NBSIR 82-2537

An Assessment of Correlations Between Laboratory and Full-Scale Experiments for the FAA Aircraft Fire Safety Program, Part 5: Some Analyses of the Post Crash

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Center for Fire Research
Washington, DC 20234

and

Building Research Institute
Japan

July 1982

Sponsored by:
U.S. Department of Transportation
Federal Aviation Administration
Technical Center
Atlantic City Airport, NJ 08405

ERRATA

NBSIR 82-2537 Quintiere, J.G. and Tanaka, T. "An Assessment of Correlations Between Laboratory and Full-Scale Experiments for the FAA Aircraft Fire Safety Program, Part 5: Some Analyses of the Post Crash."

p. 7 Table 1 CABIN TEMPERATURE DEPENDENCE ON POOL FIRE AND CABIN FIRE

line 2 , column 3 , should read 85

line 3 , column 3 , should read 70

NBSIR 82-2537

AN ASSESSMENT OF CORRELATIONS BETWEEN LABORATORY AND FULL-SCALE EXPERIMENTS FOR THE FAA AIRCRAFT FIRE SAFETY PROGRAM, PART 5: SOME ANALYSES OF THE POST CRASH

James G. Quintiere

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Center for Fire Research
Washington, DC 20234

and

Takeyoshi Tanaka (Guest Worker)
Building Research Institute
Japan

July 1982

Sponsored by:

U.S. Department of Transportation
Federal Aviation Administration
Technical Center
Atlantic City Airport, NJ 08405

U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, ***Secretary***
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, ***Director***

ABSTRACT

An attempt is made to develop mathematical predictions for various aspects of the dynamics of post crash aircraft fires. The basis of the analysis is the experimental simulation scenario under study by the FAA. The effects of wind are considered as well as the effect of interior and exterior fires. Suggestions are presented for estimating cabin door flow rates from measured temperatures.

Keywords: Doorway flows, mathematical modeling, post crash aircraft fires, wind effects

TABLE OF CONTENTS

LIST OF TABLES

ACKNOWLEDGEMENT

This study was sponsored by the Fire Safety Branch of The Federal Aviation Administration Technical Center at Atlantic City, New Jersey. The author gratefully appreciates the advice of Mr. R. Hill, the technical monitor, and also the assistance of Mr. C. Sarkos of the FAA.

INTRODUCTION

PURPOSE

The development of correlations between laboratory test methods and full-scale fire behavior does not only depend on the appropriateness of the laboratory test. The dynamics of the full-scale fire scenario must also be understood, at least in qualitative terms. Part of this insight must come from actual fire simulation experiments. In addition, it is necessary to analyze those data and develop mathematical modeling of at least aspects of the scenario to produce generalized results. Some results of data analysis and modeling will be presented for the wide-body post crash aircraft fire currently under study by the FAA.

BACKGROUND

Full-scale fire studies have been conducted by Brown [1] using a DC7 fuselage and Hill, Johnson and Sarkos [2] using a C133 fuselage. These studies addressed the post crash fire scenario by considering a large external fuel pool fire adjacent to an open cabin door. Various temperature, heat and gas data were collected, and the effect of external ambient wind conditions, pool size and door openings were examined. Eklund and Wright [3] did a small scale study to examine the effect of door location relative to the pool fire. Stuart [4] presented an analysis based on Bernoulli's equation, for computing the air flow rate through cabin door openings due to wind effects. More recently Emmons [5] presented a more complete mathematical analysis of the ingestion of fire gases into the cabin door opening. He proposed methods to include the entrainment effect of the external fire, the capture of pool fire gases due to plume expansion, and the flow due to pressure differences inherent in the wind flow. The "capture" phenomenon is very complex and, in fact, manifests itself as a pulsation of flames at the cabin door [6]. Modeling this effect may require further attention. Nevertheless an understanding of the processes can be developed through these mathematical modeling concepts, and these concepts have been used in the analyses which follow.

ANALYSIS OF WIND EFFECTS

The experimental study by Hill et al. [2] will be used as a source of data and a basis for analysis. A schematic of that experiment is shown in Figure 1 in a somewhat distorted form. For ease in illustration the doors are shown on the ends, the cabin is considered rectangular in cross-section, and the wind is directed normal to the fire door while the exit door experiences ambient pressure since it was baffled from the wind. The objective will be to construct some appropriate models and perform some sample computations to illustrate the dynamics of the transport of heat and mass in the aircraft as a function of wind conditions, and external and internal fire sizes for this port crash scenario.

The first approach taken was to attempt a correlation for the cabin temperature data (at time t = 240s) given in Figure 16-18 of reference [2]. These data represent the cabin upper gas temperature due to various wind conditions and various external pool fire dimensions. Since the external fuel fire has large flame dimensions relative to the doorway, it was assumed that the rate of energy release in the cabin is controlled by the rate of air flow into the cabin through the fire door. This flow is actually composed of fuel, air and products and is considered to be fuel rich such that sufficient fuel is available to cause all the air to react.

(1) Flow into the cabin at the fire door was assumed to react in stoichiometric proportion (i.e. burning is air controlled) such that the rate of energy added to the cabin from the pool fire due to pressure differences is

$$\dot{Q}_i = \frac{\dot{m}_i \ \Delta H}{(r+1)} . \tag{5}$$

The flow rate $\dot{m}_i$ and the energy release rate $\dot{Q}_i$ enter the hot layer of the cabin compartment in Tanaka's model [6].

(2) Flow at each door is governed by the existing pressure differences. The fire door is affected by pool fire entrainment and wind if present. The entrainment effect is negative causing flow out. The exit door has normal ambient pressure (p_∞) imposed outside the cabin. The external pressure imposed at the fire door is given by superposition of wind and pool fire effects:

$$p = p_\infty + \frac{1}{2} \rho_o V_w^2 - \frac{1}{8\pi^2 \rho_o R^2} \left(\frac{d\dot{m}}{dz}\right)^2 \tag{6}$$

R is the plume radius, z is the height and $\dot{m}$ is the plume flow rate. The last term in Eq. (6) results from an application of Bernoulli's equation to a streamline starting from rest and extending to the fire plume. McCaffrey's [7] entrainment model was used where rate of entrainment,

$$\dot{m} = \dot{Q}_p \times \begin{cases} 0.053\xi^{1.3}, & \xi < 0.2 \\ 0.063\xi^{5/3}, & \xi > 0.2 \end{cases} \tag{7}$$

where $\xi = z/\dot{Q}_p^{2/5}$ and $\dot{m}$ (kg/s), $\dot{Q}$ (kW), z(m).

For the external pool fire it follows that $\xi < 0.2$ and

$$\frac{d\dot{m}}{dz} = 0.137 \ \dot{Q}_p^{0.48} \ z^{0.3} \tag{8}$$

and $R = \sigma \ln m$, $m=10.$, $\sigma=0.128z + 0.0062\dot{Q}^{2/5}$ with $\dot{Q}_p$ (kcal/s).

(3) Two cases were computed.

Case a. Wind is considered and a net heat addition due to the "capture" or pulsating flame phenomenon is specified as a fixed rate of fuel ($\dot{m}_p$) available at the fire door. A stoichiometric amount of air is also added. A 4 x 6 ft (2.16 m^2) pool fire was used.

Case b. An internal cabin fire is specified ($\dot{m}_p$) which would simulate the ignition of cabin furnishings. The effect of fire location is not accounted for by this model. No wind or flame pulsation effects were considered, although they could in principle be included. Both 6 x 8 ft (4.5 m^2) and 8 x 8 ft (5.0 m^2) pool fires were used. The following property values and data were used for the cabin geometry in Figure 1.

It should be possible to utilize this technique in the FAA post crash fire experimental facility. The establishment of confidence in this model would lead to the prospect of considering a more realistic fire spread scenario. Such an analysis would be desirable in developing correlations between performance of materials in the post crash experiments and test method data. It is clear, however, from these calculations and observations of the full-scale tests that only some fraction of the energy, smoke, and combustion products from the interior cabin fire is flowing out of the cabin at the fire door. Also when the internal fire becomes large enough, more significant quantities of the pool fire gases are drawn into the cabin. Any correlation strategy, assessment of human tolerance levels in the cabin or egress potential at the exit door needs to account for these fire dynamic characteristics.

TABLE 1

CABIN TEMPERATURE DEPENDENCE ON POOL FIRE AND CABIN FIRE

Pool fire Area (m^2)	Cabin fire $\dot{Q}_p$ (kW)	Pool fire enters cabin (s)	Corresponding cabin temperature (°C)	Cabin temperature at 240s (°C)
4.5	2100	∞	-	390
4.5	2520	70	390	480
4.5	2940	85	400	540
6.0	420	∞	–	150
6.0	840	∞	-	230
6.0	1260	∞	-	290
6.0	1680	∞	-	350
6.0	2100	∞	-	390
6.0	2520	∞	-	440
6.0	2940	90	420	540

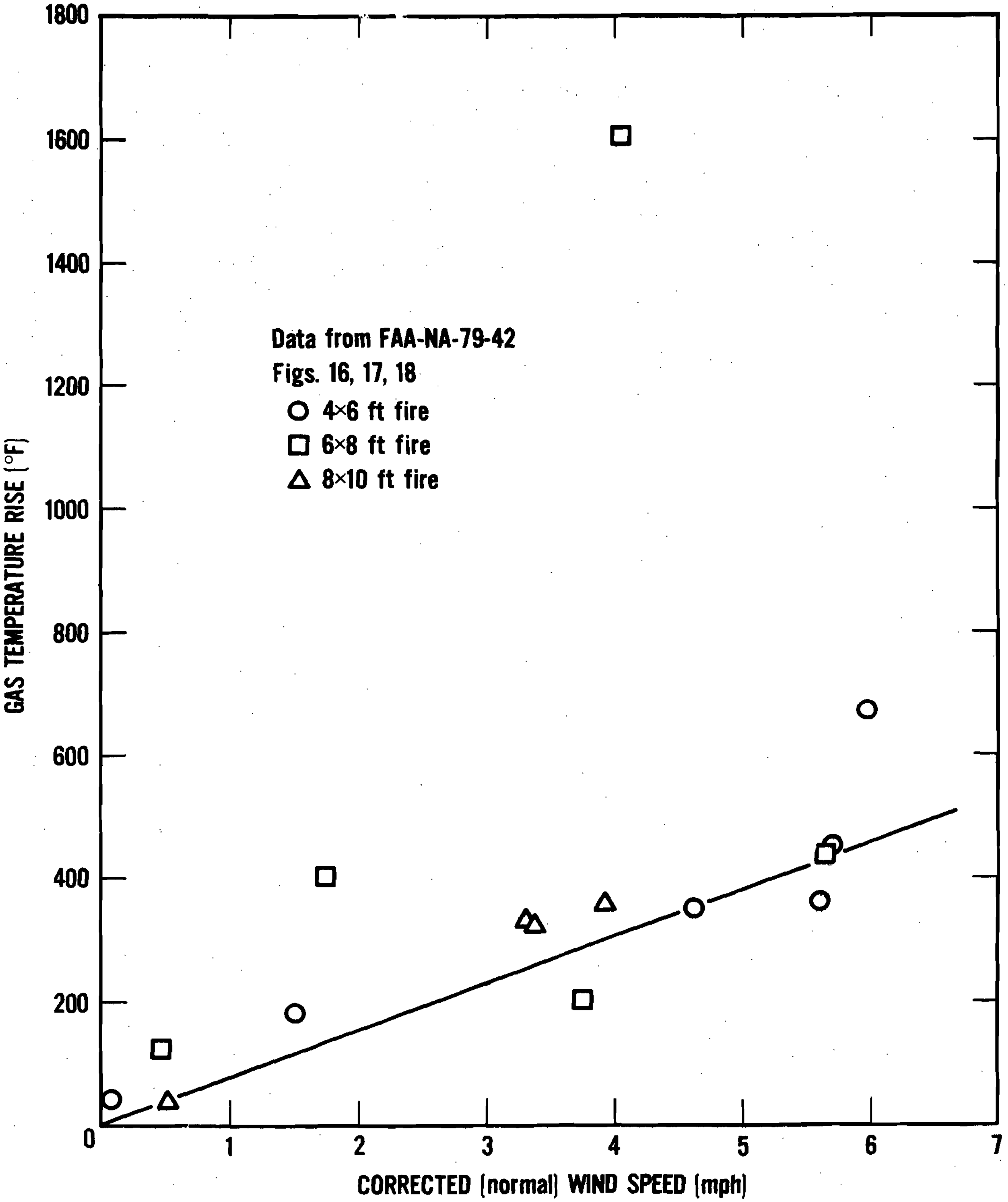

Figure 2 - Cabin Temperature Due to Wind and External Fire

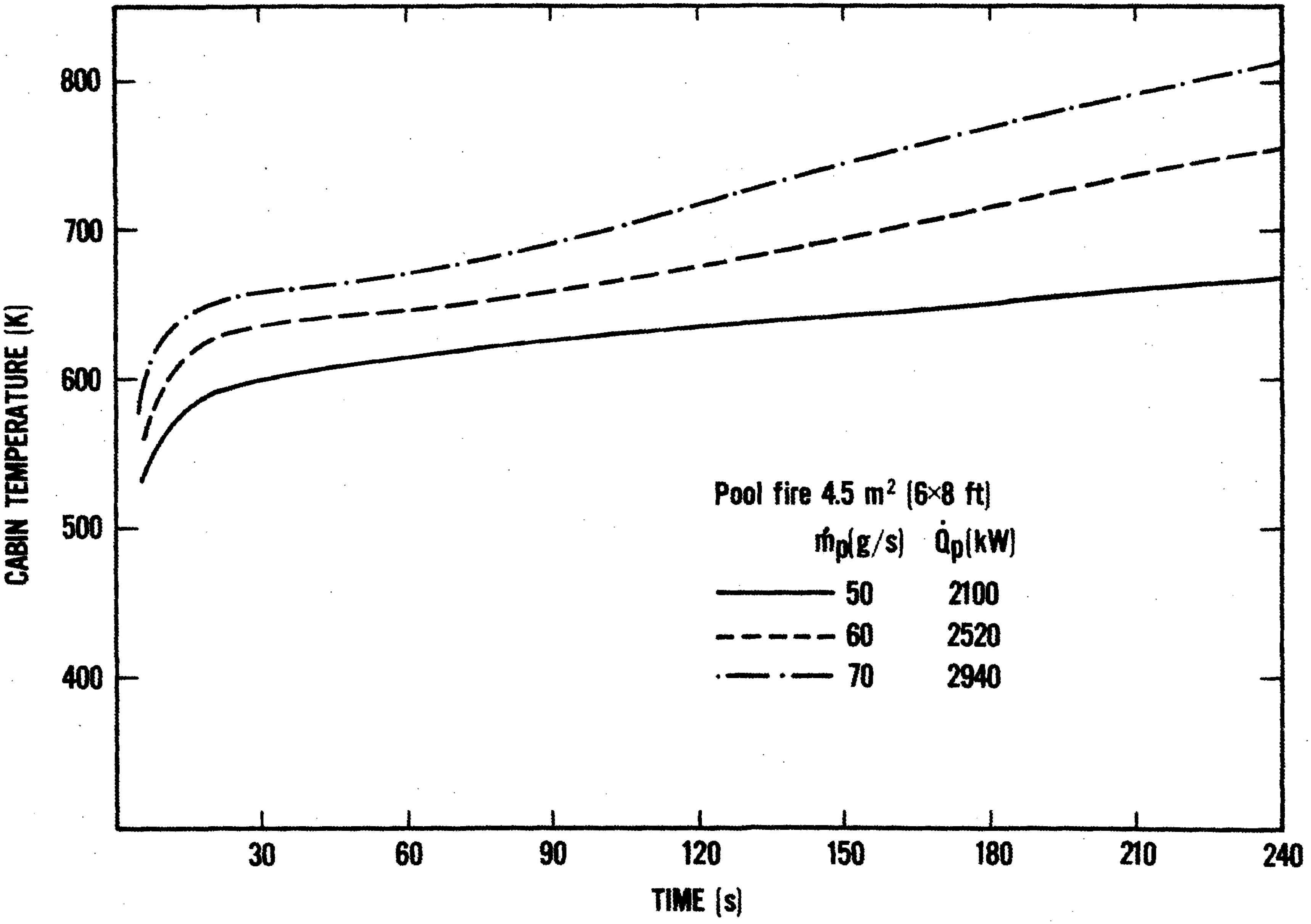

Figure 4 - Predicted Cabin Temperature Due to External Pool Fire and Cabin Fire (No Wind)

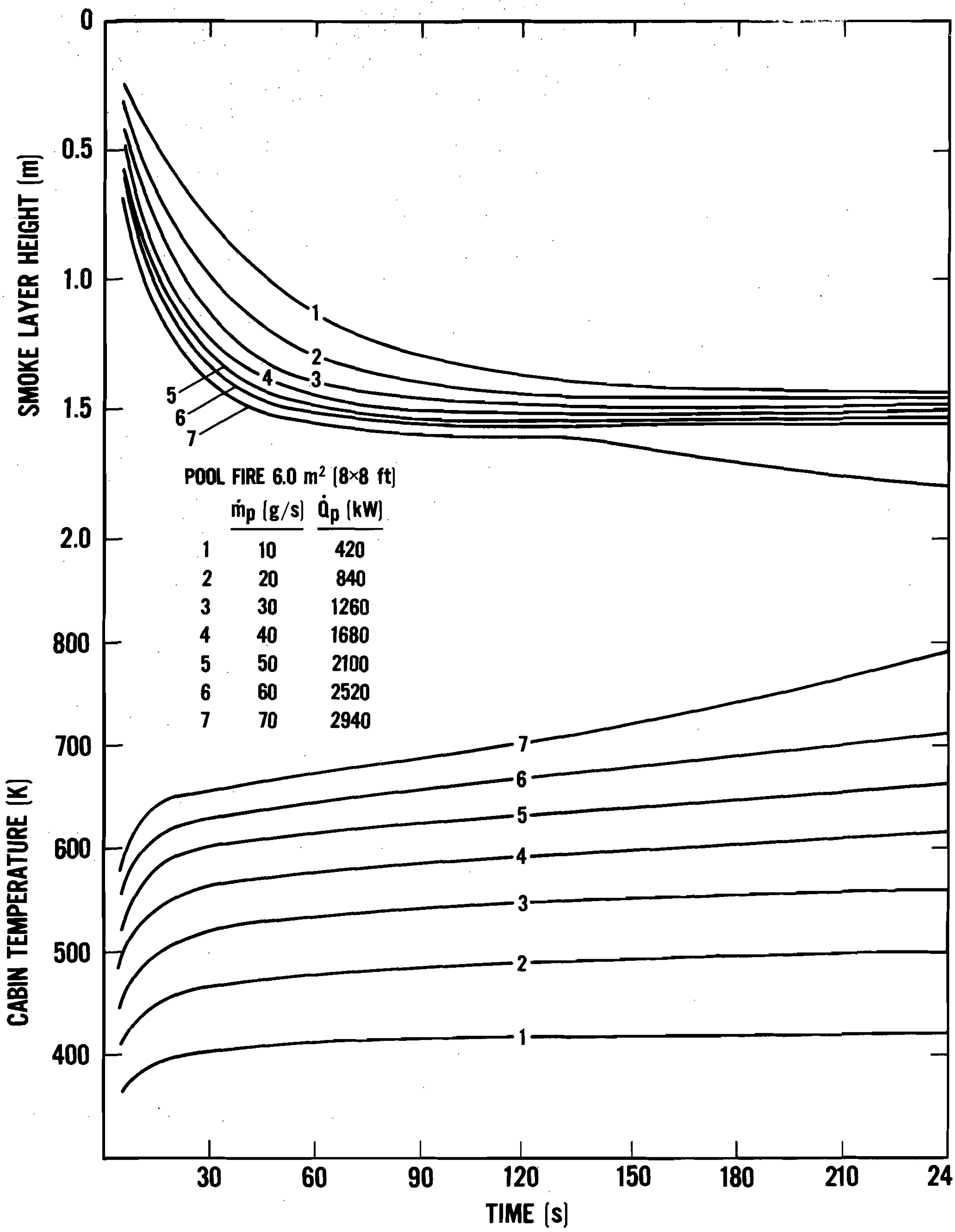

Figure 6 - Predicted Cabin Temperature and Smoke Layer Height for 6.0^2 Pool Fire and Various Cabin Fires

APPENDIX

ESTIMATING DOORWAY MASS FLOW RATES BY TEMPERATURE DATA

It has been shown, for room openings of conventional sizes, that a hydraulics flow model is appropriate for estimating the flow rates [9]. The study by Prahl and Emmons [9] and the recent work of Steckler [8] show that the required flow coefficient for this calculation is 0.7 to within about 15 percent. Moreover, the pressure distribution in a compartment subject to a fire is governed principally by hydrostatics. Therefore the flow across an opening may be determined from temperature data alone and more generally with the additional measurement of a single pressure difference across the opening. This will be described and illustrated below. A vertical opening will be considered but a similar procedure could be applied to a horizontal opening.

Figure A-1 illustrates a vertical opening with known temperature distribution on each side - referred to as "inside" (i) and "outside" (o) for labeling purposes.

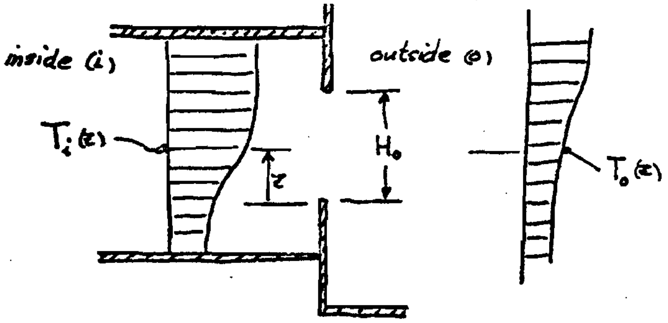

Figure A-1. Conditions at an Opening

The pressure drives the flow across the opening (except for openings that are "large" relative to the enclosure surface area), and is given by hydrostatics. The pressure drop across the opening for any height z is

$$\Delta p_{io}(z) \equiv p_i(z)-p_o(z) = \Delta p_{io}(z_o) - \int_{z}^{z_o} [\rho_o(z)-\rho_i(z)]g\,dz \qquad \text{(A-1)}$$

A reference pressure difference $\Delta p_{io}(z_o)$ must be measured in general. However if the position of flow reversal (i.e. the neutral plane height N) is known, then $\Delta p_{io}(N) = 0$ is the reference pressure. In some cases, N can be determined from temperature measurements in the plane of the opening.

The rate of mass flow, with flow from i to o taken as positive in sign, is given as

$$\dot{m}_{io} = CW_o \int_{z_1}^{z_2} \rho_d(z)\ V\,dz \qquad \text{(A-2)}$$

where W_o is the width of the opening

C is 0.7

ρ_d is the density at the opening (and may be approximated as ρ_i or ρ_o at the corresponding height z)

The limits of integration depend of the sign of Δp_{io}.

Table A-2

Rate of Air Flow Estimated from Temperature Data

$\dot{q}$ (kW)	Opening Configuration	N (m)	T_u (°C)	Estimated $\dot{m}_a$ (kg/s)	Measured [5] $\dot{m}_a$ (kg/s)	Deviation from Measured $\dot{m}_a$ (%)
62.9	4/3 Door	1.08	108	0.660	0.678	-2.7
"	1 "	1.03	117	0.561	0.563	-0.4
"	2/3 "	0.94	126	0.450	0.456	-1.3
"	1/3 "	0.86	165	0.261	0.251	+4.0
158	1 "	0.97	218	0.714	0.688	+3.8
62.9	Full Window	0.63	130	0.494	0.464	+6.5
"	2/3 "	0.42	143	0.293	0.303	-3.3
"	1/3 "	0.19	212	0.125	0.117	+6.8