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FEASIBILITY OF
FROUDE MODELING A POOL
FIRE EXTERNAL TO AN
AIRCRAFT FUSELAGE

by

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PREFACE

This evaluation was conducted as part of the Aircraft Systems Fire Safety Program, NPD No. 18-471, sponsored by ARD-520, Mr. Robert C. McGuire. The project number is 181-521-190, and the NAFEC Program Manager is Mr. Constantine P. Sarkos. The numerous discussions with and helpful advice of Messrs. McGuire and Sarkos regarding modeling requirements for integration into concurrent full-scale fire projects are acknowledged.

The assistance of Messrs. William E. Neese and Joseph A. Wright in preparing the test article and performing the tests is acknowledged.

ABSTRACT

A series of six fire tests was conducted on a 4-foot-diameter model fuselage located within a large building. A 4-foot-square pool of JP-4 was ignited adjacent to a single open door in the fuselage model. Heat and smoke accumulation within the fuselage were recorded to determine test repeatability. Concepts of Froude modeling were reviewed and developed for application to the behavior of external pool fires following an aircraft crash. The repeatability of the tests and the conceptual development indicate that Froude modeling is appropriate for studies of pool fire behavior in the presence of a fuselage. Anticipated limitations of the technique are discussed.

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INTRODUCTION

PURPOSE.

The purpose of this program is to experimentally evaluate promising methods of conducting small-scale cabin fire tests. These evaluations are motivated by a need for more economical but suitably realistic methods of aircraft fire testing. This report describes the experimental results from a series of six fire tests on a 26.5 foot-long fuselage. The model was placed adjacent to a 4-foot-square pool fire, and the resulting heat flux, temperature rise, and smoke accumulation were measured in a quiescent indoor atmosphere. This report further explores the feasibility of applying Froude modeling concepts to an external pool fire.

BACKGROUND.

The large quantities of aviation kerosene carried aboard commercial aircraft have the potential of causing large pool fires during a crash. Because the fuselage can shield the passengers for some finite time interval at the start of a major conflagration, recent full-scale tests have been directed at the effects of pool fires on the aircraft interior through open doorways (references 1 and 2). Model tests have also been used to generate a wider range of scenarios in determining the effects of pool fires on the cabin interior (references 3 and 4). The radiation heat transfer results (references 2 and 3) are in agreement for the special case of no fire penetration through a doorway. The model results reported in reference 4 describe the effects of wind, fire size, and number of door openings on hazard development within a fuselage in the presence of a 4-foot-square fire. Although reference 3 showed that radiant heat flux to a cabin interior shows good repeatability with proper relations of fuselage size to fire size, the radiant heat flux tests in reference 3 were conducted with open-ended ducts instead of a closed fuselage and provide for development of interior cabin hazards. Whether the enclosed aircraft model with a floor and ceiling as described in reference 4 can show a repeatable interior hazard from an external pool fire requires documentation before any attempts are made to compare model results with large-scale results.

Modeling aircraft fires involves scaling down a geometry characterized by a high length-to-diameter ratio typical of an aircraft fuselage. This type geometry has been scale modeled with some success in the case of building corridors (reference 5) which are similar in geometry to aircraft fuselages. However, in the corridor evaluation, the fire source was a fuel bed in a scaled room attached to the corridor. In contrast, scale modeling an aircraft crash scenario involves a free-burning pool of fuel as the fire load. However, a fire engulfing a fuselage door is similar in concept to a fire in a room attached to a corridor.

Although Froude modeling of interior fires in an enclosure has been an active area of study (references 6, 7, 8, and 9), its applicability to the effects of an exterior pool fire on interior cabin hazards remains to be demonstrated.

EXPERIMENTAL OBJECTIVE.

The experimental objective of these pool fire tests was to determine the repeatability of this type fire scenario and to determine whether or not the height of the fuselage door above the liquid fuel surface is a parameter influencing hazard development within the fuselage. The experimental objective also included evaluation of the performance of the laser transmissometers prior to initiation of outdoor testing.

DISCUSSION

FROUDE MODELING CONCEPTS.

So many different chemical reactions occur during a fire that the details of the chemical reactions are generally ignored. In most fires that represent a hazard to life and property, the chemical reactions can be imagined as occurring in a time period approaching zero. Thus, the progress of the fire (burning rate, flame spreading rate, movement of combustion products) is controlled by fluid mechanical and thermophysical parameters such as gas momentum, bouyancy, viscosity, and thermal conductivity. This domination by fluid mechanical variables provides the basis for physical modeling of fires. Just as many aerodynamic phenomena can be tested by changing the scale and holding the Reynolds number constant, so can many fires be simulated on a small scale by holding the Reynolds number and Froude numbers constant as the fire configuration is made smaller. However, it should be noted that radiation effects add a serious complication to this physical modeling approach.

This simplest physical modeling approach is Froude modeling, wherein the gases are treated as inviscid. Thus, the Reynolds number is ignored and the fire dynamics are controlled by the dynamic pressure of the gas and by the bouyancy of the hot gases. Thus, if the ratio of the dynamic pressure to the gravitational head (the Froude number) is maintained, a steady state fire can be reduced in scale. Transient fire phenomena such as flame spread would require control of the Reynolds number for accurate simulation.

The appendix shows the development of the Froude modeling relations for use in the scaling down of an aircraft fuselage in the presence of an external fuel fire. Since the external fuel fires under consideration are steady state pool fires, scaling the Froude number should result in accurate scaling with the following results:

1. If ambient winds provide the controlling dynamic pressure, the fuselage and fire can be scaled geometrically (that is, an 8-foot-square fire against a 4-foot-diameter fuselage represents a 32-foot square fire adjacent to a 16-foot-diameter aircraft). Furthermore, an ambient windspeed in the scaled test corresponds to a larger wind in the full-scale test by the square root of the ratio of the characteristic lengths for the two scales.

2. Using a conventional approach with a quiescent, ambient atmosphere where the fire plume itself provides the dynamic pressure, the width of the scale model fire pool should be the width of the full-scale fire pool times the ratio of the model diameter to the full-scale fuselage diameter to the 1.25 power. Thus, for a 1/4-scale model, the model fire width would be 0.177 times the equivalent full-scale fire size.

   In this work, it will be assumed that the fuselage and fire are scaled geometrically rather than through the 1.25 power. A case is argued in the appendix for this alternate approach (also with precedent in the literature) which would have the fire pool and fuselage model both scale in the same ratio to their respective full-scale dimensions.

In addition to holding the Froude number constant, two additional considerations must be noted. First, for the 4-foot-diameter model in these tests, reference 3 indicates a minimum fire pan size of 5.3-foot-square should be employed for proper radiative scaling. As a by-product, the external pool fires should be a minimum of 3 to 4 feet in diameter so that turbulent fires are assured.

Proper adherence to these modeling criteria should provide a sound basis for scaling external pool fires and obtaining accurate fire behavior in terms of fire plume bending and heat fluxes to the fuselage surface.

From work such as reference 5, the viability of Froude modeling the gas movement within an enclosure has been demonstrated. Since the exterior fire and the interior smoke movement can both be scale modeled, the principal question is whether external and internal scaling can be performed simultaneously. Experimentally, the feasibility of successfully matching the scaled interior to the scaled exterior will best be demonstrated by an equivalent heat flux through a fuselage door facing the fire and by equivalent temperature-time histories between a model and a full-scale fuselage.

Since a primary objective of these fuselage tests is establishment of the effects of wind and door openings on interior hazard development from an external pool fire, flow coefficients may have to be developed for the model doorway to account for differences in ventilation between small-scale and full-scale fuselages exposed to wind.

MODEL CONSTRUCTION.

The fabrication of the fuselage model is described in detail in reference 4. The model was made from mild steel in three sections. The center and rear sections were each 10 feet long, and the forward section was 6.5 feet long. The model was cylindrical in shape and 4 feet in diameter. Six doors were cut into the model walls, and each measured 10 by 20.6 inches. Figure 1 shows an overall view of the model, while figure 2 shows the overall test configuration.

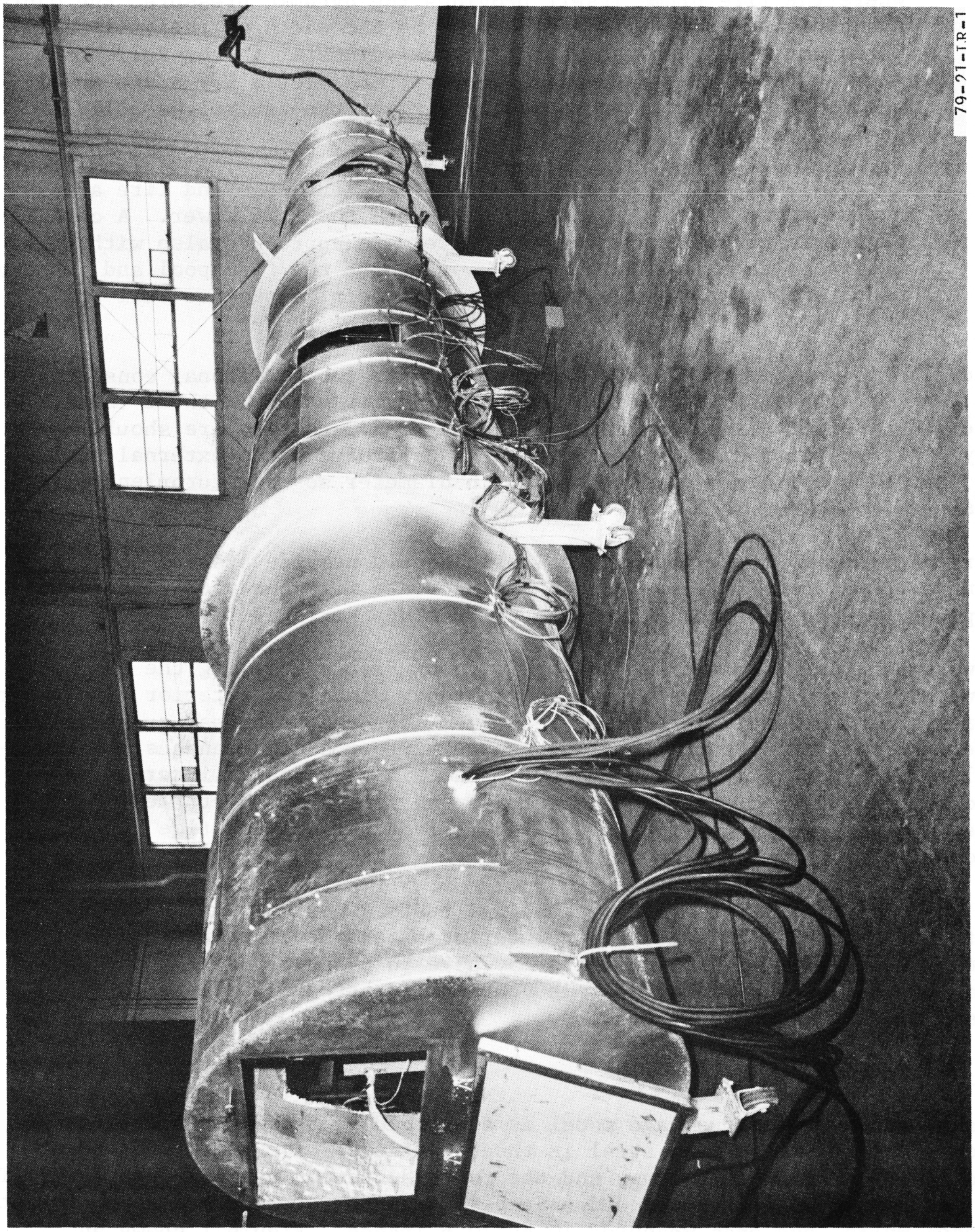

FIGURE 1. MODEL OVERALL VIEW

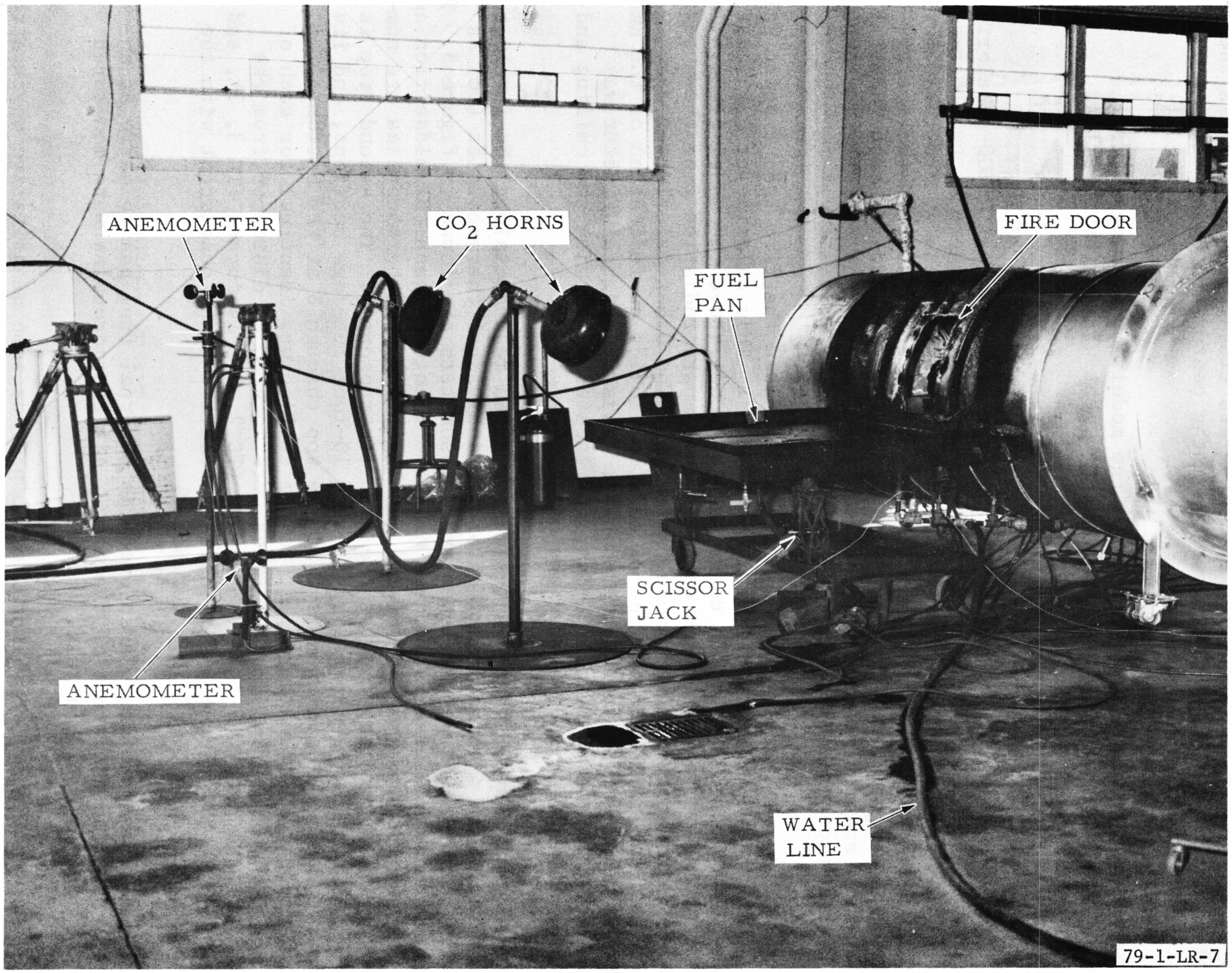

FIGURE 2. OVERALL TEST CONFIGURATION

The floor and ceiling were transite, and the interior walls were insulated with a layer of Kaowool covered by fiberglass cloth. Figure 3 shows the model opened at the hinged flange between the center and rear sections with the completed interior.

Windows were installed at both ends of the model for viewing of fire penetration through the doors and smoke movement within the interior.

INSTRUMENTATION.

The instrumentation for these tests consisted of two Hy-cal C1300-A calorimeters (C-9 and C-13) within the fuselage as shown in figure 4, two thermocouple trees within the fuselage, two laser transmissometers, and three motion picture cameras. The output from the two calorimeters and the smokemeter photocells was recorded on a Honeywell model 1858 cathode-ray tube (CRT) Visicorder, and the thermocouple outputs were recorded on an Esterline Angus D 2020 thermocouple recorder.

The midplane, or symmetry plane, calorimeter faced the fire from a point halfway across the fuselage width from the 3R door. This calorimeter was located midway between the 3R and 3L doors and 10 inches above the model floor. This symmetry plane calorimeter was employed to compare radiation from these tests with radiation from previous modeling tests. The other calorimeter was located at the ceiling above the 3R door to provide an indication of the amount of flame penetration through the doorway. This ceiling calorimeter was centered with respect to the 3R door and located flush with the ceiling and 6 inches from the right edge of the ceiling.

Eight chromel-alumel thermocouples were mounted in trees along the fuselage centerline. The precise locations of the individual thermocouples (TC) as well as the position of the laser transmissometers are found in figure 5. The front thermocouple tree is located near the flange between the midsection and the shorter 6.5-foot section of the fuselage, and its thermocouples are numbered from 1 at the top to 4 at the lower thermocouple. The second tree is located at the flange separating the two 10-foot fuselage sections, and its thermocouples are identified as 5 at the top through 8 at the bottom. The vertical positioning with respect to the ceiling was identical for each of the trees, and the four thermocouples were located at distances from the ceiling of 1/4 inch (TC 1, 5), 8 inches (TC 2, 6), 14 inches (TC 3, 7), and 20 inches (TC 4, 8). These positions were selected to be consistent with the thermocouple trees cited in reference 1.

A ninth thermocouple was placed over the external fuel pan to serve as an event marker for the start of the test. All thermocouples were monitored every 4 seconds during a test.

The laser smokemeters were installed to provide some quantitative obscuration measurements to supplement the qualitative information derived from motion pictures. The locations shown in figure 5 were based on the observations of references 1 and 4 which demonstrated the stratification of heat and smoke. The lasers were Spectra Physics model 155, and the receivers were Weston

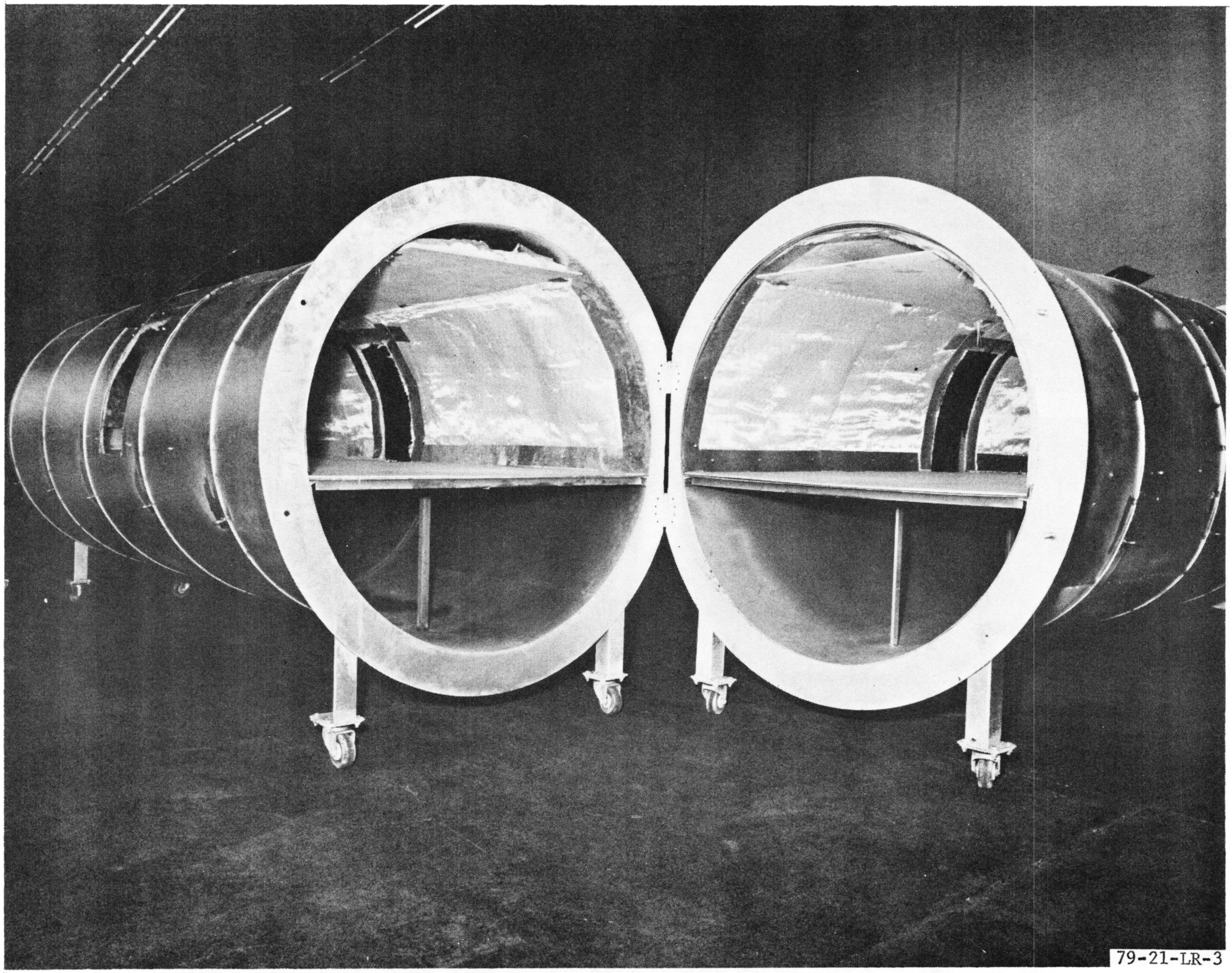

FIGURE 3. FLANGED OPENING

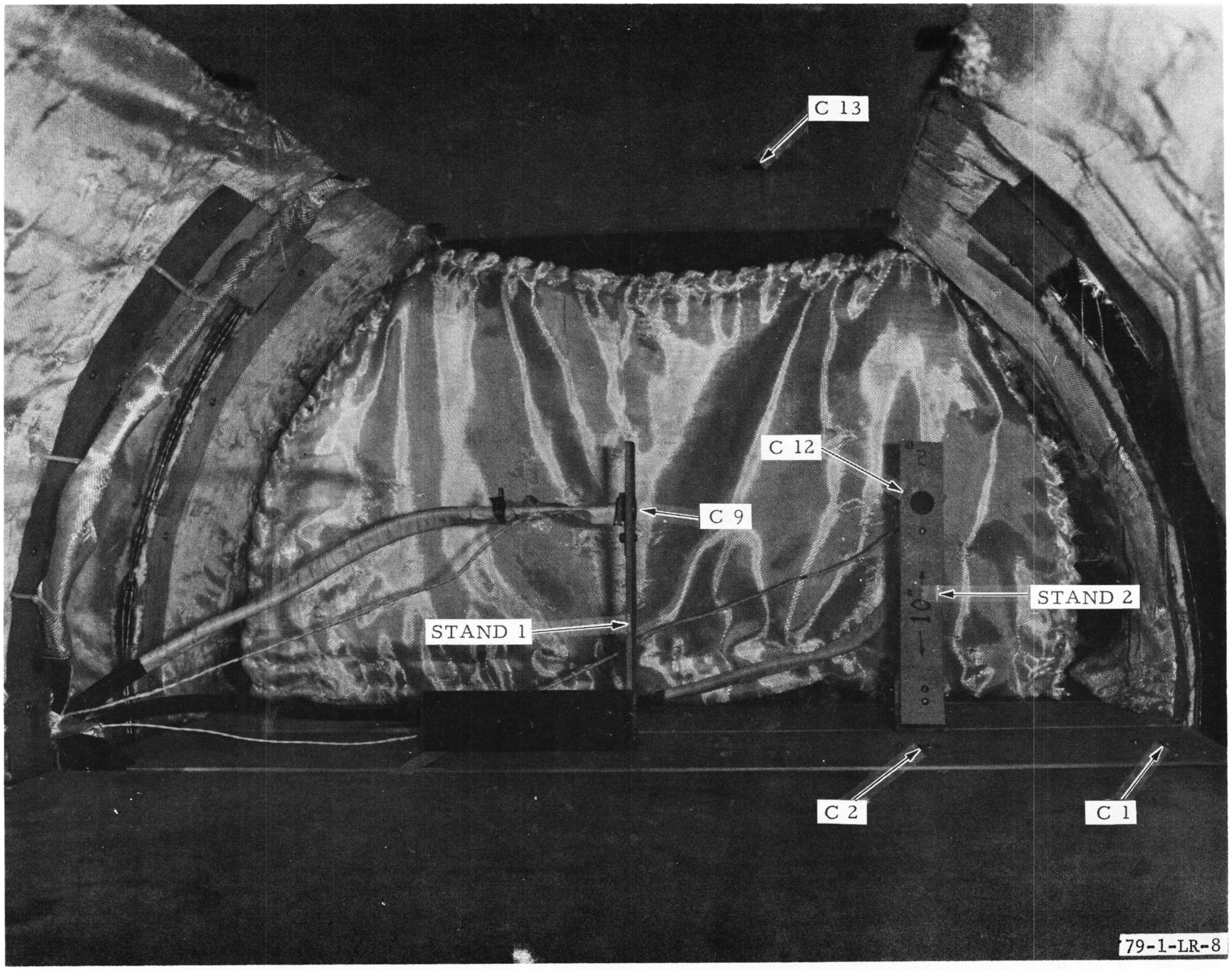

FIGURE 4. INTERIOR CALORIMETERS

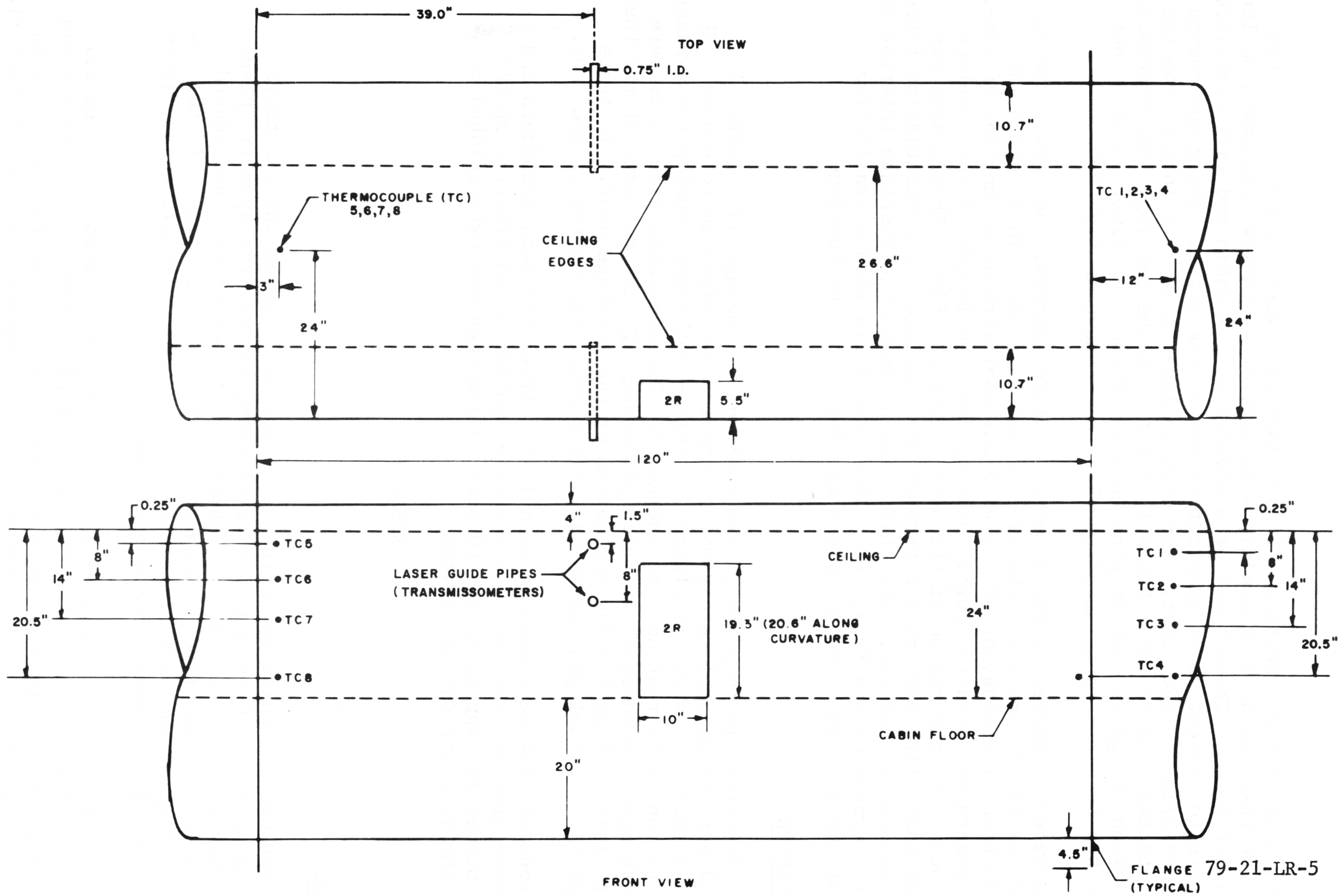

FIGURE 5. THERMOCOUPLE AND TRANSMISSOMETER PLACEMENT

photocells model 856YR. Sections of 0.75-inch pipe were passed through the walls of the fuselage at four positions to provide definitive transmission lengths for the laser beams. These tubes were covered on the cabin end with removable glass covers to prevent smoke penetration within the pipes. The glass covers were cleaned prior to each test. The beam of laser A was 1.5 inches from the ceiling, and the beam of laser B was 8 inches from the ceiling. The transmission length between the glass covered pipe ends was 2 feet for laser A and 3 feet for laser B. External mounting of the lasers is shown in figure 6.

The tests were documented by three motion picture cameras. One movie camera viewed the external fire along the side of the fuselage. This camera was used to document the behavior of the external pool fire as a function of time. A second camera was located roughly halfway down the length of the fuselage and was focused in the region of the door facing the fire. This camera was used to evaluate fire penetration through the fuselage and recirculation fluid dynamics around the doorway. The third camera viewed the fuselage interior from outside the window on the front end. This camera provided a qualitative measure of obscuration by smoke across the length of the fuselage.

TEST PROCEDURE.

The tests described in this report are numbered 50 through 55. Tests 1 through 49 were of an exploratory nature and are described in reference 4. The model interior is shown in figure 7. The 4-foot-square fuel pan was placed adjacent to the right rear door of the model. The remaining five doors were closed with aluminum covers. In tests 50 through 52, the top edge of the fuel pan was positioned 1 inch below the bottom of the fuselage door. In tests 53 through 55, the fuel pan top was 11 inches below the bottom of the door.

Four gallons of JP-4 were used in each test. After the data recorders and cameras were started, the fuel was remotely ignited by an electric spark. The fire burned for approximately 60 seconds and then was extinguished by CO_2 from the facility Cardox system.

RESULTS

HEAT FLUX.

Table 1 provides a tabulation of the heat flux data during the six tests. After allowing for a 20-second fire development period, the symmetry plane heat flux was generally 1.5 British thermal units per square foot second (Btu/ft^2 s) in the high fire-pan configuration and 1.8 Btu/ft^2 s in the low fire-pan configuration. All six tests were conducted with all doors closed except for the door exposed to the pool fire.

The ceiling heat flux for the high-pan configuration oscillated during all fire tests considerably more than the symmetry plane heat flux. The low-pan configuration resulted in more oscillations at the ceiling than the high-pan configuration, and test 55 also showed a strong continued increase in heat flux throughout the test.

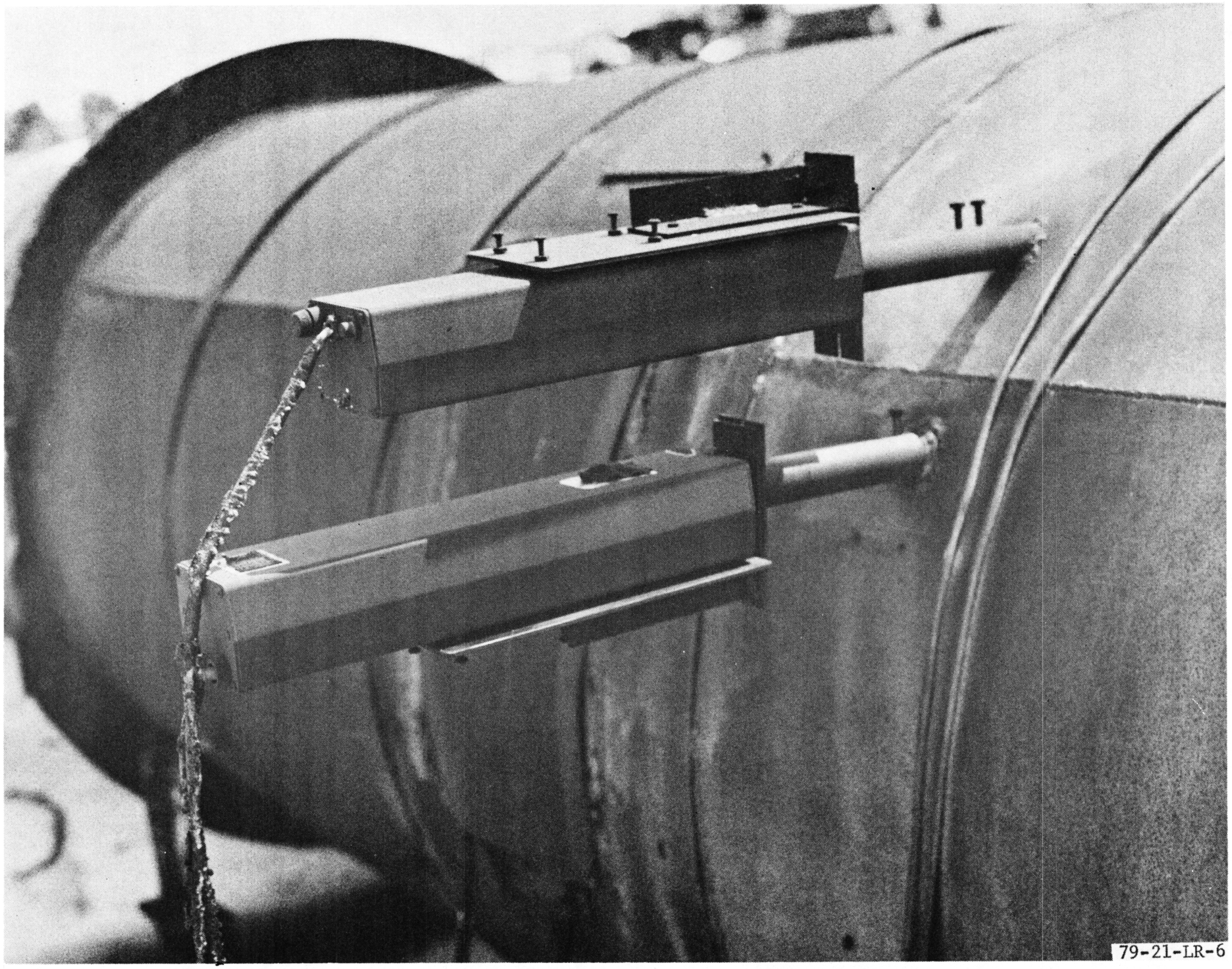

FIGURE 6.   EXTERNAL LASER MOUNTING

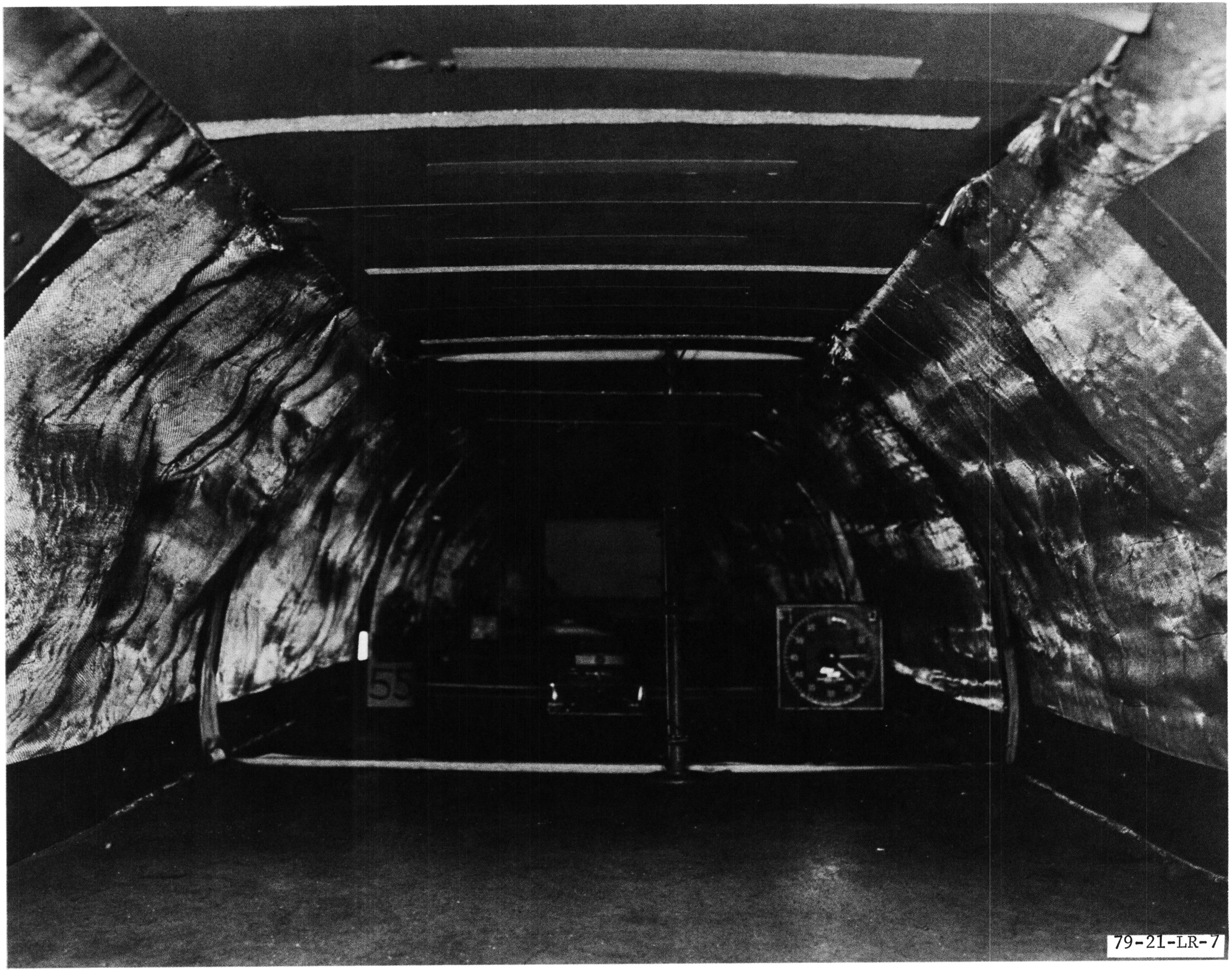

FIGURE 7. INTERIOR VIEW OF MODEL

TABLE 1. HEAT FLUX TO CABIN INTERIOR

Heat Flux (Btu/ft^2 s) at Various Times (Seconds) into Test after Fuel Ignition

Test Run	Calorimeter Identity	10	20	30	40	50	60
50	C-9 *	0.9	1.3	1.5	1.4	1.5	1.3
	C-13 **	0.3	0.4	1.0	1.2	1.4	1.2
51	C-9	0.8	1.4	1.5	1.5	1.5	1.5
	C-13	0.3	0.6	1.0	1.2	1.5	1.4
52	C-9	0.9	1.5	1.5	1.5	1.5	1.5
	C-13	0.5	1.2	1.0	1.1	1.7	1.8
53	C-9	0.8	1.5	1.7	1.9	1.8	1.8
	C-13	0.4	1.4	1.5	1.9	2.6	2.2
54	C-9	0.7	1.5	1.7	1.8	1.8	1.9
	C-13	0.3	1.1	1.4	1.2	1.5	2.1
55	C-9	0.7	1.3	1.8	2.0	2.1	2.0
	C-13	0.4	0.8	2.6	3.8	4.2	4.2

* Midplane calorimeter
** Ceiling calorimeter

In all tests, the symmetry plane heat flux showed little oscillation and a normally low-level increase throughout the test. The 60-second value was within 0.2 Btu/ft^2 s of the 30-second value in each test. The ceiling heat fluxes showed a much broader spectrum of values during the tests, and these variations are due to the oscillating nature of the flame penetration at the doorway. Examples of doorway fire pulsations are shown on a frame by frame time basis (one frame is 0.04 seconds) in figure 8 for test 50 and figure 9 for test 55. These pulsations are of a periodic nature and characteristic of pool fires in a quiescent environment. While the period of these pulsations at the ceiling is short, the variations described in the ceiling heat flux data seem to be much larger in period and related to the amount of hot gas entering the fuselage interior during each of these pulsations.

TEMPERATURE.

Figure 10 shows a plot of the temperature shown by TC 5 as a function of time for each of the six tests. The temperature is given as ΔT, which is defined as the increase in the TC temperature during the test. Two things are apparent from this figure. First, the low-pan configuration (tests 53, 54, and 55) creates a greater interior temperature hazard than does the high-pan configuration. Second, the high-pan configuration results in temperature buildups that are more repeatable between tests. The reason for this, presumably, is that the fire plume instability is more pronounced at higher positions in the fire plume, and this plume instability affects the variation in hot combustion products entering the fuselage.

Because of the short test duration, the lower thermocouples (numbers 6, 7, and 8) showed little temperature increase during any of the tests. Figure 11 shows temperature versus height for several times during test 50. The ceiling temperature (TC 1) at the front thermocouple tree showed an average temperature increase of 28° Fahrenheit (F) at the end of tests in the high-pan configuration and an average increase of 49° F in the low-pan configuration. Since TC 5 showed temperature increases in excess of 100° F in all tests, the hot gases are significantly cooled by conduction to the ceiling and/or by mixing with unvitiated air as these gases move along the fuselage ceiling away from the fire.

SMOKE.

All six tests would have been characterized by heavy smoke or total obscuration along the length of the fuselage according to the discussion of reference 4. Table 2 shows the transmission data at various times during the test, while table 3 shows the corresponding optical densities. Although the top transmissometer (laser A) showed very low transmission values for both the high-pan and low-pan configuration, the lower transmissometer (laser B) demonstrated a significantly greater smoke buildup in the low-pan configuration.

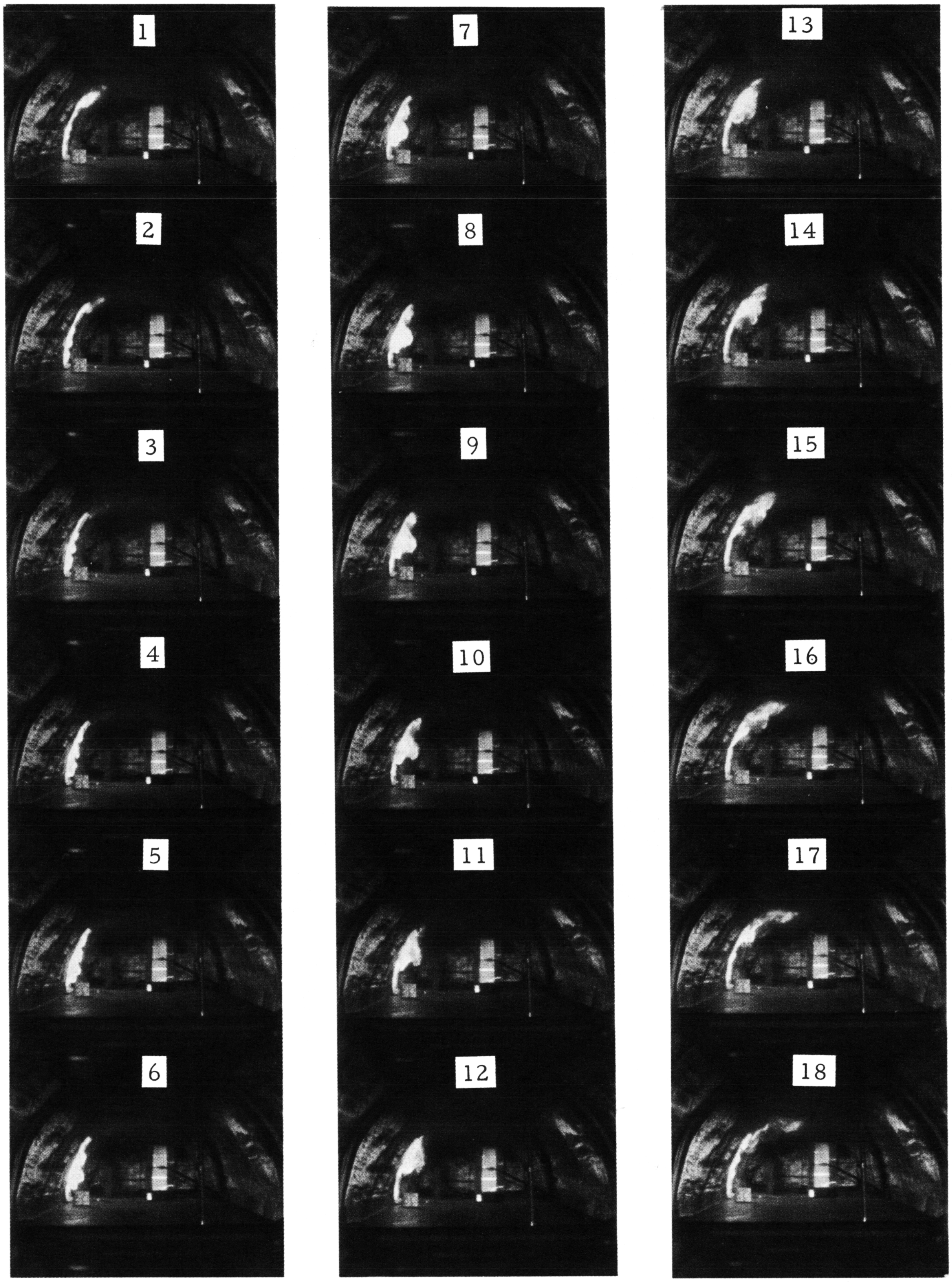

FIGURE 8. DOORWAY FIRE PULSATIONS (TEST 50) 79-21-LR-8

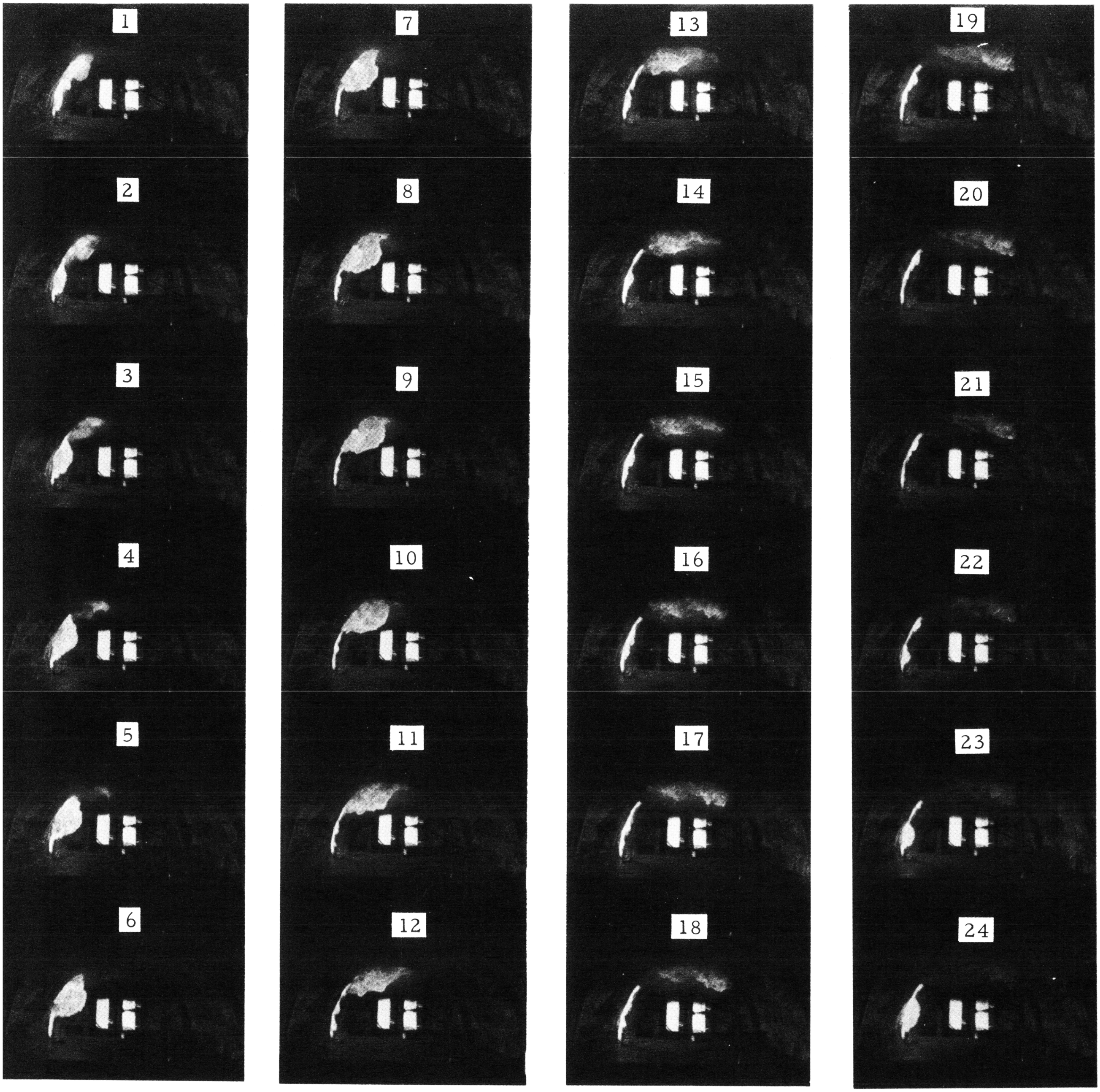

FIGURE 9. DOORWAY FIRE PULSATIONS (TEST 55)

79-21-LR-9

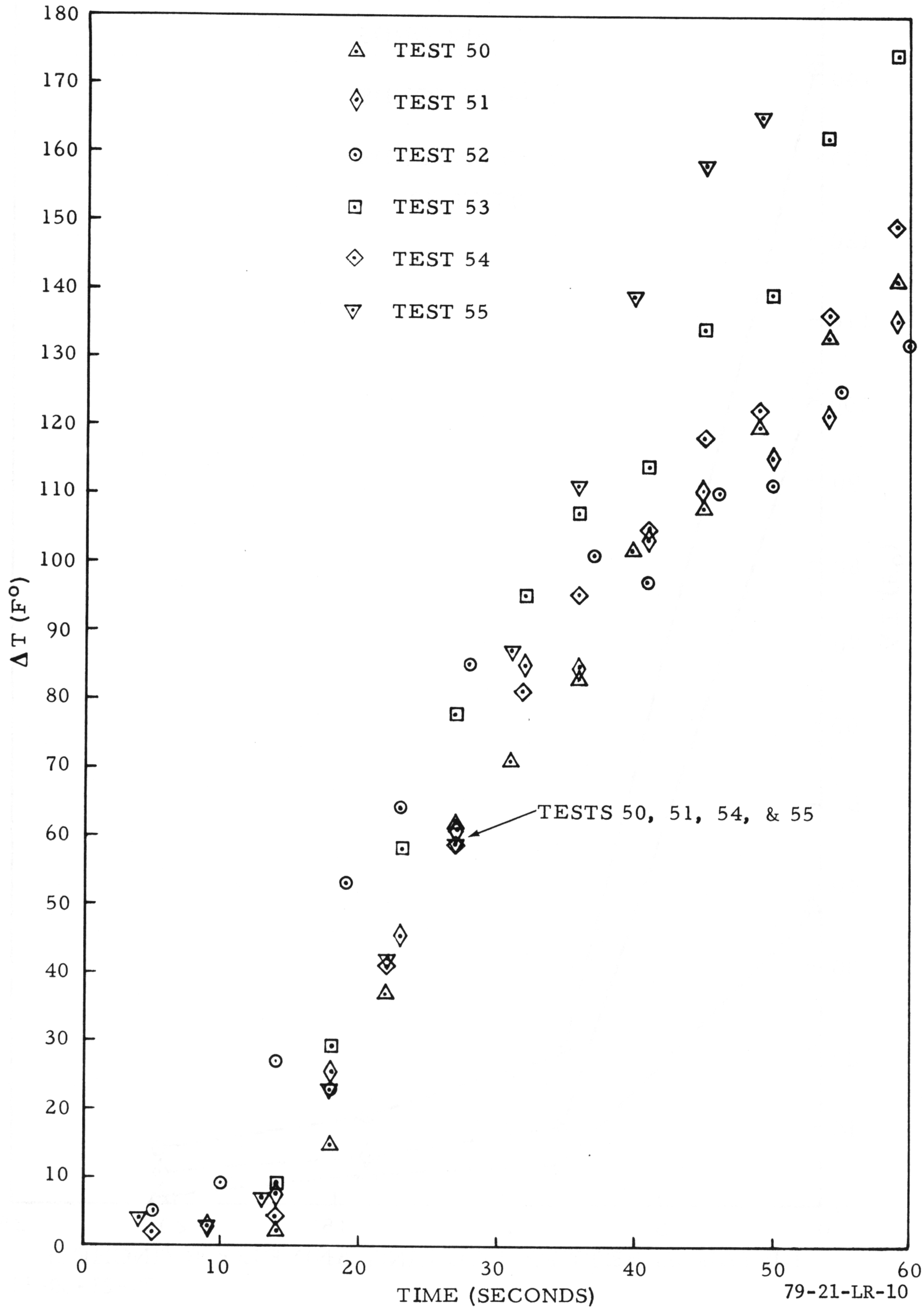

FIGURE 10. CEILING TEMPERATURES

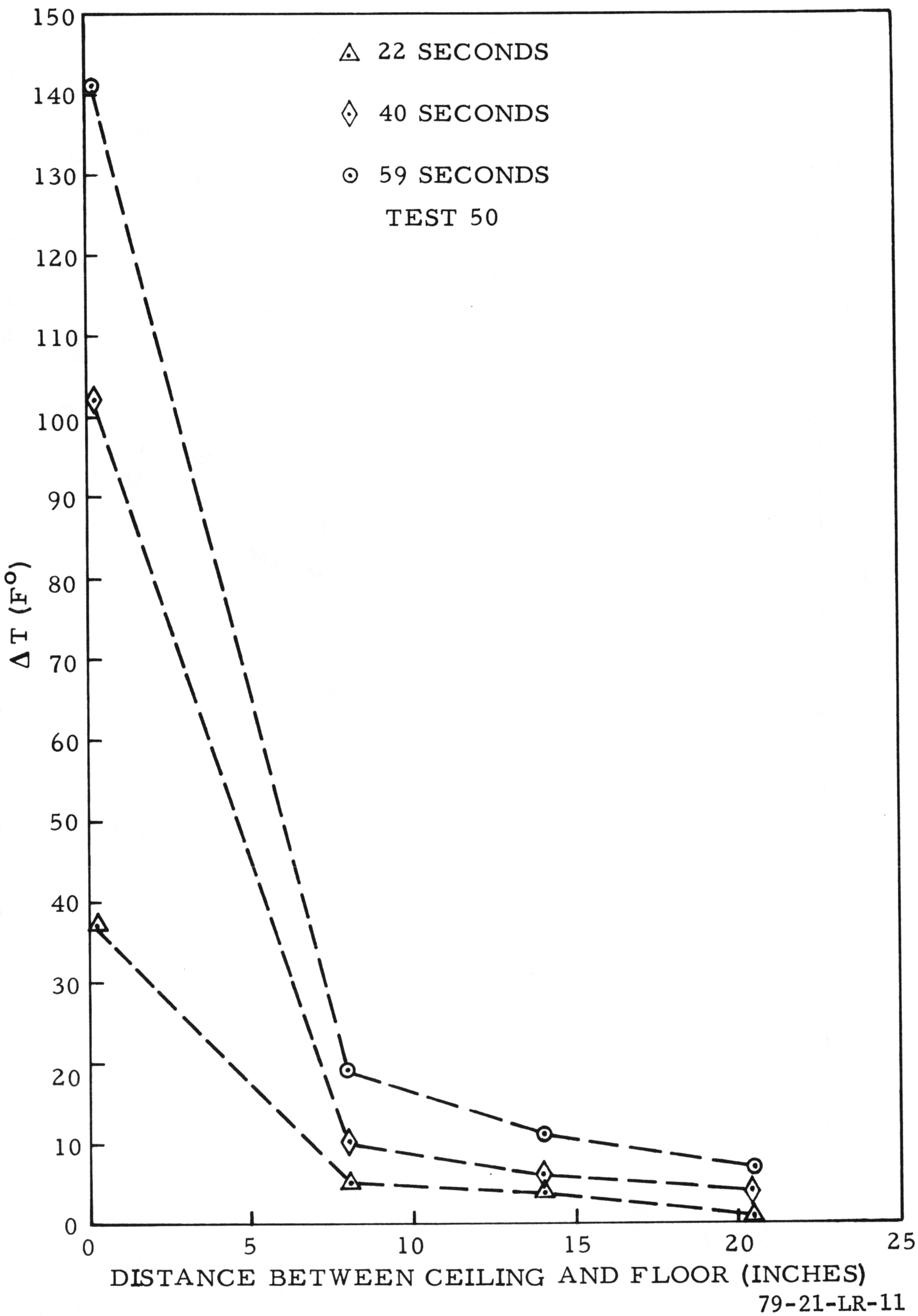

FIGURE 11. TEMPERATURE STRATIFICATION

TABLE 2. LIGHT TRANSMISSION DATA

Laser Transmission (Percent) at Various Times (Seconds) into Test after Fuel Ignition

Test Run	Laser Identity	10	20	30	40	50	60
50	A *	99	35	21	13	14	14
	B **	100	98	89	90	70	54
51	A	96	21	12	9	9	9
	B	100	98	84	87	69	40
52	A	63	12	14	11	9	12
	B	100	98	86	80	46	37
53	A	68	20	13	11	10	10
	B	100	99	91	44	17	16
54	A	78	21	11	12	10	8
	B	100	99	95	55	20	18
55	A	89	24	9	9	8	8
	B	100	99	88	77	24	8

* Top Laser (transmission length is 2 feet.)
** Bottom Laser (transmission length is 3 feet.)

TABLE 3. OPTICAL DENSITIES

Optical Density per Foot at Various Times (Seconds) into Test after Fuel Ignition

Test Run	Laser Identity	10	20	30	40	50	60
50	A	0.00	0.23	0.34	0.44	0.42	0.42
	B	0	0	0.02	0.02	0.05	0.09
51	A	0.01	0.34	0.46	0.52	0.52	0.52
	B	0	0	0.03	0.02	0.05	0.13
52	A	0.10	0.46	0.43	0.48	0.52	0.46
	B	0	0	0.02	0.03	0.11	0.14
53	A	0.08	0.35	0.44	0.48	0.50	0.50
	B	0	0	0.01	0.12	0.26	0.27
54	A	0.05	0.34	0.48	0.46	0.50	0.55
	B	0	0	0.01	0.09	0.23	0.2
55	A	0.03	0.31	0.52	0.52	0.55	0.55
	B	0	0	0.02	0.04	0.21	0.37

CONCLUSIONS

Evaluation of Froude modeling concepts indicates that they are applicable to the behavior of an external pool fire. The six tests of hazard development in a model fuselage from an external pool fire lead to three additional conclusions:

1. The scale model tests in a quiescent environment are highly repeatable.

2. The fuselage interior hazard from heat and smoke is more severe when the fire source is placed below the door bottom than when the fire source is level with the door bottom.

3. The temperature and smoke hazards in the model are both characterized by vertical stratification. The hazard at the floor is much slower in development than the hazard at the ceiling. Furthermore, there are significant decreases in temperature at the ceiling as the distance from the fire opening increases.

4. The laser transmissometers were found to be well defined and trouble-free for use in model fire can tests.

Further information can be obtained from Thor I. Eklund, ANA-420, (609) 641-8200, extension 2322.

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APPENDIX

FROUDE MODELING THE EXTERNAL FIRE

In Froude modeling, the Froude number, $W_o^2 T_\infty / Lg \Delta T$, is held constant in the fire scenario as the scenario is scaled up or down in size. In this definition of Froude number, W_o is a characteristic velocity, T_∞ is the ambient temperature, L is a characteristic length in the scenario, g is the acceleration due to gravity, and ΔT is the temperature increase of gas due to combustion.

In many fire studies of enclosures (e.g., a room fire), the enclosure dimensions are scaled down on a length basis. For instance, a 1/4-scale model would have the length, width, and height of the full-scale enclosure divided by four to get the model dimensions. The burning area may or may not be scaled by the same factor depending on whether forced or free convection controls the characteristic velocity W_o.

For an out-of-doors pool fire, the enclosure might be considered infinite in dimensions. If an aircraft fuselage were exposed to the pool fire, bringing the test to 1/4-scale would involve reducing the length and diameter of the fuselage by one-quarter. The length, width, and height of the imaginary out-of-doors enclosure containing the fuselage and fire would still remain infinite. This conceptual approach is given credibility by the fact that free-burning pool fires do scale down reasonably well provided that they are large enough to be turbulent (3 feet in diameter) and large enough to be radiatively thick (3 to 10 feet in diameter or greater).

In the case of an aircraft fuselage subjected to a pool fire in the presence of wind, holding the Froude number constant as the fire scenario is scaled down requires the following equality:

$$\frac{W_o^2}{L} = \frac{W_m^2}{L_m} \qquad (1)$$

In equation 1, W_o is the full-scale scenario windspeed, L is a characteristic dimension of the full-scale fuselage, W_m is the windspeed in the scaled down test, and L_m is a characteristic length of the model fuselage. Equation 1 can be rearranged to form the following:

$$W_o = W_m \left(\frac{L}{L_m}\right)^{1/2} \qquad (2)$$

Thus, for a 1/4-scale model with a 1/4-scale fuel bed, a 10 mile per hour (mi/h) wind in the model test would correspond to a 20 mi/h wind in a full-scale test. Such a scaled fire should show identical properties to the corresponding full-scale scenario such as flame tilt angle and steady heat transfer to the fuselage.

The development of equation (2) assumes a steady and laminar wind. In fact, low-level winds are invariably turbulent. The interaction of the large-scale turbulent eddies with the two different fuselage scales could result in intractable fluid mechanical effects that would invalidate equation 2. An additional complication to some scenarios is the wake region of the fuselage. Froude modeling ignores viscosity and, hence, Reynolds number. The wake of a cylinder goes through a number of regimes characterized by the Reynolds number. The Reynolds number of the 1/4-scale model will be one-eighth the Reynolds number of the corresponding full-scale fuselage providing that the full-scale velocity is twice the 1/4-scale velocity.

In the case of a free-burning pool fire with the ambient wind velocity equal to zero, the characteristic velocity of the Froude number must be developed from the fire plume itself. Following the development of reference 8, the heat release rate of the pool fire can be written as:

$$Q = \rho C_p \, \Delta T \left(\pi \frac{d^2}{4} \right) u \qquad (3)$$

Where Q is the heat release rate of the pool fire, ρ is the density of the fire plume gases, C_p is the fire plume specific heat at constant pressure, ΔT is the temperature of the plume over ambient temperature, d is the diameter of the burning surface (assumed circular), and u is the fire plume velocity. The density temperature product can be manipulated so that:

$$\rho \, \Delta T = T_\infty \, \Delta \rho \qquad (4)$$

where T_∞ is the ambient air temperature and $\Delta \rho$ is the difference between the ambient density and the plume density. Inserting (4) in (3) and solving for u produces equation 5.

$$u = \frac{Q}{C_p \, T_\infty \, \Delta \rho \left(\frac{\pi d^2}{4} \right)} \qquad (5)$$

Using the definition of Froude number, Fr, and inserting (5).

$$Fr^{1/2} = \frac{\rho^{1/2} \, Q}{C_p \, T_\infty \, \Delta \rho \frac{\pi d^2}{4} (\Delta \rho g L)^{1/2}} \qquad (6)$$

Multiplying both sides of equation 6 by $\frac{\pi}{4} \frac{d^2}{L^2} \frac{\rho}{\rho_\infty} \left(\frac{\Delta \rho}{\rho} \right)^{3/2}$ and cancelling appropriate terms leads to equation 7.

$$\frac{\pi}{4} \frac{d^2}{L^2} \left(\frac{\rho}{\rho_\infty} \right) \left(\frac{\Delta \rho}{\rho} \right)^{3/2} Fr^{1/2} = \frac{Q}{\rho_\infty C_p T_\infty g^{1/2} L^{5/2}} \qquad (7)$$

In reference 8, when d/L is assumed some constant ratio, then the result found in references 8 and 9 follows.

$$Q \sim L^{5/2} \tag{8}$$

With this particular approach to Froude modeling, the pool fire does not scale down with other characteristic lengths. In fact, since Q is related to area of the fire in the case of large pool fires, equation 8 can be rewritten in the following two formats:

$$\frac{d^2}{d_m{}^2} \sim \left(\frac{L}{L_m}\right)^{5/2} \tag{9}$$

$$d \sim d_m \left(\frac{L}{L_m}\right)^{5/4} \tag{10}$$

For example, equation (10) shows that a 1/4-scale model fuselage adjacent to a 4-foot-square fire pan would be equivalent to a 23-foot-square fire pan adjacent to the full-scale fuselage. However, equation 10 could be inserted into the left-hand side of equation 7 and thereby contradict the assumption that d/L is a constant.

In fact, examination of radiation from large pool fires (reference 10) indicates that these large pool fires are self-scaling. Other approaches to Froude modeling such as found in references 6 and 7 indicate that when container geometry is established to model the effects of natural convection, then the pool fire characteristic length scales as the chamber characteristic length or width.

The preferred result for scaling an external pool fire adjacent to a 1/4-scale fuselage would be that the characteristic dimension of the fuselage is scaled linearly with the characteristic dimension of the pool fire and that a characteristic velocity of the pool fire automatically be related to the square root of the pool fire characteristic dimension by some constant factor. This would yield a scaling relationship identical to equation 2. Even for the case of zero ambient winds, pool fire analyses are generally steady state (e.g., reference 11). In fact, pool fires under zero wind are characterized by pulsating flames the period of which increases with increasing diameter (reference 12). If the zero-wind pool fires truly self-scale, then the flame-height-to-pool-diameter ratio (a/d) would be a constant. In fact, a/d is a function of the Froude number and shows an observable decrease over the range of pool diameters under consideration. Reference 11 presents a suitable descriptive equation.

$$\frac{a}{d} = 2.6\ d^{-1/3} \qquad (11)$$

Nevertheless, for the aircraft pool fire, the assumption will be made that, as the pool fire increases in characteristic dimension above 3 feet in width or diameter, the Froude number will remain constant. As a result, the characteristic velocity W, will be proportional to the square root of the pool fire size, d, or fuselage diameter D.

Viewing the fire behavior this way is of importance if wind-blown pool fires are to be evaluated along with steady state pool fires. When the zero-wind pool fire is considered self-scaling, then W is proportional to the L for all cases. Then, the pool fire size and fuselage size all scale in the same proportion to full scale. If this viewpoint were not taken, then as the fuselage was reduced to 1/4-scale, the pool fire would be 1/4-scale in the wind case and some other scale in the zero-wind case. Since it is not at all clear at what respective wind velocity and pool size the wind velocity would actually be the dominant characteristic velocity, for a range of wind velocities from zero on up, the pool fire scale would be an unknown.

Thus, in this work, the pool fire characteristic length and fuselage model diameter are considered as the same fraction of their corresponding full-scale dimension. Furthermore, any winds are treated according to equation 2. This approach, if successful, should guarantee similitude between small scale and full scale on the following parameters, so long as the model fire is large enough:

1. Bending of the fire over the fuselage,

2. Flattening of the fire against the fuselage, and

3. Radiant heat transfer to the model.

For all practical thermal purposes, the model should experience the same hazards to its exterior as the full-scale counterpart.

FROUDE MODELING THE INTERIOR HAZARD

Substantial information is available on Froude modeling of interior hazards. If the procedures of references 6 and 7 provide a precedent, the external fire should provide a reasonably scaled convective heat flux to the fuselage interior. Studies of hazards in model corridors (reference 5) indicate that useful information can be derived from models with large length to diameter ratios.

The doors in a model fuselage are equivalent to windows in many model enclosure fires. Even though the fuselage door at the fire can be geometrically scaled, any other open doors may have to be scaled differently for accurate Froude modeling. For instance, reference 7 shows best results with window sizes scaled as:

$$w_m h_m^{3/2} = \left(\frac{L_m}{L_f}\right)^2 w_f h_f^{3/2} \qquad (12)$$

where w and h are window width and height, respectively, L is the length of the test enclosure, and subscripts m and f refer to the model and prototype, respectively. Furthermore, reference 7 shows the height of the model, H_m, is best scaled by the following relationship:

$$H_m^{3/2} = \frac{L_m}{L_f} H_f^{3/2} \qquad (13)$$

Thus, given a fuel source (or doorway at the fire), it is possible that the model height and dimensions of other openings may have to be scaled in some nongeometric fashion for best results.

Most model enclosure studies have been performed with no external winds. However, reference 4 clearly shows the importance of wind in hazard buildup within a model fuselage. The behavior of wind on a fuselage internal circulation without fire can be attacked by viewing the fuselage as a cylinder in a crosswind. The pressures at the various doors could be found by cylinder pressure distribution data. Flow through the fuselage would involve judicious choice of orifice coefficients for the doorways or treatment of the flow through the cabin (reference 13).

In spite of the many considerations associated with properly scaling post-crash aircraft fires, the simplest approach is to scale down all characteristic lengths in a geometric fashion. In the studies reported here, all dimensions are 1/4 scale. Viewing Froude modeling literature as a whole, it is apparent that a number of scaling techniques can be employed, and the only true measure of success is agreement with specific full-scale results.

The effects within the cabin model most likely to give results divergent from full-scale are two. First, for small-scale fires, any fire penetration due to wind will have a lower radiative output than its full-scale counterpart. Reference 3 provided adequate radiative flux by maintaining a minimum fire size and minimum fire-size-to-fuselage-diameter ratio. However, this was a special zero-wind scenario that involved no fire penetration through the door. In contrast, many of the tests reported in reference 4 involved wind and consequent fire penetration through the door and towards the ceiling. If in full-scale, a ceiling fire penetration were 2 feet thick, the corresponding model fire penetration would be 1/2 foot deep and give less radiation to the floor than precise scaling would demand. The second possible inadequacy is the large length-to-diameter ratio of the fuselage. This could result in a disproportionately large fraction of the heat convectively entering the cabin being lost to the ceiling of the model by conduction.

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