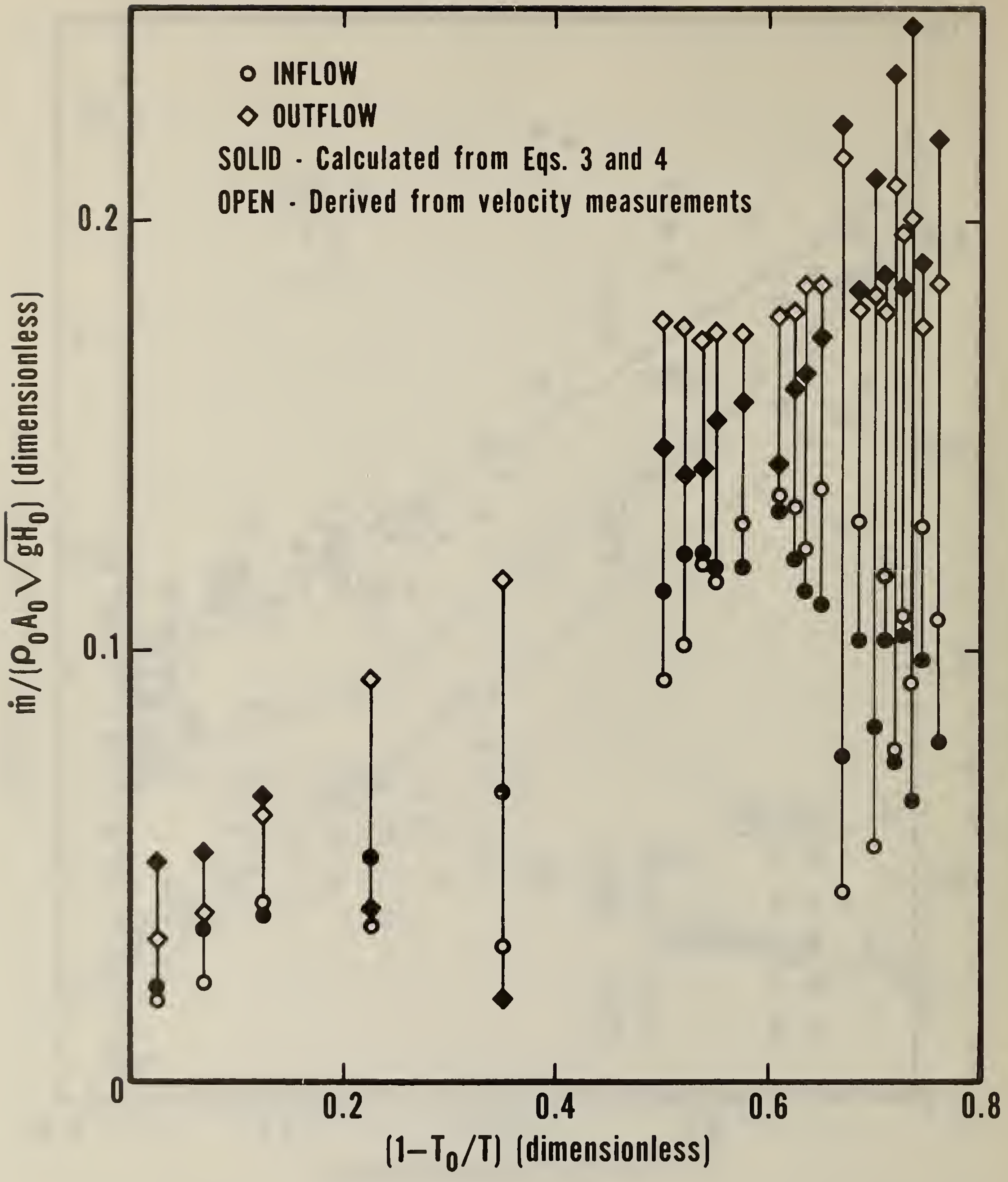

Figure 10. Comparison of measured and calculated inflow and outflow mass flow rates as a function of average upper gas temperature in test 5

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15. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

The distributions and time-varying nature of the static pressures developed due to fires in residential recreation rooms were determined for a range of combustible load densities and different types of interior lining materials. The vertical pressure differentials with respect to the ambient static pressure for various fire sizes are satisfactorily correlated by a hydrostatic perfect gas model based on temperature measurements in enclosures and an orifice flow model, and the calculated doorway inflow and outflow gas velocities are in good agreement with the measured values. The pressure differentials are found to reflect the locations of the neutral plane at the doorway and the thermal discontinuity within the fire room reasonably well, and their magnitudes depend on the average upper gas temperature. Rates of mass flow in and out of the room calculated from the ceiling and the floor pressure differentials agree fairly well with those derived from the doorway gas velocity data.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Building fires; fire tests; flow measurement; furniture; interior finishes; residential buildings; room fires; static pressure.

18. AVAILABILITY ☒ Unlimited ☐ For Official Distribution. Do Not Release to NTIS ☐ Order From Sup. of Doc., U.S. Government Printing Office, Washington, DC 20402, SD Stock No. SN003-003- ☒ Order From National Technical Information Service (NTIS), Springfield, VA. 22161	19. SECURITY CLASS (THIS REPORT) UNCLASSIFIED 20. SECURITY CLASS (THIS PAGE) UNCLASSIFIED	21. NO. OF PRINTED PAGES 29 22. Price $6.00