HSB Professional Loss Control Scott Plaza Two • Suite 422 • Philadelphia, PA 19113-1316 • (215) 521-8975

Electrical Tunnel and Penetration Area Smoke and Hot Gas Analysis For New York Power Authority Indian Point Unit 3 Station Site Specific Input

Prepared By: James M. Dewey Date: 8/9/84

Reviewed By: Wayne D. Holmes Date: 8/11/94

Approved By: Wayne D. Holmes Date: 8/23/94

Rev. 1

August, 1994

Consulting Engineers

9409130129 940906
PDR ADOCK 05000286
F PDR

TABLE OF CONTENTS

1.0 PURPOSE 1

2.0 METHODOLOGY 1

3.0 DESIGN INPUTS/ASSUMPTIONS 2

4.0 CALCULATION 9

5.0 SUMMARY/CONCLUSION 68

6.0 REFERENCES 70

ATTACHMENTS

Attachment 1 - Input Data Routines A1-1
Attachment 2 - Fire Growth Data A2-1

APPENDICES

APPENDIX A - TECHNICAL REPORT ON HAZARD I PROGRAM, "A MULTICOMPARTMENT MODEL FOR THE SPREAD OF FIRE, SMOKE AND TOXIC GASES"

1.0 PURPOSE

The objectives of this analysis are to determine if a fire in one cable tray stack, or a fire involving defined transient combustibles are likely to ignite redundant safe shutdown cables within the electrical tunnel entranceway, and to estimate the "access time" provided in the upper penetration area in the event of these fires.

In order to establish alternate safe shutdown capability at Indian Point 3 during a safe shutdown fire in the entranceway to the electrical tunnels, a plant operator is required to perform manual operations at the instrument isolation cabinets located in the upper penetration area. The upper penetration area and electrical tunnels are located within the same fire area. It has been determined that an operator may require access into the upper penetration area, through the PAB, for up to 45 minutes after the initiation of the fire in the cable tunnel entranceway should the fire involve redundant cable tray stacks. Therefore the potential for a fire to involve redundant cable tray stacks and/or the time to untenability in the upper penetration area from a safe shutdown fire in the cable tunnel entranceway must be estimated and compared to the required access time.

2.0 METHODOLOGY

Ignition of the redundant cable tray stack and time to untenability within the upper electrical penetration area due to a fire in the entranceway to the electrical tunnels were calculated using available fire protection engineering techniques and fire modeling technology. The fire modeling techniques utilized were taken from two programs, FPETOOLS, Version 3.01 and HAZARD 1, Version 1.1. Both of these programs were developed by the Center for Fire Research at the National Institute for Standards Technology. One subroutine within FPETOOLS was utilized to develop the fire growth curves. The FAST, Version 18.5, subroutine within Hazard 1 was used to generate the

smoke and hot gas layer information used to determine tenability limits within the upper penetration area. Specific information on the routine used is presented in Attachment 1.

Ignition, or absence of ignition, of the cable trays exposed by the fires was evaluated using a point source approximation which is commonly accepted within the fire protection engineering industry. In the event that ignition of an exposed fuel package occurred, the individual heat release rates are added beginning at that point in time, with the heat release rate curve of the exposed fuel package starting at time 0.

Two fire scenarios were modeled. The first fire scenario involved a two foot diameter pool fire, limited to two gallons of lubrication oil. The purpose of this scenario was to determine if the pool fire would cause ignition of the redundant cable tray stacks located on each side of the electrical tunnel prior to the oil burn-out time. Run time for this scenario was the oil burn-out time unless ignition of the cable tray stack occurred. The second fire scenario involved the self ignition of one cable tray stack in the tunnel entranceway. The purpose of this scenario was to determine if the burning tray stack would cause a cross aisle ignition of the redundant cable tray stack. Run time for this scenario was 45 minutes after ignition of the first cable tray stack. Conditions such as HVAC, actuation of fire suppression systems, and fire brigade response were not considered in this analysis because only the worst case scenario of a fire in the electrical tunnel area was considered.

3.0 DESIGN INPUTS/ASSUMPTIONS

The following design inputs were used in this analysis.

3.1 Data on fire types and materials

3.1.1 2 ft. Diameter Pool Fire with cable tray exposure

- lubrication oil - 2 gallons
- heat of combustion = 20,400 BTU/lb [1]
- mass loss rate = 0.039 kg/m^2 sec [1]
- pool located in middle of tunnel entranceway at base of stairs
- pool fire ignites at time zero
- cable tray ignition based on critical flux of 14 kW/m^2 and exposure time calculations per reference 6.13 (lowest critical value of cable types installed)
- 35% of fire plume energy is lost due to radiation
- separation of fuel packages = 24"

[1] Data obtained from reference 6.5, Table 2-1.2
(Note: the value used for analysis is not less than the values cited in the SFPE Handbook for liquid hydrocarbons, is consistent with values in the IP-3 combustible loading study, and is conservative)

3.1.2 Cable Tray Fire with cable tray exposure

- Cable insulation [1]

  3% PE/PVC

  15% PE, PP/Cl-S-PE

  82% Silicone, asbestos category
- separation of fuel packages = 72"
- 35% of fire plume energy is lost due to radiation
- ignition of redundant cable tray based on critical heat flux of 14 kW/m^2 and calculation of exposure time per reference 6.13 (lowest critical value of cable types installed)
- cable tray stack ignites at time zero
- heat of combustion = 14,000 BTU/lb [3]

- heat release rate based on weighted average of results from FMRC/EPRI tests.

[1] Data obtained from NYPA

[2] Data obtained from reference 6.4, Figure 24, page 92.

[3] Conservative value consistent with IP-3 Combustible Loading Report

3.2 Data on Tunnel and Penetration Area Configuration

For the purpose of this analysis the electrical tunnel and upper penetration area were divided into six "rooms", there are no physical boundaries (walls) between the rooms. Figures 1 & 2 show how the areas were divided, and the dimensions used as input for the FAST model. A brief description of the "room" designations is provided here. Approximate dimensions are listed by length, width, and height respectively.

Room 1: Entranceway to the electrical tunnel from the Foreman wall to the point where the division between the upper and lower electrical tunnels begin. This is the room in which each fire is positioned. Room dimensions - 10 ft. x 10 ft. x 20 ft.

Room 2: Upper electrical tunnel from the start at the top of the stairs to the point which the tunnel turns north. Room dimensions - 20 ft. x 10 ft. x 10 ft.

Room 3: Section of the upper electrical tunnel from the point which the tunnnel turns north. Room dimensions - 80 ft. x 8 ft. x 10 ft.

Room 4: Section of the upper electrical tunnel. Room dimensions - 32 ft. x 8 ft. x 10 ft.

Room 5: Section of upper electrical tunnel to the point where the upper electrical penetration area starts. Room dimensions - 35 ft. x 8 ft. x 15.5 ft.

Room 6: Upper Electrical Penetration area. This is the room which the operator must enter and perform manual safe shutdown operations. Room dimensions - 87 ft. x 18 ft. x 17 ft.

3.3 Definition of Untenability

For the purpose of this analysis untenability in the electrical penetration area (Room 6) shall be defined as:

- Temperature of upper or lower gas layer of greater than 140°F (333K).

  or

- O_2 lower than 17%

  or

- CO_2 greater than 10%

  or

- CO greater than 35,000 ppm

These values are taken from reference 6.6, Section 3, Chapter 1, "Combustion Products and Their Effects on Life Safety."

Figure 1

Area Plan View - As seen by computer model

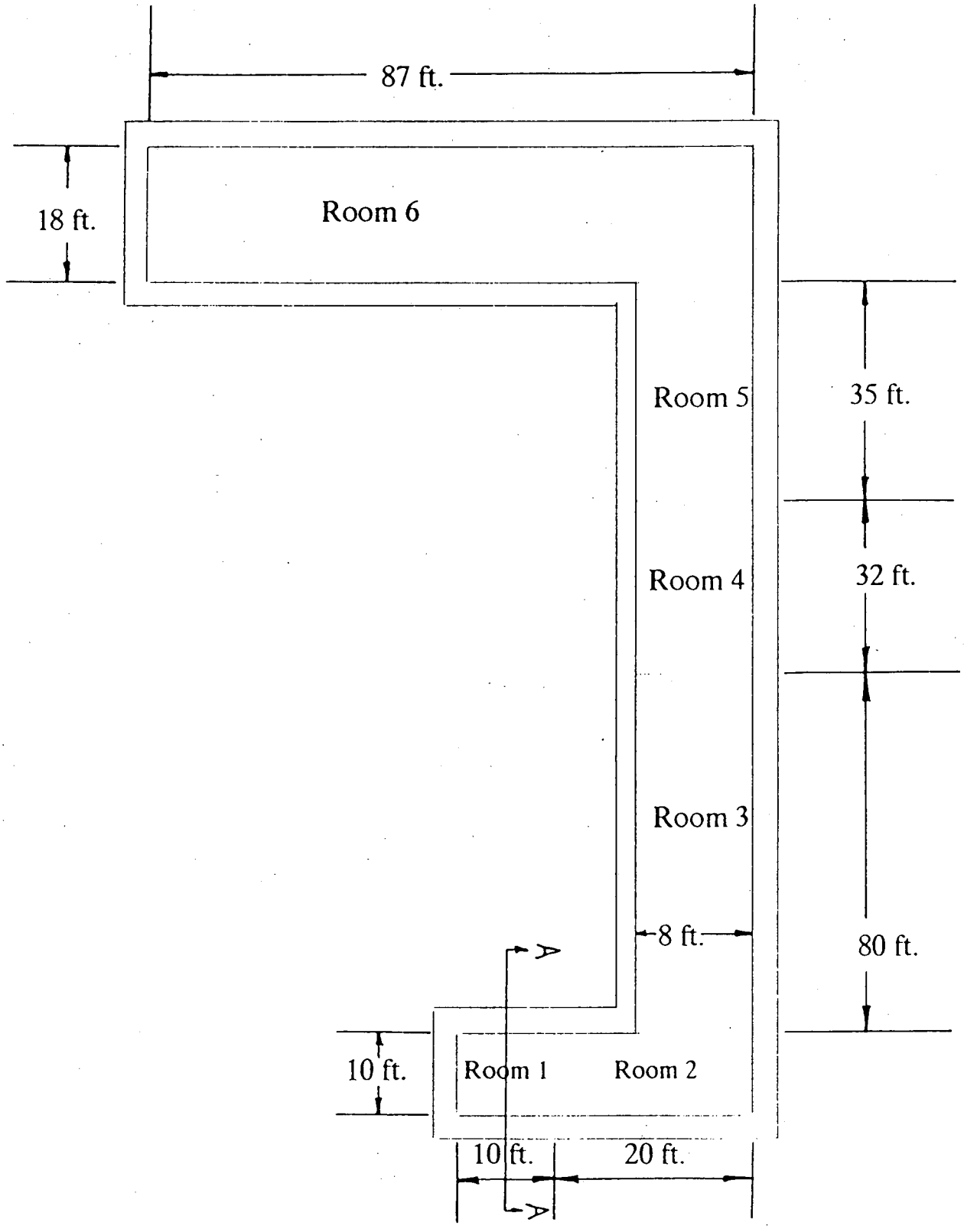


Figure 2

Area Elevation View - As seen by computer model

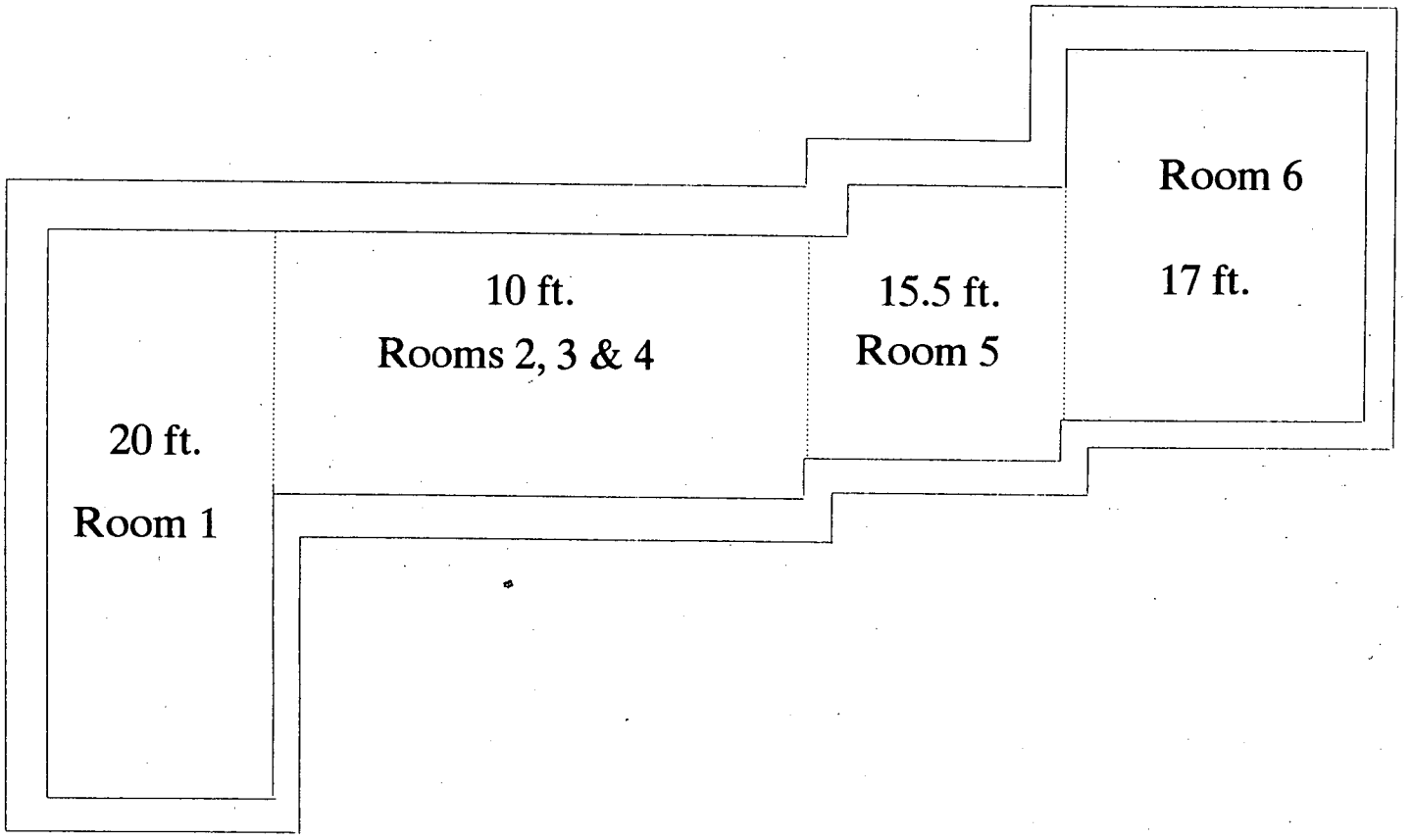
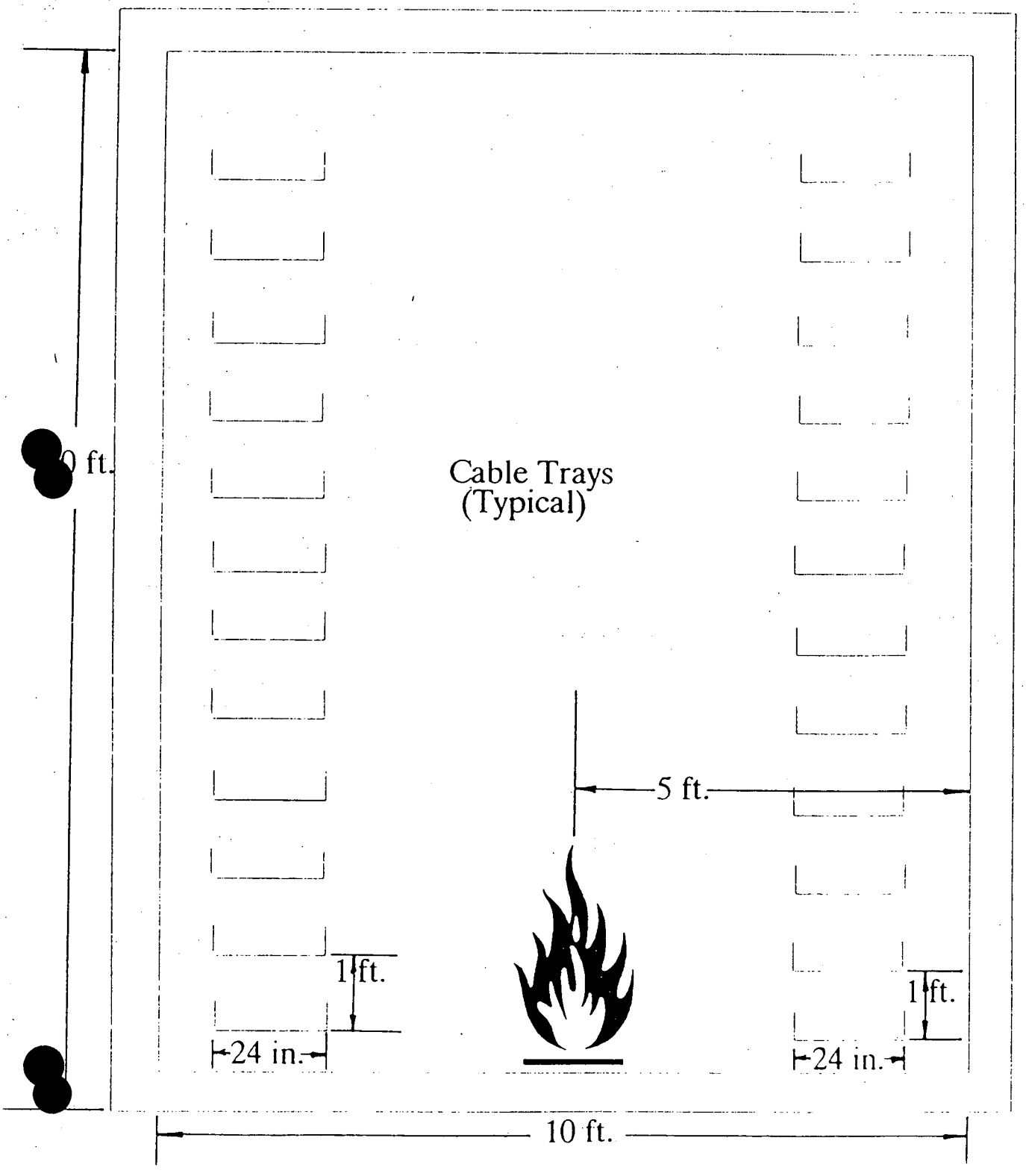


Figure 3

Section View - A-A



4.0 CALCULATION

The following pages contain the fire scenario calculations and the input and output from the FAST subroutine of the HAZARD 1 computer program. The information is arranged in the following order:

4.1 2 ft. diameter pool fire

4.2 Cable tray fire

In addition to the tabular printout from the FAST subroutine, the depth of the upper gas layer, and temperature of the upper and lower gas layers are presented in graphical form. The thin bold line indicates upper gas layer depth, the thick bold line indicates upper gas layer temperature, and the broken line indicates lower gas layer temperature.

4.1 2 ft. Diameter Pool Fire

4.1.1 Calculation of 2 ft. Pool Fire Duration

Calculation of area of pool (ft^2)

$A = \pi d^2/4$

$= 3.14\ (2\ ft)^2/4$

$= 3.14\ ft^2$

Calculation of mass loss rate in kg/sec

$3.14\ ft^2\ (0.0929\ m^2/ft^2) = 0.2917\ m^2$

$0.039\ kg/m^2\ sec\ (0.2917 m^2) \quad = 0.0114\ kg/sec$

Amount of fuel - 2 gallons

convert gallons to ft^3

$$2.0\ gal\ [\frac{0.1337\ ft^3}{gal}] = 0.2674\ ft^3$$

convert ft^3 to m^3

$$0.2674\ ft^3 [\frac{0.02832\ m^3}{ft^3}] = 0.007573\ m^3$$

convert m^3 to kg

$$0.007573\ m^3[\frac{760\ kg}{m^3}] = 5.7555\ kg$$

$$FireDuration = \frac{MASS}{MASS\ LOSS\ RATE}$$

$$= \frac{5.7555kg}{0.0144kg/\sec}$$

$$=399.7$$

4.1.2 Potential for Ignition of Redundant Cable Tray Stacks By Pool fire

Using the input detailed in Section 3.1.1, a heat release rate history for the 2 ft. diameter pool fire was developed. The impact of the pool fire on the redundant cable trays was assessed by approximating the pool fire as a point source and calculating the incident energy or flux (kW/m^2) received by the redundant cable trays. The incident flux received by the cable trays is calculated to be a constant 15.199 kW/m^2 for the duration of the pool fire. At this energy level, an exposure duration of 648 seconds is required before piloted ignition could occur. See Attachment 1 for details on these calculations. The calculations in Section 4.1.1 indicate that the pool fire will burn out at 400 seconds. Therefore, it is not expected that the pool fire will cause ignition of the redundant cable trays.

Tenability in the upper penetration area is analyzed for the duration of the pool fire. The results of this calculation are presented in section 4.1.3.

4.1.3 Calculation of Tenability - Input and Output data for 2 ft. diameter pool fire

The output listed in Section 4.1.3 is arranged so that each column represents the conditions in an individual compartment. The first column after the vertical line represents conditions in compartment #1, the second column represents conditions in compartment #2, and so on through the last column, which represents conditions in compartment #6.

```
VERSN  18  2'-DIA POOL FIRE SPECIES
TIMES  540 60  0  0  0
TAMB  300. 101300.    0.
EAMB  300. 101300.    0.
HI/F   0.00  3.05  3.05  3.36  3.36  3.96
WIDTH   3.05  3.05  2.44  2.44  2.44  5.49
DEPTH   3.05  6.10 24.38  9.76 10.68 26.54
HEIGH   6.10  3.05  3.05  3.05  4.73  5.18
HVENT  1 2 1  3.05  6.10  3.05
HVENT  2 3 1  2.44  3.05  0.00
HVENT  3 4 1  2.44  3.05  0.31
HVENT  4 5 1  2.44  3.05  0.00
HVENT  5 6 1  2.44  4.73  0.61
CVENT  1 2 1  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
CVENT  2 3 1  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
CVENT  3 4 1  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
CVENT  4 5 1  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
CVENT  5 6 1  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
CEILI CONCRETE  CONCRETE  CONCRETE  CONCRETE  CONCRETE  CONCRETE
WALLS CONCRETE  CONCRETE  CONCRETE  CONCRETE  CONCRETE  CONCRETE
FLOOR CONCRETE  CONCRETE  CONCRETE  CONCRETE  CONCRETE  CONCRETE
CHEMI   16.  60. 10.0   47450000. 300.
LFBO  1
LFBT  2
LFPOS  1
LFMAX 12
FTIME  540.
FMASS  0.0114  0.0114
FHIGH   0.00  0.00
FAREA   0.07  0.07
FQDOT  5.43E+05 5.43E+05
HCR    0.330  0.330
CO     0.007  0.007
OD     0.030  0.030
```

Fast V 18.5 Created 5/1/91, Run 3/31/94

Time = 0.0 seconds.

Upper layer species

N2	%	79.3	79.3	79.3	79.3	79.3	79.3
O2	%	20.7	20.7	20.7	20.7	20.7	20.7
CO2	%	0.000	0.000	0.000	0.000	0.000	0.000
CO	ppm	0.000	0.000	0.000	0.000	0.000	0.000
TUHC	%	0.000	0.000	0.000	0.000	0.000	0.000
H2O	%	0.000	0.000	0.000	0.000	0.000	0.000
OD	1/m	0.000	0.000	0.000	0.000	0.000	0.000

Lower layer species

N2	%	79.3	79.3	79.3	79.3	79.3	79.3
O2	%	20.7	20.7	20.7	20.7	20.7	20.7
CO2	%	0.000	0.000	0.000	0.000	0.000	0.000
CO	ppm	0.000	0.000	0.000	0.000	0.000	0.000
TUHC	%	0.000	0.000	0.000	0.000	0.000	0.000
H2O	%	0.000	0.000	0.000	0.000	0.000	0.000
OD	1/m	0.000	0.000	0.000	0.000	0.000	0.000

Time = 60.0 seconds.

Upper layer species

N2	%	78.2	78.3	78.6	78.8	79.1	79.3
O2	%	19.1	19.3	19.7	20.1	20.5	20.7
CO2	%	1.11	1.02	0.688	0.463	0.156	2.000E-02
CO	ppm	122.	112.	75.7	50.9	17.1	2.20
TUHC	%	0.000	0.000	0.000	0.000	0.000	0.000
H2O	%	1.44	1.32	0.894	0.601	0.202	2.595E-02
OD	1/m	1.31	1.37	1.04	0.761	0.286	3.913E-02

Lower layer species

N2	%	78.8	79.2	79.2	79.2	79.3	79.3
O2	%	20.1	20.5	20.6	20.6	20.7	20.7
CO2	%	0.456	0.129	6.271E-02	5.279E-02	2.271E-02	0.000
CO	ppm	50.1	14.2	6.90	5.81	2.50	0.000
TUHC	%	0.000	0.000	0.000	0.000	0.000	0.000
H2O	%	0.592	0.168	8.139E-02	6.851E-02	2.947E-02	0.000
OD	1/m	0.685	0.232	0.114	0.102	4.498E-02	0.000

Time = 120.0 seconds.

Upper layer species

N2	%	77.8	77.9	78.2	78.4	78.8	79.2
O2	%	18.6	18.7	19.1	19.4	20.0	20.6
CO2	%	1.47	1.38	1.12	0.890	0.475	0.105
CO	ppm	161.	151.	123.	97.9	52.3	11.6
TUHC	%	0.000	0.000	0.000	0.000	0.000	0.000
H2O	%	1.90	1.79	1.45	1.15	0.617	0.136
OD	1/m	1.70	1.88	1.67	1.43	0.844	0.204

Lower layer species

N2	%	78.5	78.9	79.0	79.1	79.2	79.3
O2	%	19.5	20.1	20.2	20.4	20.6	20.7
CO2	%	0.818	0.411	0.329	0.196	7.910E-02	0.000
CO	ppm	90.0	45.2	36.2	21.5	8.70	0.000
TUHC	%	0.000	0.000	0.000	0.000	0.000	0.000
H2O	%	1.06	0.533	0.427	0.254	0.103	0.000
OD	1/m	1.19	0.732	0.589	0.380	0.160	0.000

Time = 180.0 seconds.

Upper layer species

N2	%	77.7	77.7	77.9	78.1	78.5	79.1
O2	%	18.4	18.5	18.7	19.0	19.6	20.4
CO2	%	1.59	1.56	1.42	1.21	0.768	0.232
CO	ppm	175.	172.	156.	133.	84.4	25.5
TUHC	%	0.000	0.000	0.000	0.000	0.000	0.000
H2O	%	2.07	2.02	1.84	1.57	0.996	0.300
OD	1/m	1.93	2.21	2.20	2.00	1.37	0.443

Lower layer species

N2	%	78.3	78.7	78.8	79.1	79.2	79.3
O2	%	19.3	19.9	20.1	20.4	20.6	20.7
CO2	%	0.987	0.558	0.452	0.227	6.779E-02	0.000
CO	ppm	109.	61.4	49.7	24.9	7.46	0.000
TUHC	%	0.000	0.000	0.000	0.000	0.000	0.000
H2O	%	1.28	0.724	0.587	0.294	8.798E-02	0.000
OD	1/m	1.49	1.03	0.840	0.456	0.141	0.000

Time = 240.0 seconds.

Upper layer species

N2	%	77.7	77.7	77.8	77.9	78.3	78.9
O2	%	18.4	18.4	18.5	18.7	19.3	20.2
CO2	%	1.60	1.59	1.55	1.41	0.993	0.365
CO	ppm	176.	175.	171.	155.	109.	40.2
TUHC	%	0.000	0.000	0.000	0.000	0.000	0.000
H2O	%	2.08	2.07	2.01	1.83	1.29	0.474
OD	1/m	2.00	2.36	2.50	2.41	1.80	0.695

Lower layer species

N2	%	78.3	78.7	78.8	79.1	79.3	79.3
O2	%	19.3	19.9	20.1	20.5	20.7	20.7
CO2	%	1.02	0.570	0.456	0.184	2.959E-02	0.000
CO	ppm	112.	62.7	50.2	20.3	3.25	0.000
TUHC	%	0.000	0.000	0.000	0.000	0.000	0.000
H2O	%	1.32	0.740	0.592	0.239	3.840E-02	0.000
OD	1/m	1.59	1.10	0.885	0.384	6.334E-02	0.000

Time = 300.0 seconds.

Upper layer species

N2	%	77.7	77.7	77.7	77.8	78.2	78.8
O2	%	18.4	18.4	18.4	18.5	19.2	20.0
CO2	%	1.60	1.59	1.58	1.52	1.09	0.491
CO	ppm	176.	175.	174.	168.	119.	54.1
TUHC	%	0.000	0.000	0.000	0.000	0.000	0.000
H2O	%	2.07	2.07	2.05	1.98	1.41	0.638
OD	1/m	2.05	2.42	2.64	2.69	2.01	0.937

Lower layer species

N2	%	78.3	78.8	78.9	79.2	79.3	79.3
O2	%	19.3	20.0	20.1	20.5	20.7	20.7
CO2	%	1.01	0.514	0.403	0.119	1.995E-02	0.000
CO	ppm	111.	56.5	44.3	13.1	2.19	0.000
TUHC	%	0.000	0.000	0.000	0.000	0.000	0.000
H2O	%	1.30	0.667	0.523	0.155	2.590E-02	0.000
OD	1/m	1.61	1.03	0.811	0.257	4.370E-02	0.000

Time = 360.0 seconds.

Upper layer species

N2	%	77.6	77.7	77.7	77.8	78.2	78.7
O2	%	18.3	18.3	18.4	18.5	19.1	19.9
CO2	%	1.70	1.66	1.61	1.52	1.11	0.589
CO	ppm	187.	182.	177.	167.	122.	64.8
TUHC	%	0.000	0.000	0.000	0.000	0.000	0.000
H2O	%	2.21	2.15	2.09	1.97	1.44	0.765
OD	1/m	2.18	2.57	2.75	2.78	2.10	1.13

Lower layer species

N2	%	78.2	78.8	78.9	79.2	79.2	79.3
O2	%	19.2	20.1	20.2	20.5	20.6	20.7
CO2	%	1.05	0.447	0.354	0.125	9.000E-02	0.000
CO	ppm	116.	49.1	38.9	13.8	9.90	0.000
TUHC	%	0.000	0.000	0.000	0.000	0.000	0.000
H2O	%	1.36	0.580	0.460	0.163	0.117	0.000
OD	1/m	1.67	0.922	0.734	0.278	0.202	0.000

Time = 420.0 seconds.

Upper layer species

N2	%	77.3	77.4	77.6	77.8	78.2	78.6
O2	%	17.8	18.0	18.3	18.6	19.1	19.8
CO2	%	2.01	1.86	1.70	1.50	1.11	0.659
CO	ppm	221.	205.	187.	166.	122.	72.4
TUHC	%	0.000	0.000	0.000	0.000	0.000	0.000
H2O	%	2.61	2.42	2.21	1.95	1.44	0.855
OD	1/m	2.59	2.94	2.97	2.82	2.14	1.27

Lower layer species

N2	%	78.0	78.8	78.8	79.0	79.0	79.3
O2	%	18.8	20.0	20.1	20.3	20.3	20.7
CO2	%	1.35	0.506	0.453	0.275	0.278	0.000
CO	ppm	148.	55.6	49.8	30.3	30.6	0.000
TUHC	%	0.000	0.000	0.000	0.000	0.000	0.000
H2O	%	1.75	0.656	0.588	0.357	0.361	0.000
OD	1/m	2.11	1.11	0.998	0.654	0.655	0.000

Time = 480.0 seconds.

Upper layer species

N2	%	76.9	77.1	77.4	77.8	78.2	78.6
O2	%	17.2	17.6	18.0	18.5	19.1	19.7
CO2	%	2.44	2.18	1.87	1.56	1.14	0.709
CO	ppm	269.	239.	205.	171.	125.	78.0
TUHC	%	0.000	0.000	0.000	0.000	0.000	0.000
H2O	%	3.17	2.82	2.42	2.02	1.47	0.920
OD	1/m	3.47	3.40	3.36	2.95	2.21	1.38

Lower layer species

N2	%	77.4	78.5	78.6	78.8	78.8	79.3
O2	%	18.0	19.6	19.7	20.0	20.1	20.7
CO2	%	1.92	0.749	0.727	0.479	0.466	0.000
CO	ppm	211.	82.4	80.0	52.7	51.2	0.000
TUHC	%	0.000	0.000	0.000	0.000	0.000	0.000
H2O	%	2.49	0.973	0.944	0.621	0.604	0.000
OD	1/m	3.24	1.65	1.62	1.06	0.990	0.000

Time = 540.0 seconds.

Upper layer species

N2	%	76.4	76.8	77.2	77.6	78.1	78.5
O2	%	16.5	17.1	17.7	18.3	19.0	19.6
CO2	%	2.91	2.54	2.12	1.69	1.20	0.753
CO	ppm	321.	280.	233.	186.	132.	82.8
TUHC	%	0.000	0.000	0.000	0.000	0.000	0.000
H2O	%	3.78	3.30	2.75	2.20	1.56	0.977
OD	1/m	4.10	4.08	3.89	3.26	2.36	1.47

Lower layer species

N2	%	76.9	78.2	78.3	78.7	78.7	79.3
O2	%	17.2	19.2	19.2	19.8	19.8	20.7
CO2	%	2.42	1.05	1.03	0.640	0.616	0.000
CO	ppm	266.	115.	113.	70.4	67.7	0.000
TUHC	%	0.000	0.000	0.000	0.000	0.000	0.000
H2O	%	3.14	1.36	1.33	0.830	0.799	0.000
OD	1/m	4.00	2.16	2.10	1.25	1.17	0.000

FAST version 18.5.2 - created May 1, 1990 2' DIA POOL FIRE SPECIES

Total compartments = 6

FLOOR PLAN

Width	3.0	3.0	2.4	2.4	2.4	5.5	
Depth	3.0	6.1	24.4	9.8	10.7	26.5	
Height	6.1	3.0	3.0	3.0	4.7	5.2	
Area	9.3	18.6	59.5	23.8	26.1	145.7	
Volume	56.7	56.7	181.4	72.6	123.3	754.7	
Ceiling	6.1	6.1	6.1	6.4	8.1	9.1	
Floor	0.0	3.0	3.0	3.4	3.4	4.0	

NORMAL CONNECTIONS

1 (1)	Width	0.00	3.05	0.00	0.00	0.00	0.00	0.00
	Soffit	0.00	6.10	0.00	0.00	0.00	0.00	0.00
	Sill	0.00	3.05	0.00	0.00	0.00	0.00	0.00
	a.Soffit	0.00	6.10	0.00	0.00	0.00	0.00	0.00
	a.Sill	0.00	3.05	0.00	0.00	0.00	0.00	0.00
2 (1)	Width	3.05	0.00	2.44	0.00	0.00	0.00	0.00
	Soffit	3.05	0.00	3.05	0.00	0.00	0.00	0.00
	Sill	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	a.Soffit	6.10	0.00	6.10	0.00	0.00	0.00	0.00
	a.Sill	3.05	0.00	3.05	0.00	0.00	0.00	0.00
3 (1)	Width	0.00	2.44	0.00	2.44	0.00	0.00	0.00
	Soffit	0.00	3.05	0.00	3.05	0.00	0.00	0.00
	Sill	0.00	0.00	0.00	0.31	0.00	0.00	0.00
	a.Soffit	0.00	6.10	0.00	6.10	0.00	0.00	0.00
	a.Sill	0.00	3.05	0.00	3.36	0.00	0.00	0.00
4 (1)	Width	0.00	0.00	2.44	0.00	2.44	0.00	0.00
	Soffit	0.00	0.00	2.74	0.00	3.05	0.00	0.00
	Sill	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	a.Soffit	0.00	0.00	6.10	0.00	6.41	0.00	0.00
	a.Sill	0.00	0.00	3.36	0.00	3.36	0.00	0.00
5 (1)	Width	0.00	0.00	0.00	2.44	0.00	2.44	0.00
	Soffit	0.00	0.00	0.00	3.05	0.00	4.73	0.00
	Sill	0.00	0.00	0.00	0.00	0.00	0.61	0.00
	a.Soffit	0.00	0.00	0.00	6.41	0.00	8.09	0.00
	a.Sill	0.00	0.00	0.00	3.36	0.00	3.97	0.00
6 (1)	Width	0.00	0.00	0.00	0.00	2.44	0.00	0.00
	Soffit	0.00	0.00	0.00	0.00	4.13	0.00	0.00
	Sill	0.00	0.00	0.00	0.00	0.01	0.00	0.00
	a.Soffit	0.00	0.00	0.00	0.00	8.09	0.00	0.00
	a.Sill	0.00	0.00	0.00	0.00	3.97	0.00	0.00

THERE ARE NO FAN CONNECTIONS

Material names

Ceiling:	CONCRETE	CONCRETE	CONCRETE	CONCRETE	CONCRETE	CONCRETE
Walls:	CONCRETE	CONCRETE	CONCRETE	CONCRETE	CONCRETE	CONCRETE
Floor:	CONCRETE	CONCRETE	CONCRETE	CONCRETE	CONCRETE	CONCRETE

Thermal data base used: THERMAL.TPF

Name	Conductivity	Specific heat	Density	Thickness	Emissivity	
CONCRETE	1.75	1.000E+03	2.200E+03	0.150	0.940	0.00E+00
	0.00E+00	0.00E+00	0.00E+00	188	U	

Compartment of origin is	1
Print interval (seconds)	60
Number of fire specification intervals is	1
Total time (seconds)	540
Fire position	1
Limiting oxygen index (%) =	10.0
Initial relative humidity (%) =	0.0
Fire type is a SPECIFIED (CONSTRAINED)	
Pyrolysis temperature (K) =	300.
Ambient air temperature (K) =	300.
Ambient reference pressure (Pa) =	101300.
Reference elevation (m) =	0.
External ambient temperature (K) =	300.
External reference pressure (Pa) =	101300.
Reference elevation (m) =	0.

Fmass=	1.14E-02	1.14E-02
Hcomb=	4.76E+07	4.76E+07
Fqdot=	5.43E+05	5.43E+05
Fhigh=	0.00	0.00
C/CO2=	3.00E-02	3.00E-02
CO/CO2=	7.00E-03	7.00E-03
H/C=	0.33	0.33
Ftime=	5.40E+02	

Time = 0.0 seconds.

Upper temp(K)	300.0	300.0	300.0	300.0	300.0	300.0
Lower temp(K)	300.0	300.0	300.0	300.0	300.0	300.0
Upper vol(m**3)	0.1	0.1	0.2	0.1	0.1	0.8
Layer depth(m)	0.0	0.0	0.0	0.0	0.0	0.0
Ceiling temp(K)	300.0	300.0	300.0	300.0	300.0	300.0
Up wall temp(K)	300.0	300.0	300.0	300.0	300.0	300.0
Low wall temp(K)	300.0	300.0	300.0	300.0	300.0	300.0
Floor temp(K)	300.0	300.0	300.0	300.0	300.0	300.0

Time = 60.0 seconds.

Upper temp(K)	449.2	412.7	360.6	337.4	313.0	301.6
Lower temp(K)	359.2	314.0	306.1	304.8	302.1	300.0
Upper vol(m**3)	27.8	41.6	115.4	38.2	59.6	127.9
Layer depth(m)	3.0	2.2	1.9	1.6	2.3	0.9
Ceiling temp(K)	306.5	304.4	301.8	300.8	300.2	300.0
Up wall temp(K)	304.9	303.3	301.3	300.6	300.1	300.0
Low wall temp(K)	301.2	300.9	300.3	300.1	300.0	300.0
Floor temp(K)	300.5	300.8	300.3	300.1	300.0	300.0

Time = 120.0 seconds.

Upper temp(K)	474.2	429.0	370.8	347.1	323.5	305.5
Lower temp(K)	386.5	330.9	321.8	311.8	304.7	300.0
Upper vol(m**3)	28.8	42.7	118.7	37.2	59.4	337.6
Layer depth(m)	3.1	2.3	2.0	1.6	2.3	2.3
Ceiling temp(K)	312.4	308.3	303.7	302.1	300.7	300.1
Up wall temp(K)	309.5	306.3	302.8	301.5	300.5	300.1
Low wall temp(K)	302.8	302.1	300.8	300.4	300.1	300.0
Floor temp(K)	301.2	301.7	300.6	300.3	300.1	300.0

Time = 180.0 seconds.

Upper temp(K)	477.2	433.9	375.7	351.4	327.9	308.5
Lower temp(K)	392.1	333.6	323.3	310.3	302.9	300.0
Upper vol(m**3)	28.8	41.9	115.5	37.3	64.3	462.8
Layer depth(m)	3.1	2.3	1.9	1.6	2.5	3.2
Ceiling temp(K)	317.0	311.5	305.3	303.1	301.3	300.2
Up wall temp(K)	313.1	308.7	304.0	302.3	301.0	300.2
Low wall temp(K)	304.3	303.1	301.3	300.6	300.2	300.0
Floor temp(K)	301.7	302.5	301.0	300.4	300.1	300.0

Time = 240.0 seconds.

Upper temp(K)	476.8	433.7	376.5	353.0	329.2	310.0
Lower temp(K)	392.1	330.8	320.4	307.1	301.0	300.0
Upper vol(m**3)	29.2	42.3	117.6	40.5	75.5	562.6
Layer depth(m)	3.1	2.3	2.0	1.7	2.9	3.9
Ceiling temp(K)	320.4	313.9	306.6	304.0	301.8	300.4
Up wall temp(K)	315.9	310.7	304.9	303.0	301.3	300.3
Low wall temp(K)	305.3	303.9	301.7	300.8	300.2	300.1
Floor temp(K)	302.1	303.1	301.2	300.6	300.2	300.1

Time = 300.0 seconds.

Upper temp(K)	479.1	432.6	375.6	352.4	327.0	310.6
Lower temp(K)	393.4	326.8	317.0	304.2	300.6	300.0
Upper vol(m**3)	30.3	43.9	125.5	46.8	89.4	636.4
Layer depth(m)	3.3	2.4	2.1	2.0	3.4	4.4
Ceiling temp(K)	323.3	315.9	307.6	304.7	302.1	300.5
Up wall temp(K)	318.2	312.2	305.7	303.5	301.6	300.4
Low wall temp(K)	306.3	304.5	302.0	300.9	300.3	300.1
Floor temp(K)	302.5	303.7	301.5	300.7	300.3	300.1

Time = 360.0 seconds.

Upper temp(K)	487.6	431.2	373.5	346.6	323.6	310.3
Lower temp(K)	400.1	322.2	314.3	303.6	302.2	300.0
Upper vol(m**3)	32.4	47.2	140.4	56.1	101.7	686.9
Layer depth(m)	3.5	2.5	2.4	2.4	3.9	4.7
Ceiling temp(K)	326.2	317.5	308.4	305.1	302.2	300.6
Up wall temp(K)	320.6	313.5	306.3	303.8	301.7	300.5
Low wall temp(K)	307.3	305.1	302.2	301.0	300.4	300.2
Floor temp(K)	303.0	304.3	301.7	300.9	300.3	300.2

Time = 420.0 seconds.

Upper temp(K)	497.4	429.9	370.3	341.2	320.5	309.5
Lower temp(K)	420.1	321.1	316.1	306.3	305.8	300.0
Upper vol(m**3)	36.4	50.6	155.3	63.2	110.1	713.5
Layer depth(m)	3.9	2.7	2.6	2.7	4.2	4.9
Ceiling temp(K)	329.4	318.9	309.0	305.2	302.3	300.7
Up wall temp(K)	323.2	314.6	306.8	303.9	301.7	300.5
Low wall temp(K)	308.6	305.7	302.5	301.1	300.4	300.2
Floor temp(K)	303.6	304.9	302.0	301.0	300.4	300.2

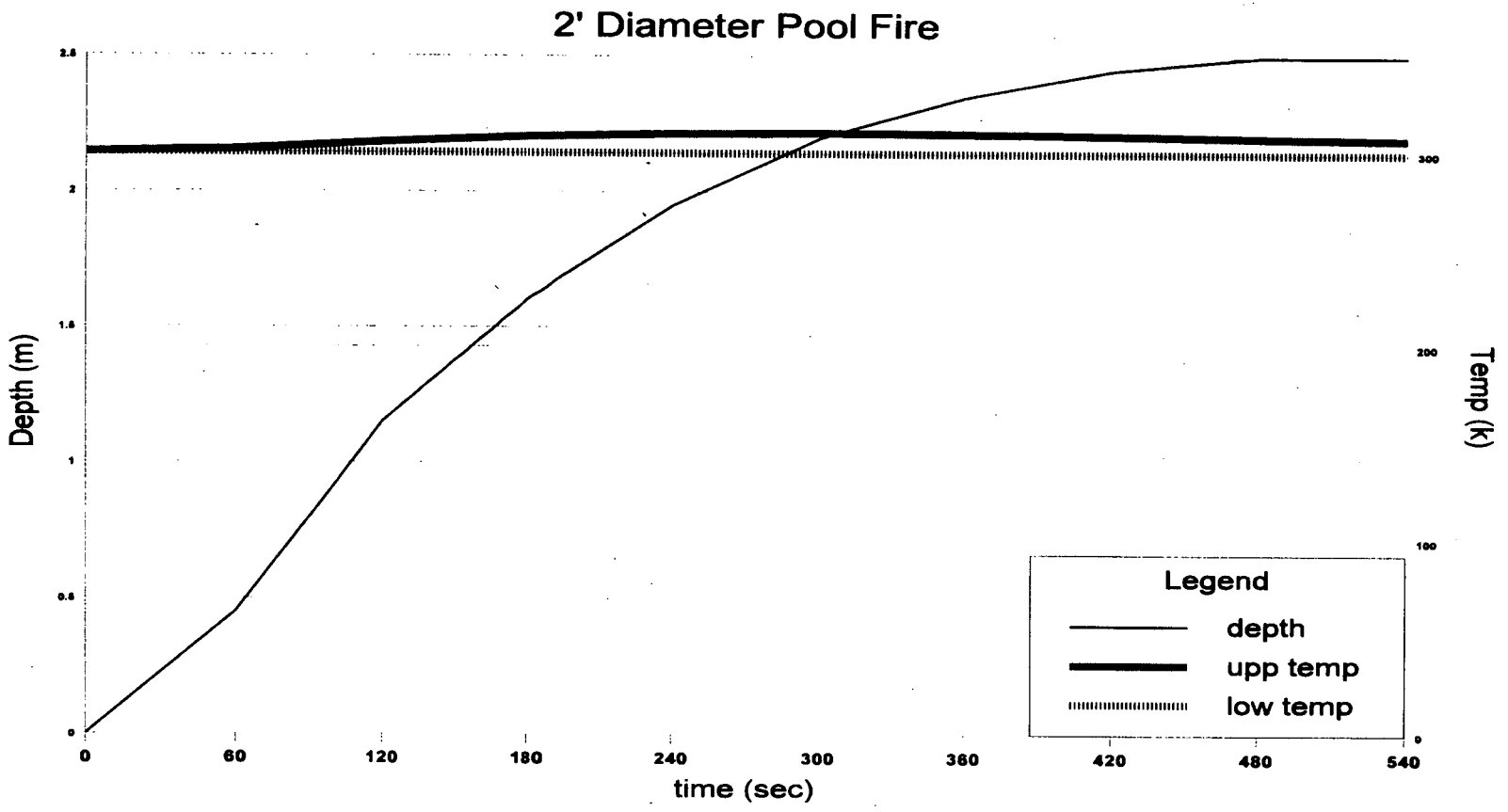
Time = 480.0 seconds.

Upper temp(K)	497.9	425.8	366.7	337.5	318.2	308.4
Lower temp(K)	425.6	324.4	321.4	308.6	307.6	300.1
Upper vol(m**3)	39.2	52.5	163.6	66.3	113.9	723.7
Layer depth(m)	4.2	2.8	2.7	2.8	4.4	5.0
Ceiling temp(K)	332.4	320.0	309.4	305.3	302.3	300.7
Up wall temp(K)	325.7	315.5	307.1	304.0	301.7	300.6
Low wall temp(K)	310.2	306.4	302.8	301.3	300.5	300.2
Floor temp(K)	304.3	305.6	302.2	301.1	300.4	300.2

Time = 540.0 seconds.

Upper temp(K)	495.9	422.4	363.9	335.1	316.7	307.5
Lower temp(K)	421.7	326.1	323.7	308.7	307.4	300.1
Upper vol(m**3)	39.9	53.4	167.4	67.4	115.4	729.4
Layer depth(m)	4.3	2.9	2.8	2.8	4.4	5.0
Ceiling temp(K)	334.7	320.8	309.7	305.3	302.3	300.7
Up wall temp(K)	327.6	316.2	307.3	304.0	301.7	300.6
Low wall temp(K)	311.4	307.0	303.1	301.4	300.6	300.2
Floor temp(K)	304.9	306.1	302.4	301.2	300.5	300.2

FIGURE 4.1.3


2' Diameter Pool Fire
Depth (m)
Temp (k)
time (sec)
0
60
120
180
240
300
360
420
480
540
Legend
depth
upp temp
low temp

4.2 Cable tray fire

4.2.1 Potential for Ignition of Redundant Cable Tray Stack

Using the input detailed in Section 3.1.2, a heat release rate history for a cable tray fire was developed. The impact of the cable tray fire on the redundant cable tray was assessed by approximating the cable tray fire as a point source and calculating the incident energy or flux (kW/m^2) received by the redundant cable tray. The incident flux received by the redundant cable tray is calculated to reach a maximum value of 1.307 kW/m^2. These calculations are detailed in Attachment 1. This value is well below the 14 kW/m^2 critical flux necessary to enable piloted ignition of silicone, glass braid/asbestos cable. Therefore, ignition of the redundant cable tray is not expected to occur.

4.2.2 Calculation of Tenability - Cable Tray Fire

The output listed in Section 4.2.2 is arranged so that each column represents the conditions in an individual compartment. The first column after the vertical line represents conditions in compartment #1, the second column represents conditions in compartment #2, and so on through the last column, which represents conditions in compartment #6.

```
VERSN  18 SINGLE CABLE TRAY STACK
TIMES  2700 60 60 60  0
TAMB  300. 101300.    0.
EAMB  300. 101300.    0.
HI/F   0.00  3.05  3.05  3.36  3.36  3.96
WIDTH   3.05  3.05  2.44  2.44  2.44  5.49
DEPTH   3.05  6.10 24.38  9.76 10.68 26.54
HEIGH   6.10  3.05  3.05  3.05  4.73  5.18
HVENT  1 2 1  3.05  6.10  3.05
HVENT  2 3 1  2.44  3.05  0.00
HVENT  3 4 1  2.44  3.05  0.31
HVENT  4 5 1  2.44  3.05  0.00
HVENT  5 6 1  2.44  4.73  0.61
CVENT  1 2 1  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
CVENT  2 3 1  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
CVENT  3 4 1  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
CVENT  4 5 1  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
CVENT  5 6 1  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
CEILI CONCRETE  CONCRETE  CONCRETE  CONCRETE  CONCRETE  CONCRETE
WALLS CONCRETE  CONCRETE  CONCRETE  CONCRETE  CONCRETE  CONCRETE
FLOOR CONCRETE  CONCRETE  CONCRETE  CONCRETE  CONCRETE  CONCRETE
CHEMI   16.   1.  10.0   33000000.  300.
LFBO  1
LFBT  2
LFPOS  3
LFMAX 12
FTIME   100.  100.  100.  100.  100.  100.  100.  200.  200.  500.  500.  600.
FMASS  0.0000 0.0019 0.0035 0.0048 0.0058 0.0067 0.0075 0.0081 0.0089 0.0096 0.0104 0.0108  0.0108
FHIGH   0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00
FAREA   0.29  0.29  0.29  0.29  0.29  0.29  0.29  0.29  0.29  0.29  0.29  0.29  0.29
FQDOT  0.00    6.20E+04 1.13E+05 1.56E+05 1.90E+05 2.19E+05 2.43E+05 2.63E+05 2.92E+05
3.12E+05 3.39E+05 3.52E+05 3.52E+05
HCR  0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333
CO   0.023 0.023 0.023 0.023 0.023 0.023 0.023 0.023 0.023 0.023 0.023 0.023 0.023
OD   0.034 0.034 0.034 0.034 0.034 0.034 0.034 0.034 0.034 0.034 0.034 0.034 0.034
```

Number of compartments = 6

FLOOR PLAN

Width	3.0	3.0	2.4	2.4	2.4	5.5
Depth	3.0	6.1	24.4	9.8	10.7	26.5
Height	6.1	3.0	3.0	3.0	4.7	5.2
Area	9.3	18.6	59.5	23.8	26.1	145.7
Volume	56.7	56.7	181.4	72.6	123.3	754.7
Ceiling	6.1	6.1	6.1	6.4	8.1	9.1
Floor	0.0	3.0	3.0	3.4	3.4	4.0

NORMAL CONNECTIONS

1 (1)	Width	0.00	3.05	0.00	0.00	0.00	0.00	0.00
	Soffit	0.00	6.10	0.00	0.00	0.00	0.00	0.00
	Sill	0.00	3.05	0.00	0.00	0.00	0.00	0.00
	a.Soffit	0.00	6.10	0.00	0.00	0.00	0.00	0.00
	a.Sill	0.00	3.05	0.00	0.00	0.00	0.00	0.00
2 (1)	Width	3.05	0.00	2.44	0.00	0.00	0.00	0.00
	Soffit	3.05	0.00	3.05	0.00	0.00	0.00	0.00
	Sill	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	a.Soffit	6.10	0.00	6.10	0.00	0.00	0.00	0.00
	a.Sill	3.05	0.00	3.05	0.00	0.00	0.00	0.00
3 (1)	Width	0.00	2.44	0.00	2.44	0.00	0.00	0.00
	Soffit	0.00	3.05	0.00	3.05	0.00	0.00	0.00
	Sill	0.00	0.00	0.00	0.31	0.00	0.00	0.00
	a.Soffit	0.00	6.10	0.00	6.10	0.00	0.00	0.00
	a.Sill	0.00	3.05	0.00	3.36	0.00	0.00	0.00
4 (1)	Width	0.00	0.00	2.44	0.00	2.44	0.00	0.00
	Soffit	0.00	0.00	2.74	0.00	3.05	0.00	0.00
	Sill	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	a.Soffit	0.00	0.00	6.10	0.00	6.41	0.00	0.00
	a.Sill	0.00	0.00	3.36	0.00	3.36	0.00	0.00
5 (1)	Width	0.00	0.00	0.00	2.44	0.00	2.44	0.00
	Soffit	0.00	0.00	0.00	3.05	0.00	4.73	0.00
	Sill	0.00	0.00	0.00	0.00	0.00	0.61	0.00
	a.Soffit	0.00	0.00	0.00	6.41	0.00	8.09	0.00
	a.Sill	0.00	0.00	0.00	3.36	0.00	3.97	0.00
6 (1)	Width	0.00	0.00	0.00	0.00	2.44	0.00	0.00
	Soffit	0.00	0.00	0.00	0.00	4.13	0.00	0.00
	Sill	0.00	0.00	0.00	0.00	0.01	0.00	0.00
	a.Soffit	0.00	0.00	0.00	0.00	8.09	0.00	0.00
	a.Sill	0.00	0.00	0.00	0.00	3.97	0.00	0.00

THERE ARE NO FAN CONNECTIONS

Compartment of origin is	1
Print interval (seconds)	60
Number of fire specification intervals is	12
Total time (seconds)	2700
Fire position	3
Limiting oxygen index (%) =	10.0

```
    Initial relative humidity (%) =                          1.0
    Fire type is a SPECIFIED (CONSTRAINED)
    Pyrolysis  temperature (K) =                            300.
    Ambient air temperature (K) =                           300.
    Ambient reference pressure (Pa) =                       101300.
    Reference elevation (m) =                                 0.
    Fmass=   0.0      1.9E-03  3.5E-03  4.8E-03  5.8E-03  6.7E-03  7.5E-03  8.1E-03  8.9E-03
9.6E-03  1.0E-02  1.1E-02   1.1E-02
    Hcomb=   3.3E+07  3.3E+07  3.2E+07  3.2E+07  3.3E+07  3.3E+07  3.2E+07  3.2E+07  3.3E+07
3.2E+07  3.3E+07     3.3E+07  3.3E+07
    Fqdot=   0.0      6.2E+04  1.1E+05  1.6E+05  1.9E+05  2.2E+05  2.4E+05  2.6E+05  2.9E+05
3.1E+05  3.4E+05     3.5E+05  3.5E+05
     Fhigh=   0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0
  0.0      0.0      0.0
     C/CO2=   3.4E-02  3.4E-02  3.4E-02  3.4E-02  3.4E-02  3.4E-02  3.4E-02  3.4E-02  3.4E-02
       3.4E-02  3.4E-02     3.4E-02  3.4E-02
     CO/CO2=  2.3E-02  2.3E-02  2.3E-02  2.3E-02  2.3E-02  2.3E-02  2.3E-02  2.3E-02  2.3E-02
       2.3E-02  2.3E-02     2.3E-02  2.3E-02
     H/C=     0.3      0.3      0.3      0.3      0.3      0.3      0.3      0.3      0.3      0.3
  0.3      0.3      0.3
     Ftime=   1.0E+02  1.0E+02  1.0E+02  1.0E+02  1.0E+02  1.0E+02  1.0E+02  2.0E+02  2.0E+02
5.0E+02  5.0E+02     6.0E+02
```

Time = 0.0 seconds.

Upper layer species

N2 %	79.1	79.1	79.1	79.1	79.1	79.1
O2 %	20.7	20.7	20.7	20.7	20.7	20.7
CO2 %	0.000	0.000	0.000	0.000	0.000	0.000
CO ppm	0.000	0.000	0.000	0.000	0.000	0.000
TUHC %	0.000	0.000	0.000	0.000	0.000	0.000
H2O %	0.273	0.273	0.273	0.273	0.273	0.273
OD 1/m	0.000	0.000	0.000	0.000	0.000	0.000

Lower layer species

N2 %	79.1	79.1	79.1	79.1	79.1	79.1
O2 %	20.7	20.7	20.7	20.7	20.7	20.7
CO2 %	0.000	0.000	0.000	0.000	0.000	0.000
CO ppm	0.000	0.000	0.000	0.000	0.000	0.000
TUHC %	0.000	0.000	0.000	0.000	0.000	0.000
H2O %	0.273	0.273	0.273	0.273	0.273	0.273
OD 1/m	0.000	0.000	0.000	0.000	0.000	0.000

Time = 60.0 seconds.

Upper layer species

N2 %	78.7	78.8	79.0	79.1	79.1	79.1
O2 %	20.2	20.4	20.6	20.7	20.7	20.7
CO2 %	0.282	0.165	4.519E-02	5.059E-03	1.885E-05	2.272E-08
CO ppm	102.	59.8	16.3	1.83	6.812E-03	8.210E-06
TUHC %	0.000	0.000	0.000	0.000	0.000	0.000
H2O %	0.778	0.569	0.354	0.282	0.273	0.273
OD 1/m	0.589	0.312	0.101	1.068E-02	4.028E-05	4.819E-08

Lower layer species

N2 %	79.1	79.1	79.1	79.1	79.1	79.1
O2 %	20.7	20.7	20.7	20.7	20.7	20.7
CO2 %	5.724E-03	1.934E-03	4.131E-08	2.173E-10	3.243E-13	4.427E-17
CO ppm	2.07	0.699	1.493E-05	7.852E-08	1.168E-10	0.000
TUHC %	0.000	0.000	0.000	0.000	0.000	0.000
H2O %	0.283	0.277	0.273	0.273	0.273	0.273
OD 1/m	1.264E-02	3.692E-03	8.843E-08	4.618E-10	6.893E-13	0.000

Time = 120.0 seconds.

Upper layer species

N2 %	78.2	78.4	78.8	79.0	79.1	79.1
O2 %	19.7	20.0	20.3	20.6	20.7	20.7
CO2 %	0.620	0.470	0.211	4.650E-02	1.355E-03	2.769E-05
CO ppm	224.	170.	76.2	16.8	0.490	1.001E-02
TUHC %	0.000	0.000	0.000	0.000	0.000	0.000
H2O %	1.39	1.12	0.651	0.357	0.276	0.273
OD 1/m	1.14	0.823	0.432	9.808E-02	2.891E-03	5.889E-05

Lower layer species

N2 %	79.0	79.0	79.1	79.1	79.1	79.1
O2 %	20.6	20.6	20.7	20.7	20.7	20.7
CO2 %	1.123E-02	1.898E-02	4.285E-04	1.588E-09	3.554E-11	7.075E-14
CO ppm	4.06	6.86	0.155	5.740E-07	1.284E-08	2.535E-11
TUHC %	0.000	0.000	0.000	0.000	0.000	0.000
H2O %	0.293	0.307	0.274	0.273	0.273	0.273
OD 1/m	2.401E-02	3.929E-02	9.104E-04	3.398E-09	7.602E-11	1.502E-13

Time = 180.0 seconds.

Upper layer species

N2 %	77.9	78.0	78.5	78.8	79.0	79.1
O2 %	19.4	19.6	20.1	20.4	20.6	20.7
CO2 %	0.819	0.720	0.409	0.167	1.183E-02	5.099E-04
CO ppm	296.	260.	148.	60.4	4.28	0.184
TUHC %	0.000	0.000	0.000	0.000	0.000	0.000
H2O %	1.75	1.57	1.01	0.573	0.295	0.274
OD 1/m	1.41	1.27	0.817	0.348	2.530E-02	1.090E-03

Lower layer species

N2 %	79.0	79.0	79.1	79.1	79.1	79.1
O2 %	20.6	20.6	20.7	20.7	20.7	20.7
CO2 %	1.347E-02	1.132E-02	6.544E-03	1.883E-03	6.473E-11	2.823E-13
CO ppm	4.87	4.09	2.37	0.681	2.340E-08	1.017E-10
TUHC %	0.000	0.000	0.000	0.000	0.000	0.000
H2O %	0.297	0.294	0.285	0.277	0.273	0.273
OD 1/m	2.884E-02	2.330E-02	1.388E-02	4.029E-03	1.393E-10	6.057E-13

Time = 240.0 seconds.

Upper layer species

N2 %	77.5	77.8	78.2	78.5	79.0	79.1
O2 %	19.1	19.3	19.8	20.1	20.6	20.7
CO2 %	1.03	0.883	0.595	0.350	5.226E-02	2.266E-03
CO ppm	374.	319.	215.	127.	18.9	0.819
TUHC %	0.000	0.000	0.000	0.000	0.000	0.000
H2O %	2.14	1.87	1.35	0.904	0.367	0.277
OD 1/m	1.61	1.56	1.17	0.722	0.111	4.873E-03

Lower layer species

N2 %	79.0	79.0	79.0	79.0	79.1	79.1
O2 %	20.6	20.6	20.6	20.6	20.7	20.7
CO2 %	1.225E-02	1.292E-02	1.997E-02	2.603E-02	7.101E-04	3.715E-13
CO ppm	4.43	4.67	7.22	9.41	0.257	1.340E-10
TUHC %	0.000	0.000	0.000	0.000	0.000	0.000
H2O %	0.295	0.297	0.309	0.320	0.275	0.273
OD 1/m	2.569E-02	2.817E-02	4.187E-02	5.574E-02	1.539E-03	8.028E-13

Time = 300.0 seconds.

Upper layer species

N2 %	77.3	77.6	77.9	78.3	78.8	79.1
O2 %	18.9	19.1	19.5	19.8	20.4	20.7
CO2 %	1.17	1.02	0.770	0.549	0.151	7.963E-03
CO ppm	423.	368.	278.	198.	54.7	2.88
TUHC %	0.000	0.000	0.000	0.000	0.000	0.000
H2O %	2.38	2.11	1.66	1.26	0.546	0.288
OD 1/m	1.85	1.73	1.51	1.12	0.321	1.719E-02

Lower layer species

N2 %	79.0	79.0	79.0	79.0	79.0	79.1
O2 %	20.6	20.6	20.6	20.6	20.6	20.7
CO2 %	1.669E-02	2.705E-02	4.714E-02	7.589E-02	2.835E-02	3.715E-13
CO ppm	6.03	9.77	17.0	27.4	10.2	1.348E-10
TUHC %	0.000	0.000	0.000	0.000	0.000	0.000
H2O %	0.303	0.322	0.358	0.410	0.324	0.273
OD 1/m	3.564E-02	5.662E-02	9.920E-02	0.162	6.145E-02	8.077E-13

Time = 360.0 seconds.

Upper layer species

N2 %	77.1	77.4	77.7	78.0	78.6	79.0
O2 %	18.7	18.9	19.3	19.5	20.2	20.6
CO2 %	1.31	1.16	0.932	0.750	0.298	2.385E-02
CO ppm	475.	418.	337.	271.	108.	8.62
TUHC %	0.000	0.000	0.000	0.000	0.000	0.000
H2O %	2.64	2.35	1.95	1.63	0.811	0.316
OD 1/m	1.99	1.96	1.81	1.52	0.628	5.161E-02

Lower layer species

N2 %	79.0	79.0	78.9	78.8	78.9	79.1
O2 %	20.6	20.6	20.5	20.4	20.5	20.7
CO2 %	3.424E-02	6.467E-02	0.106	0.156	8.011E-02	3.715E-13
CO ppm	12.4	23.4	38.1	56.3	29.0	1.348E-10
TUHC %	0.000	0.000	0.000	0.000	0.000	0.000
H2O %	0.335	0.390	0.464	0.554	0.418	0.273
OD 1/m	7.252E-02	0.134	0.223	0.332	0.173	8.142E-13

Time = 420.0 seconds.

Upper layer species

N2 %	76.9	77.2	77.5	77.7	78.4	79.0
O2 %	18.5	18.7	19.0	19.3	20.0	20.6
CO2 %	1.46	1.31	1.09	0.935	0.465	5.505E-02
CO ppm	527.	472.	394.	338.	168.	19.9
TUHC %	0.000	0.000	0.000	0.000	0.000	0.000
H2O %	2.89	2.62	2.24	1.96	1.11	0.373
OD 1/m	2.24	2.13	2.10	1.88	0.977	0.119

Lower layer species

N2 %	79.0	78.9	78.8	78.7	78.9	79.1
O2 %	20.6	20.5	20.4	20.3	20.5	20.7
CO2 %	7.437E-02	0.132	0.187	0.229	0.127	3.715E-13
CO ppm	26.9	47.8	67.4	82.9	45.9	1.354E-10
TUHC %	0.000	0.000	0.000	0.000	0.000	0.000
H2O %	0.407	0.512	0.610	0.687	0.503	0.273
OD 1/m	0.158	0.257	0.401	0.487	0.276	8.209E-13

Time = 480.0 seconds.

Upper layer species

N2 %	76.7	76.9	77.2	77.4	78.1	78.9
O2 %	18.2	18.4	18.8	19.0	19.7	20.5
CO2 %	1.64	1.48	1.26	1.11	0.629	0.105
CO ppm	593.	536.	454.	400.	227.	37.9
TUHC %	0.000	0.000	0.000	0.000	0.000	0.000
H2O %	3.22	2.93	2.53	2.26	1.41	0.462
OD 1/m	2.41	2.37	2.40	2.21	1.32	0.226

Lower layer species

N2 %	78.9	78.8	78.7	78.6	78.8	79.1
O2 %	20.5	20.3	20.3	20.2	20.4	20.7
CO2 %	0.137	0.212	0.266	0.284	0.153	3.715E-13
CO ppm	49.6	76.5	96.2	103.	55.2	1.354E-10
TUHC %	0.000	0.000	0.000	0.000	0.000	0.000
H2O %	0.521	0.655	0.753	0.785	0.549	0.273
OD 1/m	0.287	0.416	0.577	0.605	0.333	8.274E-13

Time = 540.0 seconds.

Upper layer species

N2 %	76.5	76.6	77.0	77.2	77.9	78.8
O2 %	18.0	18.2	18.5	18.8	19.5	20.4
CO2 %	1.78	1.65	1.43	1.28	0.781	0.171
CO ppm	644.	597.	518.	462.	282.	61.8
TUHC %	0.000	0.000	0.000	0.000	0.000	0.000
H2O %	3.48	3.24	2.85	2.57	1.68	0.581
OD 1/m	2.60	2.59	2.72	2.54	1.64	0.369

Lower layer species

N2 %	78.8	78.6	78.6	78.6	78.8	79.1
O2 %	20.3	20.2	20.2	20.2	20.4	20.7
CO2 %	0.210	0.285	0.330	0.310	0.153	3.715E-13
CO ppm	75.9	103.	119.	112.	55.3	1.338E-10
TUHC %	0.000	0.000	0.000	0.000	0.000	0.000
H2O %	0.652	0.786	0.868	0.831	0.549	0.273
OD 1/m	0.440	0.562	0.723	0.666	0.337	8.387E-13

Time = 600.0 seconds.

Upper layer species

N2 %	76.2	76.4	76.7	77.0	77.7	78.7
O2 %	17.8	18.0	18.3	18.5	19.3	20.3
CO2 %	1.92	1.80	1.60	1.44	0.932	0.246
CO ppm	693.	650.	579.	522.	337.	89.1
TUHC %	0.000	0.000	0.000	0.000	0.000	0.000
H2O %	3.74	3.51	3.15	2.87	1.95	0.717
OD 1/m	2.73	2.82	3.02	2.86	1.95	0.531

Lower layer species

N2 %	78.7	78.6	78.5	78.6	78.9	79.1
O2 %	20.2	20.2	20.1	20.2	20.5	20.7
CO2 %	0.278	0.340	0.372	0.307	0.131	3.715E-13
CO ppm	101.	123.	134.	111.	47.4	1.320E-10
TUHC %	0.000	0.000	0.000	0.000	0.000	0.000
H2O %	0.774	0.886	0.942	0.826	0.510	0.273
OD 1/m	0.582	0.678	0.823	0.666	0.291	8.500E-13

Time = 660.0 seconds.

Upper layer species

N2 %	76.1	76.2	76.5	76.7	77.5	78.6
O2 %	17.6	17.8	18.0	18.3	19.0	20.2
CO2 %	2.02	1.92	1.76	1.61	1.09	0.326
CO ppm	729.	695.	635.	580.	392.	118.
TUHC %	0.000	0.000	0.000	0.000	0.000	0.000
H2O %	3.91	3.74	3.44	3.16	2.23	0.859
OD 1/m	2.84	2.99	3.31	3.18	2.27	0.700

Lower layer species

N2 %	78.6	78.5	78.5	78.7	78.9	79.1
O2 %	20.2	20.1	20.1	20.2	20.5	20.7
CO2 %	0.331	0.373	0.387	0.277	9.281E-02	3.715E-13
CO ppm	120.	135.	140.	100.	33.5	1.307E-10
TUHC %	0.000	0.000	0.000	0.000	0.000	0.000
H2O %	0.869	0.944	0.970	0.771	0.440	0.273
OD 1/m	0.699	0.748	0.866	0.604	0.208	8.611E-13

Time = 720.0 seconds.

Upper layer species

N2 %	76.0	76.1	76.3	76.5	77.3	78.5
O2 %	17.6	17.7	17.8	18.0	18.8	20.1
CO2 %	2.07	2.01	1.88	1.75	1.22	0.409
CO ppm	749.	725.	681.	634.	441.	148.
TUHC %	0.000	0.000	0.000	0.000	0.000	0.000
H2O %	4.01	3.89	3.67	3.44	2.47	1.01
OD 1/m	2.90	3.12	3.55	3.48	2.55	0.879

Lower layer species

N2 %	78.5	78.5	78.5	78.7	79.0	79.1
O2 %	20.1	20.1	20.1	20.3	20.6	20.7
CO2 %	0.362	0.380	0.376	0.226	5.226E-02	3.715E-13
CO ppm	131.	137.	136.	81.8	18.9	1.315E-10
TUHC %	0.000	0.000	0.000	0.000	0.000	0.000
H2O %	0.924	0.957	0.951	0.681	0.367	0.273
OD 1/m	0.773	0.769	0.851	0.500	0.118	8.735E-13

Time = 780.0 seconds.

Upper layer species

N2 %	76.0	76.1	76.2	76.3	77.1	78.3
O2 %	17.5	17.6	17.7	17.9	18.7	19.9
CO2 %	2.10	2.04	1.97	1.88	1.32	0.494
CO ppm	757.	739.	712.	679.	478.	179.
TUHC %	0.000	0.000	0.000	0.000	0.000	0.000
H2O %	4.04	3.96	3.82	3.66	2.65	1.16
OD 1/m	2.96	3.17	3.73	3.74	2.77	1.06

Lower layer species

N2 %	78.5	78.5	78.6	78.8	79.0	79.1
O2 %	20.1	20.1	20.1	20.4	20.6	20.7
CO2 %	0.368	0.363	0.345	0.170	2.542E-02	3.715E-13
CO ppm	133.	131.	125.	61.3	9.19	1.318E-10
TUHC %	0.000	0.000	0.000	0.000	0.000	0.000
H2O %	0.936	0.927	0.895	0.579	0.319	0.273
OD 1/m	0.795	0.740	0.790	0.378	5.768E-02	8.780E-13

Time = 840.0 seconds.

Upper layer species

N2 %	76.0	76.1	76.1	76.2	77.0	78.2
O2 %	17.5	17.6	17.6	17.7	18.6	19.8
CO2 %	2.10	2.06	2.02	1.96	1.38	0.578
CO ppm	758.	743.	730.	710.	497.	209.
TUHC %	0.000	0.000	0.000	0.000	0.000	0.000
H2O %	4.04	3.97	3.91	3.81	2.75	1.31
OD 1/m	2.98	3.20	3.85	3.94	2.89	1.24

Lower layer species

N2 %	78.5	78.6	78.6	78.9	79.0	79.1
O2 %	20.1	20.2	20.2	20.5	20.6	20.7
CO2 %	0.352	0.328	0.299	0.112	1.232E-02	3.715E-13
CO ppm	127.	118.	108.	40.5	4.45	1.315E-10
TUHC %	0.000	0.000	0.000	0.000	0.000	0.000
H2O %	0.908	0.864	0.813	0.475	0.295	0.273
OD 1/m	0.769	0.669	0.694	0.251	2.816E-02	8.803E-13

Time = 900.0 seconds.

Upper layer species

N2 %	76.0	76.1	76.1	76.2	77.0	78.1
O2 %	17.5	17.6	17.6	17.7	18.6	19.7
CO2 %	2.10	2.05	2.04	1.98	1.40	0.655
CO ppm	760.	742.	737.	716.	506.	237.
TUHC %	0.000	0.000	0.000	0.000	0.000	0.000
H2O %	4.04	3.96	3.94	3.84	2.80	1.45
OD 1/m	2.98	3.22	3.91	4.01	2.96	1.41

Lower layer species

N2 %	78.6	78.7	78.7	79.0	79.1	79.1
O2 %	20.2	20.2	20.3	20.6	20.7	20.7
CO2 %	0.318	0.277	0.240	5.782E-02	5.882E-03	3.715E-13
CO ppm	115.	100.	86.8	20.9	2.13	1.382E-10
TUHC %	0.000	0.000	0.000	0.000	0.000	0.000
H2O %	0.846	0.773	0.706	0.377	0.284	0.273
OD 1/m	0.697	0.580	0.562	0.131	1.358E-02	8.754E-13

Time = 960.0 seconds.

Upper layer species

N2 %	76.0	76.1	76.1	76.2	77.0	78.0
O2 %	17.6	17.6	17.6	17.8	18.5	19.6
CO2 %	2.08	2.02	2.04	1.94	1.41	0.724
CO ppm	752.	731.	736.	703.	510.	262.
TUHC %	0.000	0.000	0.000	0.000	0.000	0.000
H2O %	4.01	3.90	3.93	3.77	2.81	1.58
OD 1/m	2.99	3.23	3.94	3.98	3.00	1.56

Lower layer species

N2 %	78.7	78.7	78.8	79.0	79.0	79.1
O2 %	20.3	20.3	20.4	20.6	20.6	20.7
CO2 %	0.269	0.216	0.176	2.471E-02	9.993E-03	3.714E-13
CO ppm	97.1	78.1	63.8	8.93	3.61	1.480E-10
TUHC %	0.000	0.000	0.000	0.000	0.000	0.000
H2O %	0.757	0.662	0.591	0.318	0.291	0.273
OD 1/m	0.593	0.460	0.417	5.682E-02	2.342E-02	8.892E-13

Time = 1020.0 seconds.

Upper layer species

N2 %	76.1	76.2	76.1	76.3	77.0	77.9
O2 %	17.6	17.7	17.7	17.8	18.6	19.5
CO2 %	2.04	1.97	2.00	1.88	1.41	0.787
CO ppm	739.	714.	724.	681.	510.	284.
TUHC %	0.000	0.000	0.000	0.000	0.000	0.000
H2O %	3.95	3.82	3.87	3.66	2.81	1.69
OD 1/m	3.08	3.17	3.93	3.88	3.01	1.70

Lower layer species

N2 %	78.8	78.8	78.9	79.0	79.0	79.1
O2 %	20.3	20.4	20.5	20.6	20.6	20.7
CO2 %	0.211	0.156	0.125	2.840E-02	5.009E-02	3.714E-13
CO ppm	76.3	56.5	45.3	10.3	18.1	1.622E-10
TUHC %	0.000	0.000	0.000	0.000	0.000	0.000
H2O %	0.653	0.555	0.499	0.324	0.363	0.273
OD 1/m	0.465	0.327	0.302	6.643E-02	0.120	9.244E-13

Time = 1080.0 seconds.

Upper layer species

N2 %	76.1	76.2	76.2	76.4	77.0	77.8
O2 %	17.6	17.8	17.7	18.0	18.6	19.4
CO2 %	2.04	1.95	1.96	1.81	1.40	0.843
CO ppm	739.	703.	707.	655.	505.	305.
TUHC %	0.000	0.000	0.000	0.000	0.000	0.000
H2O %	3.95	3.77	3.79	3.53	2.79	1.79
OD 1/m	3.10	3.20	3.88	3.76	3.00	1.82

Lower layer species

N2 %	78.8	78.9	78.9	78.9	78.8	79.1
O2 %	20.4	20.5	20.5	20.5	20.4	20.7
CO2 %	0.158	0.114	0.101	8.991E-02	0.160	3.715E-13
CO ppm	57.1	41.3	36.4	32.5	57.8	1.836E-10
TUHC %	0.000	0.000	0.000	0.000	0.000	0.000
H2O %	0.558	0.479	0.455	0.435	0.561	0.273
OD 1/m	0.342	0.244	0.248	0.217	0.397	1.073E-12

Time = 1140.0 seconds.

Upper layer species

N2 %	76.1	76.3	76.3	76.5	77.1	77.8
O2 %	17.7	17.8	17.8	18.1	18.6	19.3
CO2 %	2.01	1.91	1.91	1.75	1.37	0.889
CO ppm	728.	689.	689.	631.	496.	321.
TUHC %	0.000	0.000	0.000	0.000	0.000	0.000
H2O %	3.90	3.70	3.70	3.41	2.74	1.87
OD 1/m	3.17	3.22	3.82	3.65	2.96	1.93

Lower layer species

N2 %	78.9	78.9	78.9	78.7	78.5	79.1
O2 %	20.5	20.5	20.5	20.3	20.1	20.7
CO2 %	0.126	0.113	0.127	0.248	0.360	3.715E-13
CO ppm	45.4	41.0	46.0	89.5	130.	2.091E-10
TUHC %	0.000	0.000	0.000	0.000	0.000	0.000
H2O %	0.499	0.478	0.502	0.718	0.920	0.273
OD 1/m	0.271	0.261	0.331	0.658	0.963	1.201E-12

Time = 1200.0 seconds.

Upper layer species

N2 %	76.2	76.3	76.3	76.6	77.1	77.7
O2 %	17.7	17.9	17.9	18.1	18.6	19.3
CO2 %	1.98	1.87	1.86	1.70	1.37	0.931
CO ppm	717.	677.	671.	615.	494.	336.
TUHC %	0.000	0.000	0.000	0.000	0.000	0.000
H2O %	3.85	3.65	3.62	3.33	2.73	1.95
OD 1/m	3.24	3.33	3.78	3.59	2.96	2.02

Lower layer species

N2 %	78.9	78.8	78.7	78.4	78.2	79.1
O2 %	20.4	20.4	20.3	19.9	19.8	20.7
CO2 %	0.144	0.195	0.245	0.484	0.561	3.715E-13
CO ppm	52.1	70.3	88.5	175.	203.	2.546E-10
TUHC %	0.000	0.000	0.000	0.000	0.000	0.000
H2O %	0.533	0.623	0.713	1.14	1.28	0.273
OD 1/m	0.314	0.488	0.678	1.33	1.49	1.412E-12

Time = 1260.0 seconds.

Upper layer species

N2 %	76.0	76.2	76.4	76.6	77.1	77.6
O2 %	17.6	17.8	17.9	18.2	18.6	19.2
CO2 %	2.06	1.93	1.84	1.67	1.36	0.969
CO ppm	744.	696.	666.	604.	492.	350.
TUHC %	5.508E-08	3.028E-08	7.125E-09	1.352E-09	1.058E-10	1.107E-12
H2O %	3.98	3.74	3.59	3.28	2.72	2.02
OD 1/m	3.49	3.53	3.83	3.58	2.96	2.11

Lower layer species

N2 %	78.7	78.4	78.3	78.1	78.1	79.1
O2 %	20.3	20.0	19.9	19.7	19.6	20.7
CO2 %	0.264	0.432	0.527	0.674	0.681	3.718E-13
CO ppm	95.6	156.	190.	244.	246.	3.075E-10
TUHC %	7.221E-12	6.543E-11	2.013E-10	1.785E-11	8.509E-12	0.000
H2O %	0.749	1.05	1.22	1.49	1.50	0.273
OD 1/m	0.584	1.16	1.48	1.88	1.83	1.895E-12

Time = 1320.0 seconds.

Upper layer species

N2 %	75.7	76.0	76.3	76.6	77.1	77.6
O2 %	17.3	17.5	17.8	18.2	18.6	19.2
CO2 %	2.28	2.09	1.90	1.67	1.36	1.00
CO ppm	823.	754.	685.	605.	492.	362.
TUHC %	7.455E-08	5.266E-08	2.689E-08	1.126E-08	2.434E-09	8.496E-11
H2O %	4.38	4.03	3.69	3.29	2.72	2.08
OD 1/m	3.92	3.85	4.00	3.64	2.98	2.19

Lower layer species

N2 %	78.3	77.8	77.7	77.9	77.9	79.1
O2 %	19.9	19.4	19.3	19.5	19.5	20.7
CO2 %	0.538	0.852	0.927	0.776	0.765	3.713E-13
CO ppm	194.	308.	335.	281.	276.	3.677E-10
TUHC %	9.670E-10	3.385E-09	4.619E-09	6.053E-10	5.366E-10	0.000
H2O %	1.24	1.81	1.94	1.67	1.65	0.273
OD 1/m	1.25	2.40	2.66	2.09	2.00	2.363E-12

Time = 1380.0 seconds.

Upper layer species

N2 %	75.3	75.7	76.1	76.5	77.0	77.6
O2 %	16.8	17.2	17.6	18.1	18.6	19.1
CO2 %	2.55	2.30	2.02	1.73	1.38	1.03
CO ppm	922.	832.	731.	625.	500.	373.
TUHC %	9.527E-08	7.027E-08	4.372E-08	2.334E-08	7.523E-09	4.849E-10
H2O %	4.87	4.42	3.91	3.39	2.76	2.13
OD 1/m	4.34	4.21	4.28	3.79	3.05	2.26

Lower layer species

N2 %	77.8	77.3	77.3	77.8	77.8	79.1
O2 %	19.3	18.9	18.9	19.4	19.4	20.7
CO2 %	0.883	1.19	1.20	0.845	0.836	3.719E-13
CO ppm	319.	431.	433.	305.	302.	4.239E-10
TUHC %	7.455E-09	1.333E-08	1.356E-08	2.370E-09	2.399E-09	0.000
H2O %	1.86	2.42	2.43	1.79	1.78	0.273
OD 1/m	2.17	3.44	3.33	2.33	2.24	3.097E-12

Time = 1440.0 seconds.

Upper layer species

N2 %	75.0	75.4	75.9	76.4	77.0	77.5
O2 %	16.5	16.9	17.4	17.9	18.5	19.1
CO2 %	2.78	2.49	2.17	1.82	1.43	1.06
CO ppm	1.003E+03	900.	784.	657.	516.	384.
TUHC %	1.172E-07	8.994E-08	6.031E-08	3.534E-08	1.372E-08	1.331E-09
H2O %	5.27	4.76	4.18	3.55	2.84	2.19
OD 1/m	4.72	4.56	4.60	4.00	3.16	2.34

Lower layer species

N2 %	77.1	77.1	77.1	77.7	77.7	79.1
O2 %	18.6	18.6	18.6	19.3	19.3	20.7
CO2 %	1.36	1.35	1.35	0.907	0.903	3.726E-13
CO ppm	491.	489.	488.	328.	326.	4.663E-10
TUHC %	2.900E-08	2.279E-08	2.287E-08	5.067E-09	5.256E-09	0.000
H2O %	2.72	2.71	2.70	1.90	1.90	0.273
OD 1/m	3.21	3.98	3.85	2.65	2.54	4.299E-12

Time = 1500.0 seconds.

Upper layer species

N2 %	74.7	75.1	75.7	76.3	76.9	77.5
O2 %	16.2	16.6	17.2	17.8	18.4	19.0
CO2 %	3.00	2.68	2.32	1.92	1.48	1.10
CO ppm	1.084E+03	970.	839.	694.	536.	396.
TUHC %	1.315E-07	1.062E-07	7.630E-08	4.735E-08	2.037E-08	2.621E-09
H2O %	5.67	5.10	4.45	3.73	2.94	2.24
OD 1/m	5.25	4.78	4.96	4.23	3.30	2.42

Lower layer species

N2 %	76.4	76.9	76.9	77.6	77.6	79.1
O2 %	17.9	18.4	18.4	19.2	19.2	20.7
CO2 %	1.83	1.48	1.48	0.975	0.981	3.719E-13
CO ppm	661.	536.	536.	352.	354.	5.369E-10
TUHC %	5.676E-08	3.245E-08	3.268E-08	8.370E-09	8.709E-09	0.000
H2O %	3.56	2.94	2.94	2.03	2.04	0.273
OD 1/m	4.19	4.31	4.33	2.96	2.84	6.010E-12

Time = 1560.0 seconds.

Upper layer species

N2 %	74.3	74.9	75.4	76.1	76.8	77.4
O2 %	15.8	16.4	17.0	17.6	18.3	19.0
CO2 %	3.23	2.88	2.48	2.03	1.55	1.13
CO ppm	1.167E+03	1.040E+03	896.	734.	560.	408.
TUHC %	1.402E-07	1.168E-07	8.909E-08	5.817E-08	2.709E-08	4.330E-09
H2O %	6.08	5.45	4.74	3.93	3.06	2.31
OD 1/m	5.62	5.16	5.31	4.48	3.47	2.50

Lower layer species

N2 %	75.8	76.7	76.7	77.5	77.5	79.1
O2 %	17.3	18.2	18.2	19.1	19.1	20.7
CO2 %	2.26	1.63	1.64	1.06	1.08	3.754E-13
CO ppm	815.	589.	592.	383.	389.	6.166E-10
TUHC %	8.221E-08	4.251E-08	4.298E-08	1.225E-08	1.290E-08	0.000
H2O %	4.33	3.21	3.22	2.18	2.21	0.273
OD 1/m	4.96	7.61	4.63	3.32	3.15	8.801E-12

Time = 1620.0 seconds.

Upper layer species

N2 %	74.0	74.6	75.2	75.9	76.7	77.4
O2 %	15.5	16.1	16.7	17.4	18.2	18.9
CO2 %	3.45	3.07	2.64	2.15	1.62	1.17
CO ppm	1.246E+03	1.108E+03	955.	777.	587.	421.
TUHC %	1.522E-07	1.274E-07	9.968E-08	6.726E-08	3.338E-08	6.406E-09
H2O %	6.48	5.79	5.03	4.14	3.19	2.37
OD 1/m	5.88	5.63	5.65	4.76	3.64	2.59

Lower layer species

N2 %	75.2	76.4	76.4	77.3	77.3	79.1
O2 %	16.7	17.9	17.9	18.9	18.9	20.7
CO2 %	2.64	1.81	1.82	1.17	1.21	3.863E-13
CO ppm	954.	655.	660.	424.	436.	6.626E-10
TUHC %	1.039E-07	5.313E-08	5.374E-08	1.674E-08	1.782E-08	0.000
H2O %	5.02	3.54	3.56	2.38	2.44	0.273
OD 1/m	5.66	6.91	5.24	3.73	3.53	1.177E-11

Time = 1680.0 seconds.

Upper layer species

N2 %	73.7	74.3	75.0	75.7	76.6	77.3
O2 %	15.2	15.8	16.5	17.3	18.1	18.9
CO2 %	3.66	3.25	2.80	2.27	1.70	1.21
CO ppm	1.323E+03	1.176E+03	1.013E+03	820.	615.	436.
TUHC %	1.608E-07	1.361E-07	1.090E-07	7.527E-08	3.915E-08	8.781E-09
H2O %	6.86	6.13	5.32	4.36	3.33	2.44
OD 1/m	6.19	6.02	6.02	5.04	3.83	2.68

Lower layer species

N2 %	74.7	76.1	76.1	77.1	77.1	79.1
O2 %	16.2	17.6	17.6	18.7	18.6	20.7
CO2 %	3.01	2.03	2.06	1.32	1.37	3.906E-13
CO ppm	1.086E+03	735.	743.	478.	497.	6.747E-10
TUHC %	1.235E-07	6.479E-08	6.594E-08	2.196E-08	2.370E-08	0.000
H2O %	5.68	3.93	3.97	2.65	2.75	0.273
OD 1/m	6.17	5.60	6.24	4.48	4.26	1.341E-11

Time = 1740.0 seconds.

Upper layer species

N2 %	73.4	74.0	74.7	75.6	76.5	77.2
O2 %	14.9	15.5	16.2	17.1	18.0	18.8
CO2 %	3.86	3.43	2.96	2.39	1.78	1.25
CO ppm	1.396E+03	1.241E+03	1.071E+03	864.	644.	451.
TUHC %	1.736E-07	1.473E-07	1.181E-07	8.257E-08	4.452E-08	1.140E-08
H2O %	7.22	6.45	5.61	4.58	3.48	2.52
OD 1/m	6.46	6.42	6.35	5.33	4.03	2.79

Lower layer species

N2 %	74.2	75.7	75.7	77.0	77.0	79.1
O2 %	15.7	17.2	17.2	18.6	18.6	20.7
CO2 %	3.35	2.28	2.32	1.40	1.41	3.914E-13
CO ppm	1.210E+03	825.	838.	507.	510.	6.760E-10
TUHC %	1.428E-07	7.808E-08	8.022E-08	2.549E-08	2.602E-08	0.000
H2O %	6.30	4.38	4.45	2.80	2.81	0.273
OD 1/m	6.67	6.96	8.46	4.85	2.08	1.686E-11

Time = 1800.0 seconds.

Upper layer species

N2 %	73.1	73.8	74.5	75.4	76.3	77.2
O2 %	14.6	15.2	16.0	16.9	17.9	18.7
CO2 %	4.07	3.62	3.12	2.52	1.87	1.29
CO ppm	1.470E+03	1.307E+03	1.129E+03	909.	675.	467.
TUHC %	1.839E-07	1.567E-07	1.275E-07	9.015E-08	4.984E-08	1.423E-08
H2O %	7.59	6.78	5.90	4.80	3.63	2.60
OD 1/m	6.79	6.72	6.70	5.62	4.24	2.90

Lower layer species

N2 %	73.6	74.9	74.9	77.0	77.0	79.1
O2 %	15.1	16.5	16.4	18.5	18.6	20.7
CO2 %	3.70	2.81	2.86	1.44	1.41	3.914E-13
CO ppm	1.338E+03	1.017E+03	1.034E+03	521.	510.	6.760E-10
TUHC %	1.630E-07	1.093E-07	1.121E-07	2.779E-08	2.602E-08	0.000
H2O %	6.94	5.34	5.42	2.87	2.81	0.273
OD 1/m	7.02	4.16	6.47	0.551	0.183	2.619E-11

Time = 1860.0 seconds.

Upper layer species

N2 %	72.8	73.5	74.3	75.2	76.2	77.1
O2 %	14.3	15.0	15.7	16.7	17.7	18.7
CO2 %	4.26	3.80	3.29	2.64	1.96	1.34
CO ppm	1.540E+03	1.372E+03	1.188E+03	956.	707.	485.
TUHC %	1.892E-07	1.626E-07	1.351E-07	9.718E-08	5.518E-08	1.729E-08
H2O %	7.94	7.10	6.19	5.03	3.79	2.69
OD 1/m	7.07	6.98	7.03	5.91	4.45	3.02

Lower layer species

N2 %	73.2	74.4	74.4	76.5	77.0	79.1
O2 %	14.7	15.9	15.9	18.1	18.6	20.7
CO2 %	3.98	3.17	3.19	1.72	1.41	3.914E-13
CO ppm	1.438E+03	1.145E+03	1.153E+03	622.	510.	6.760E-10
TUHC %	1.750E-07	1.293E-07	1.304E-07	4.395E-08	2.603E-08	0.000
H2O %	7.43	5.98	6.02	3.37	2.81	0.273
OD 1/m	7.22	4.16	6.53	8.245E-02	1.592E-02	2.619E-11

Time = 1920.0 seconds.

Upper layer species

N2 %	72.6	73.3	74.0	75.0	76.1	77.0
O2 %	14.0	14.7	15.5	16.5	17.6	18.6
CO2 %	4.44	3.96	3.44	2.77	2.05	1.40
CO ppm	1.605E+03	1.433E+03	1.244E+03	1.001E+03	739.	504.
TUHC %	1.977E-07	1.716E-07	1.427E-07	1.036E-07	6.024E-08	2.055E-08
H2O %	8.26	7.41	6.47	5.26	3.95	2.78
OD 1/m	7.23	7.33	7.32	6.20	4.67	3.15

Lower layer species

N2 %	72.9	74.1	74.1	75.4	77.0	79.1
O2 %	14.4	15.6	15.6	16.9	18.6	20.7
CO2 %	4.19	3.36	3.38	2.48	1.41	3.914E-13
CO ppm	1.513E+03	1.216E+03	1.221E+03	898.	510.	6.760E-10
TUHC %	1.853E-07	1.388E-07	1.396E-07	8.740E-08	2.600E-08	0.000
H2O %	7.81	6.33	6.35	4.74	2.81	0.273
OD 1/m	7.51	7.37	6.43	4.051E-02	1.360E-03	2.619E-11

Time = 1980.0 seconds.

Upper layer species

N2 %	72.3	73.0	73.8	74.8	75.9	76.9
O2 %	13.8	14.5	15.3	16.3	17.5	18.5
CO2 %	4.61	4.12	3.59	2.89	2.13	1.45
CO ppm	1.665E+03	1.490E+03	1.299E+03	1.046E+03	772.	525.
TUHC %	2.034E-07	1.775E-07	1.498E-07	1.097E-07	6.508E-08	2.396E-08
H2O %	8.56	7.69	6.74	5.48	4.11	2.89
OD 1/m	7.50	7.57	7.62	6.46	4.88	3.29

Lower layer species

N2 %	72.7	73.9	73.9	74.9	77.0	79.1
O2 %	14.1	15.4	15.4	16.4	18.6	20.7
CO2 %	4.37	3.52	3.54	2.83	1.41	3.914E-13
CO ppm	1.579E+03	1.273E+03	1.278E+03	1.023E+03	510.	6.760E-10
TUHC %	1.932E-07	1.465E-07	1.471E-07	1.065E-07	3.935E-08	0.000
H2O %	8.14	6.61	6.64	5.37	2.81	0.273
OD 1/m	7.80	3.62	6.26	3.511E-02	1.127E-04	2.586E-11

Time = 2040.0 seconds.

Upper layer species

N2 %	72.1	72.8	73.6	74.7	75.8	76.9
O2 %	13.5	14.3	15.1	16.2	17.3	18.4
CO2 %	4.76	4.28	3.74	3.01	2.22	1.51
CO ppm	1.721E+03	1.545E+03	1.351E+03	1.089E+03	804.	546.
TUHC %	2.102E-07	1.844E-07	1.562E-07	1.155E-07	6.983E-08	2.752E-08
H2O %	8.84	7.97	7.00	5.70	4.28	2.99
OD 1/m	7.70	7.79	7.91	6.72	5.09	3.44

Lower layer species

N2 %	72.4	73.7	73.7	74.7	77.0	79.1
O2 %	13.9	15.2	15.2	16.2	18.6	20.7
CO2 %	4.54	3.67	3.68	2.98	1.41	3.914E-13
CO ppm	1.640E+03	1.326E+03	1.331E+03	1.077E+03	510.	6.760E-10
TUHC %	2.002E-07	1.532E-07	1.538E-07	1.139E-07	1.647E-07	0.000
H2O %	8.44	6.88	6.90	5.64	2.81	0.273
OD 1/m	8.00	5.31	7.45	3.717E-02	9.468E-06	2.619E-11

Time = 2100.0 seconds.

Upper layer species

N2 %	71.9	72.6	73.4	74.5	75.7	76.8
O2 %	13.3	14.0	14.9	16.0	17.2	18.3
CO2 %	4.91	4.42	3.88	3.13	2.31	1.57
CO ppm	1.775E+03	1.598E+03	1.401E+03	1.132E+03	836.	569.
TUHC %	2.172E-07	1.913E-07	1.623E-07	1.209E-07	7.440E-08	3.119E-08
H2O %	9.11	8.23	7.25	5.91	4.44	3.11
OD 1/m	7.94	7.98	8.18	6.97	5.31	3.59

Lower layer species

N2 %	72.2	73.5	73.5	74.5	77.0	79.1
O2 %	13.6	15.0	14.9	16.0	18.6	20.7
CO2 %	4.70	3.81	3.82	3.10	1.41	3.914E-13
CO ppm	1.697E+03	1.377E+03	1.382E+03	1.120E+03	510.	6.760E-10
TUHC %	2.070E-07	1.593E-07	1.598E-07	1.195E-07	1.956E-06	0.000
H2O %	8.72	7.13	7.15	5.85	2.81	0.273
OD 1/m	8.15	4.23	7.72	3.897E-02	7.708E-07	2.619E-11

Time = 2160.0 seconds.

Upper layer species

N2 %	71.7	72.4	73.2	74.3	75.5	76.7
O2 %	13.1	13.8	14.7	15.8	17.1	18.2
CO2 %	5.05	4.56	4.01	3.24	2.40	1.64
CO ppm	1.826E+03	1.647E+03	1.448E+03	1.172E+03	869.	592.
TUHC %	1.446E-07	1.496E-07	1.512E-07	1.212E-07	7.823E-08	3.495E-08
H2O %	9.36	8.47	7.48	6.11	4.60	3.22
OD 1/m	8.09	8.23	8.43	7.22	5.52	3.76

Lower layer species

N2 %	72.0	73.3	73.3	74.4	77.0	79.1
O2 %	13.4	14.8	14.7	15.9	18.6	20.7
CO2 %	4.84	3.95	3.96	3.21	1.41	3.914E-13
CO ppm	1.750E+03	1.426E+03	1.430E+03	1.162E+03	510.	6.760E-10
TUHC %	1.732E-07	1.574E-07	1.562E-07	1.219E-07	2.445E-05	0.000
H2O %	8.98	7.37	7.39	6.06	2.81	0.273
OD 1/m	8.31	8.13	7.52	4.430E-02	6.164E-08	2.619E-11

Time = 2220.0 seconds.

Upper layer species

N2 %	71.5	72.2	73.0	74.2	75.4	76.6
O2 %	12.9	13.7	14.5	15.7	16.9	18.1
CO2 %	5.18	4.68	4.13	3.35	2.49	1.71
CO ppm	1.872E+03	1.693E+03	1.493E+03	1.210E+03	900.	617.
TUHC %	1.305E-07	1.352E-07	1.369E-07	1.144E-07	7.889E-08	3.859E-08
H2O %	9.59	8.70	7.71	6.30	4.75	3.34
OD 1/m	8.26	8.49	8.66	7.45	5.72	3.92

Lower layer species

N2 %	71.8	73.1	73.1	74.2	6.26	79.1
O2 %	13.2	14.6	14.5	15.7	1.51	20.7
CO2 %	4.97	4.07	4.08	3.32	0.115	3.914E-13
CO ppm	1.798E+03	1.472E+03	1.476E+03	1.200E+03	41.5	6.760E-10
TUHC %	1.479E-07	1.433E-07	1.420E-07	1.164E-07	2.516E-05	0.000
H2O %	9.22	7.60	7.62	6.25	0.229	0.273
OD 1/m	8.69	4.86	8.01	4.001E-02	4.876E-09	2.568E-11

Time = 2280.0 seconds.

Upper layer species

N2 %	71.3	72.0	72.8	74.0	75.3	76.5
O2 %	12.7	13.5	14.3	15.5	16.8	18.0
CO2 %	5.30	4.81	4.25	3.45	2.58	1.77
CO ppm	1.916E+03	1.737E+03	1.536E+03	1.248E+03	931.	641.
TUHC %	1.217E-07	1.241E-07	1.254E-07	1.073E-07	7.770E-08	4.190E-08
H2O %	9.81	8.92	7.92	6.49	4.91	3.47
OD 1/m	8.54	8.58	8.91	7.67	5.92	4.09

Lower layer species

N2 %	71.6	72.9	72.9	74.1	0.494	79.1
O2 %	13.0	14.4	14.4	15.5	0.119	20.7
CO2 %	5.10	4.19	4.20	3.43	9.049E-03	3.914E-13
CO ppm	1.845E+03	1.516E+03	1.520E+03	1.238E+03	3.27	6.760E-10
TUHC %	1.323E-07	1.307E-07	1.296E-07	1.092E-07	2.516E-05	0.000
H2O %	9.46	7.82	7.84	6.44	1.804E-02	0.273
OD 1/m	8.82	9.56	8.03	4.415E-02	3.830E-10	2.619E-11

Time = 2340.0 seconds.

Upper layer species

N2 %	71.1	71.9	72.7	73.9	75.2	76.4
O2 %	12.5	13.3	14.1	15.3	16.7	17.9
CO2 %	5.42	4.92	4.36	3.56	2.66	1.85
CO ppm	1.959E+03	1.779E+03	1.577E+03	1.285E+03	962.	667.
TUHC %	1.150E-07	1.162E-07	1.167E-07	1.011E-07	7.590E-08	4.481E-08
H2O %	10.0	9.13	8.12	6.67	5.06	3.59
OD 1/m	8.64	8.83	9.14	7.90	6.13	4.27

Lower layer species

N2 %	71.4	72.8	72.7	73.9	3.862E-02	79.1
O2 %	12.8	14.2	14.2	15.4	9.305E-03	20.7
CO2 %	5.23	4.31	4.32	3.53	7.075E-04	3.914E-13
CO ppm	1.889E+03	1.558E+03	1.561E+03	1.275E+03	0.411	6.760E-10
TUHC %	1.225E-07	1.208E-07	1.200E-07	1.027E-07	2.516E-05	0.000
H2O %	9.68	8.03	8.05	6.62	1.411E-03	0.273
OD 1/m	9.01	20.5	7.96	4.998E-02	3.969E-11	2.619E-11

Time = 2400.0 seconds.

Upper layer species

N2 %	71.0	71.7	72.5	73.7	75.0	76.3
O2 %	12.4	13.1	14.0	15.2	16.6	17.8
CO2 %	5.53	5.03	4.47	3.65	2.75	1.92
CO ppm	1.998E+03	1.818E+03	1.616E+03	1.320E+03	992.	693.
TUHC %	1.090E-07	1.102E-07	1.095E-07	9.584E-08	7.415E-08	4.733E-08
H2O %	10.2	9.33	8.32	6.85	5.21	3.72
OD 1/m	8.78	9.07	9.34	8.12	6.33	4.44

Lower layer species

N2 %	71.3	72.6	72.6	73.8	2.994E-03	79.1
O2 %	12.7	14.0	14.0	15.2	7.210E-04	20.7
CO2 %	5.34	4.42	4.43	3.63	5.567E-05	3.914E-13
CO ppm	1.929E+03	1.598E+03	1.601E+03	1.311E+03	0.144	6.760E-10
TUHC %	1.151E-07	1.128E-07	1.121E-07	9.723E-08	2.516E-05	0.000
H2O %	9.88	8.23	8.24	6.80	1.126E-04	0.273
OD 1/m	9.30	5.56	8.85	4.651E-02	1.143E-11	2.619E-11

Time = 2460.0 seconds.

Upper layer species

N2 %	70.8	71.5	72.4	73.6	74.9	76.2
O2 %	12.2	13.0	13.8	15.1	16.4	17.7
CO2 %	5.64	5.14	4.58	3.75	2.83	1.99
CO ppm	2.037E+03	1.856E+03	1.654E+03	1.354E+03	1.022E+03	719.
TUHC %	1.031E-07	1.042E-07	1.036E-07	9.147E-08	7.262E-08	4.951E-08
H2O %	10.4	9.51	8.51	7.01	5.36	3.85
OD 1/m	9.01	9.24	9.56	8.33	6.53	4.62

Lower layer species

N2 %	71.1	72.4	72.4	73.6	2.317E-04	79.1
O2 %	12.5	13.9	13.9	15.1	5.941E-05	20.7
CO2 %	5.45	4.53	4.54	3.72	1.482E-05	3.914E-13
CO ppm	1.970E+03	1.636E+03	1.640E+03	1.345E+03	0.141	6.760E-10
TUHC %	1.086E-07	1.063E-07	1.057E-07	9.272E-08	2.473E-05	0.000
H2O %	10.1	8.42	8.44	6.97	3.200E-05	0.273
OD 1/m	9.47	3.05	8.62	4.315E-02	1.123E-11	2.533E-11

Time = 2520.0 seconds.

Upper layer species

N2 %	70.7	71.4	72.2	73.4	74.8	76.0
O2 %	12.1	12.8	13.7	14.9	16.3	17.6
CO2 %	5.74	5.24	4.68	3.84	2.91	2.06
CO ppm	2.074E+03	1.893E+03	1.691E+03	1.389E+03	1.053E+03	746.
TUHC %	9.637E-08	9.828E-08	9.837E-08	8.784E-08	7.140E-08	5.140E-08
H2O %	10.6	9.70	8.69	7.19	5.52	3.99
OD 1/m	9.07	9.45	9.76	8.55	6.73	4.81

Lower layer species

N2 %	70.9	72.3	72.3	73.5	3.569E-05	79.1
O2 %	12.3	13.7	13.7	14.9	1.518E-05	20.7
CO2 %	5.56	4.63	4.64	3.82	8.989E-06	3.914E-13
CO ppm	2.008E+03	1.673E+03	1.677E+03	1.380E+03	0.141	6.760E-10
TUHC %	1.029E-07	1.008E-07	1.003E-07	8.888E-08	2.473E-05	0.000
H2O %	10.3	8.60	8.62	7.14	2.197E-05	0.273
OD 1/m	9.47	21.8	8.19	5.122E-02	1.113E-11	2.590E-11

Time = 2580.0 seconds.

Upper layer species

N2 %	70.5	71.3	72.1	73.3	74.7	75.9
O2 %	11.9	12.7	13.5	14.8	16.2	17.5
CO2 %	5.83	5.34	4.77	3.93	3.00	2.14
CO ppm	2.108E+03	1.929E+03	1.726E+03	1.421E+03	1.083E+03	773.
TUHC %	9.439E-08	9.540E-08	9.408E-08	8.461E-08	7.032E-08	5.304E-08
H2O %	10.8	9.87	8.86	7.35	5.66	4.12
OD 1/m	9.36	9.53	9.97	8.75	6.93	5.00

Lower layer species

N2 %	70.8	72.1	72.1	73.3	1.413E-05	79.1
O2 %	12.2	13.6	13.6	14.8	1.236E-05	20.7
CO2 %	5.66	4.73	4.74	3.91	8.989E-06	3.914E-13
CO ppm	2.045E+03	1.709E+03	1.712E+03	1.413E+03	0.141	6.760E-10
TUHC %	9.877E-08	9.590E-08	9.553E-08	8.547E-08	2.473E-05	0.000
H2O %	10.5	8.78	8.80	7.31	2.197E-05	0.273
OD 1/m	9.68	4.49	8.13	5.058E-02	1.115E-11	2.601E-11

Time = 2640.0 seconds.

Upper layer species

N2 %	70.4	71.1	71.9	73.2	74.6	75.8
O2 %	11.8	12.5	13.4	14.6	16.1	17.3
CO2 %	5.93	5.43	4.87	4.02	3.08	2.22
CO ppm	2.142E+03	1.963E+03	1.760E+03	1.453E+03	1.112E+03	801.
TUHC %	9.092E-08	9.210E-08	9.096E-08	8.221E-08	6.948E-08	5.446E-08
H2O %	10.9	10.0	9.03	7.50	5.81	4.26
OD 1/m	9.65	9.56	10.2	8.94	7.13	5.19

Lower layer species

N2 %	70.6	72.0	72.0	73.2	1.413E-05	79.1
O2 %	12.0	13.4	13.4	14.7	1.236E-05	20.7
CO2 %	5.76	4.82	4.83	4.00	8.989E-06	3.914E-13
CO ppm	2.081E+03	1.743E+03	1.747E+03	1.444E+03	0.141	6.760E-10
TUHC %	9.549E-08	9.239E-08	9.209E-08	8.294E-08	2.473E-05	0.000
H2O %	10.6	8.95	8.97	7.46	2.197E-05	0.273
OD 1/m	9.85	4.46	8.51	4.564E-02	1.120E-11	2.564E-11

Time = 2700.0 seconds.

Upper layer species

N2 %	70.3	71.0	71.8	73.1	74.4	75.7
O2 %	11.7	12.4	13.2	14.5	15.9	17.2
CO2 %	6.02	5.52	4.96	4.11	3.16	2.29
CO ppm	2.176E+03	1.996E+03	1.792E+03	1.484E+03	1.142E+03	828.
TUHC %	8.927E-08	8.879E-08	8.795E-08	8.020E-08	6.888E-08	5.571E-08
H2O %	11.1	10.2	9.20	7.66	5.96	4.40
OD 1/m	9.56	9.90	10.3	9.14	7.33	5.38

Lower layer species

N2 %	70.5	71.9	71.9	73.1	1.413E-05	79.1
O2 %	11.9	13.3	13.3	14.5	1.236E-05	20.7
CO2 %	5.85	4.92	4.92	4.08	8.989E-06	3.914E-13
CO ppm	2.113E+03	1.777E+03	1.780E+03	1.476E+03	0.141	6.760E-10
TUHC %	9.225E-08	8.933E-08	8.906E-08	8.080E-08	2.473E-05	0.000
H2O %	10.8	9.12	9.13	7.62	2.197E-05	0.273
OD 1/m	10.1	6.97	9.83	5.219E-02	1.123E-11	2.619E-11

Fast V 18.5 Created 5/1/91, Run 8/5/94

Number of compartments = 6

FLOOR PLAN

Width	3.0	3.0	2.4	2.4	2.4	5.5
Depth	3.0	6.1	24.4	9.8	10.7	26.5
Height	6.1	3.0	3.0	3.0	4.7	5.2
Area	9.3	18.6	59.5	23.8	26.1	145.7
Volume	56.7	56.7	181.4	72.6	123.3	754.7
Ceiling	6.1	6.1	6.1	6.4	8.1	9.1
Floor	0.0	3.0	3.0	3.4	3.4	4.0

NORMAL CONNECTIONS

1 (1)	Width	0.00	3.05	0.00	0.00	0.00	0.00	0.00
	Soffit	0.00	6.10	0.00	0.00	0.00	0.00	0.00
	Sill	0.00	3.05	0.00	0.00	0.00	0.00	0.00
	a.Soffit	0.00	6.10	0.00	0.00	0.00	0.00	0.00
	a.Sill	0.00	3.05	0.00	0.00	0.00	0.00	0.00
2 (1)	Width	3.05	0.00	2.44	0.00	0.00	0.00	0.00
	Soffit	3.05	0.00	3.05	0.00	0.00	0.00	0.00
	Sill	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	a.Soffit	6.10	0.00	6.10	0.00	0.00	0.00	0.00
	a.Sill	3.05	0.00	3.05	0.00	0.00	0.00	0.00
3 (1)	Width	0.00	2.44	0.00	2.44	0.00	0.00	0.00
	Soffit	0.00	3.05	0.00	3.05	0.00	0.00	0.00
	Sill	0.00	0.00	0.00	0.31	0.00	0.00	0.00
	a.Soffit	0.00	6.10	0.00	6.10	0.00	0.00	0.00
	a.Sill	0.00	3.05	0.00	3.36	0.00	0.00	0.00
4 (1)	Width	0.00	0.00	2.44	0.00	2.44	0.00	0.00
	Soffit	0.00	0.00	2.74	0.00	3.05	0.00	0.00
	Sill	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	a.Soffit	0.00	0.00	6.10	0.00	6.41	0.00	0.00
	a.Sill	0.00	0.00	3.36	0.00	3.36	0.00	0.00
5 (1)	Width	0.00	0.00	0.00	2.44	0.00	2.44	0.00
	Soffit	0.00	0.00	0.00	3.05	0.00	4.73	0.00
	Sill	0.00	0.00	0.00	0.00	0.00	0.61	0.00
	a.Soffit	0.00	0.00	0.00	6.41	0.00	8.09	0.00
	a.Sill	0.00	0.00	0.00	3.36	0.00	3.97	0.00
6 (1)	Width	0.00	0.00	0.00	0.00	2.44	0.00	0.00
	Soffit	0.00	0.00	0.00	0.00	4.13	0.00	0.00
	Sill	0.00	0.00	0.00	0.00	0.01	0.00	0.00
	a.Soffit	0.00	0.00	0.00	0.00	8.09	0.00	0.00
	a.Sill	0.00	0.00	0.00	0.00	3.97	0.00	0.00

THERE ARE NO FAN CONNECTIONS

```
Compartment of origin is                                  1
Print interval (seconds)                                 60
Number of fire specification intervals is                12
Total time (seconds)                                     2700
Fire position                                             3
Limiting oxygen index (%) =                              10.0
Initial relative humidity (%) =                           1.0
Fire type is a SPECIFIED (CONSTRAINED)
Pyrolysis  temperature (K) =                             300.
Ambient air temperature (K) =                            300.
Ambient reference pressure (Pa) =                      101300.
Reference elevation (m) =                                 0.0
Fmass=   0.0      1.9E-03  3.5E-03  4.8E-03  5.8E-03  6.7E-03  7.5E-03  8.1E-03  8.9E-03
       9.6E-03  1.0E-02  1.1E-02  1.1E-02
Hcomb=   3.3E+07  3.3E+07  3.2E+07  3.2E+07  3.3E+07  3.3E+07  3.2E+07  3.2E+07      3.3E+07
       3.2E+07  3.3E+07  3.3E+07  3.3E+07
Fqdot=   0.0      6.2E+04  1.1E+05  1.6E+05  1.9E+05  2.2E+05  2.4E+05  2.6E+05  2.9E+05
       3.1E+05  3.4E+05  3.5E+05  3.5E+05
Fhigh=   0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0
0.0      0.0      0.0
C/CO2=   3.4E-02  3.4E-02  3.4E-02  3.4E-02  3.4E-02  3.4E-02  3.4E-02  3.4E-02  3.4E-02
       3.4E-02  3.4E-02  3.4E-02  3.4E-02
CO/CO2=  2.3E-02  2.3E-02  2.3E-02  2.3E-02  2.3E-02  2.3E-02  2.3E-02  2.3E-02  2.3E-02
       2.3E-02  2.3E-02  2.3E-02  2.3E-02
H/C=     0.3      0.3      0.3      0.3      0.3      0.3      0.3      0.3      0.3      0.3
0.3    0.3      0.3
Ftime=   1.0E+02  1.0E+02  1.0E+02  1.0E+02  1.0E+02  1.0E+02  1.0E+02  2.0E+02  2.0E+02     5.0E+02
5.0E+02   6.0E+02
```

Time = 0.0 seconds.

Upper temp(K)	300.0	300.0	300.0	300.0	300.0	300.0
Lower temp(K)	300.0	300.0	300.0	300.0	300.0	300.0
Upper vol(m**3)	0.1	0.1	0.2	0.1	0.1	0.8
Layer depth(m)	0.0	0.0	0.0	0.0	0.0	0.0
Ceiling temp(K)	300.0	300.0	300.0	300.0	300.0	300.0
Up wall temp(K)	300.0	300.0	300.0	300.0	300.0	300.0
Low wall temp(K)	300.0	300.0	300.0	300.0	300.0	300.0
Floor temp(K)	300.0	300.0	300.0	300.0	300.0	300.0

Time = 60.0 seconds.

Upper temp(K)	337.4	316.3	302.8	300.1	300.0	300.0
Lower temp(K)	300.6	300.2	300.0	300.0	300.0	300.0
Upper vol(m**3)	9.5	17.1	8.5	0.3	0.4	0.8
Layer depth(m)	1.0	0.9	0.1	0.0	0.0	0.0
Ceiling temp(K)	300.8	300.2	300.0	300.0	300.0	300.0
Up wall temp(K)	300.6	300.2	300.0	300.0	300.0	300.0
Low wall temp(K)	300.0	300.0	300.0	300.0	300.0	300.0
Floor temp(K)	300.0	300.0	300.0	300.0	300.0	300.0

Time = 120.0 seconds.

Upper temp(K)	371.2	339.2	311.8	301.9	300.0	300.0
Lower temp(K)	300.9	301.5	300.0	300.0	300.0	300.0
Upper vol(m**3)	9.5	18.3	46.0	9.7	6.9	2.1
Layer depth(m)	1.0	1.0	0.8	0.4	0.3	0.0
Ceiling temp(K)	302.8	301.2	300.2	300.0	300.0	300.0
Up wall temp(K)	302.1	300.9	300.2	300.0	300.0	300.0
Low wall temp(K)	300.1	300.1	300.0	300.0	300.0	300.0
Floor temp(K)	300.1	300.1	300.0	300.0	300.0	300.0

Time = 180.0 seconds.

Upper temp(K)	394.3	354.1	318.0	305.6	300.3	300.0
Lower temp(K)	301.0	300.8	300.3	300.0	300.0	300.0
Upper vol(m**3)	10.0	20.1	67.7	24.7	32.3	10.4
Layer depth(m)	1.1	1.1	1.1	1.0	1.2	0.1
Ceiling temp(K)	305.4	302.5	300.6	300.1	300.0	300.0
Up wall temp(K)	304.0	301.9	300.4	300.1	300.0	300.0
Low wall temp(K)	300.3	300.3	300.1	300.0	300.0	300.0
Floor temp(K)	300.3	300.3	300.1	300.0	300.0	300.0

Time = 240.0 seconds.

Upper temp(K)	412.1	363.3	323.0	309.5	301.3	300.0
Lower temp(K)	300.8	300.6	300.8	300.7	300.0	300.0
Upper vol(m**3)	10.8	22.8	80.5	32.5	58.5	48.0
Layer depth(m)	1.2	1.2	1.4	1.4	2.2	0.3
Ceiling temp(K)	308.1	303.9	301.0	300.3	300.0	300.0
Up wall temp(K)	306.1	302.9	300.7	300.2	300.0	300.0
Low wall temp(K)	300.4	300.5	300.1	300.0	300.0	300.0
Floor temp(K)	300.4	300.5	300.1	300.0	300.0	300.0

Time = 300.0 seconds.

Upper temp(K)	425.1	370.7	327.6	312.9	303.0	300.1
Lower temp(K)	300.8	301.0	301.6	301.8	300.6	300.0
Upper vol(m**3)	11.7	25.0	88.7	35.5	60.7	118.2
Layer depth(m)	1.3	1.3	1.5	1.5	2.3	0.8
Ceiling temp(K)	310.9	305.2	301.5	300.5	300.1	300.0
Up wall temp(K)	308.2	303.9	301.1	300.4	300.0	300.0
Low wall temp(K)	300.6	300.7	300.2	300.1	300.0	300.0
Floor temp(K)	300.6	300.7	300.2	300.1	300.0	300.0

Time = 360.0 seconds.

Upper temp(K)	436.8	377.9	332.0	316.5	305.0	300.3
Lower temp(K)	301.2	302.0	303.0	303.3	301.4	300.0
Upper vol(m**3)	12.1	25.9	91.7	35.2	60.2	204.4
Layer depth(m)	1.3	1.4	1.5	1.5	2.3	1.4
Ceiling temp(K)	313.6	306.6	302.0	300.7	300.1	300.0
Up wall temp(K)	310.4	304.9	301.5	300.6	300.1	300.0
Low wall temp(K)	300.7	300.9	300.3	300.1	300.0	300.0
Floor temp(K)	300.7	300.9	300.3	300.1	300.0	300.0

Time = 420.0 seconds.

Upper temp(K)	449.2	385.6	336.0	319.6	307.0	300.7
Lower temp(K)	302.1	303.4	304.7	304.3	302.0	300.0
Upper vol(m**3)	12.1	25.9	91.0	34.4	60.2	277.1
Layer depth(m)	1.3	1.4	1.5	1.4	2.3	1.9
Ceiling temp(K)	316.4	308.0	302.5	301.0	300.2	300.0
Up wall temp(K)	312.6	306.0	301.9	300.8	300.2	300.0
Low wall temp(K)	300.9	301.1	300.4	300.2	300.0	300.0
Floor temp(K)	300.9	301.1	300.4	300.2	300.0	300.0

Time = 480.0 seconds.

Upper temp(K)	462.1	393.4	339.7	322.4	308.8	301.2
Lower temp(K)	303.3	304.8	306.0	304.9	302.1	300.0
Upper vol(m**3)	11.8	25.1	88.3	33.3	19.9	335.2
Layer depth(m)	1.3	1.4	1.5	1.4	2.3	2.3
Ceiling temp(K)	319.4	309.5	303.1	301.3	300.3	300.0
Up wall temp(K)	315.0	307.1	302.3	301.0	300.3	300.0
Low wall temp(K)	301.2	301.4	300.5	300.3	300.1	300.0
Floor temp(K)	301.1	301.3	300.5	300.2	300.0	300.0

Time = 540.0 seconds.

Upper temp(K)	473.6	400.9	343.2	324.9	310.3	301.7
Lower temp(K)	304.3	305.8	306.8	305.0	302.0	300.0
Upper vol(m**3)	11.5	24.3	84.8	32.2	59.8	385.7
Layer depth(m)	1.2	1.3	1.4	1.4	2.3	2.6
Ceiling temp(K)	322.6	311.1	303.7	301.7	300.5	300.0
Up wall temp(K)	317.5	308.4	302.7	301.3	300.4	300.0
Low wall temp(K)	301.4	301.6	300.6	300.3	300.1	300.0
Floor temp(K)	301.4	301.6	300.6	300.2	300.1	300.0

Time = 600.0 seconds.

Upper temp(K)	484.4	407.7	346.2	327.0	311.7	302.2
Lower temp(K)	305.1	306.3	307.0	304.7	301.6	300.0
Upper vol(m**3)	11.2	23.4	81.4	31.3	60.9	434.4
Layer depth(m)	1.2	1.3	1.4	1.3	2.3	3.0
Ceiling temp(K)	325.8	312.7	304.2	302.0	300.6	300.1
Up wall temp(K)	320.1	309.6	303.2	301.5	300.5	300.0
Low wall temp(K)	301.7	301.9	300.8	300.4	300.1	300.0
Floor temp(K)	301.6	301.8	300.6	300.3	300.1	300.0

Time = 660.0 seconds.

Upper temp(K)	492.7	413.5	348.8	328.9	312.9	302.7
Lower temp(K)	305.6	306.4	306.7	304.1	301.1	300.0
Upper vol(m**3)	11.0	22.8	78.7	31.1	63.6	482.4
Layer depth(m)	1.2	1.2	1.3	1.3	2.4	3.3
Ceiling temp(K)	328.9	314.3	304.8	302.3	300.8	300.1
Up wall temp(K)	322.7	310.9	303.6	301.8	300.6	300.1
Low wall temp(K)	301.9	302.2	300.9	300.4	300.1	300.0
Floor temp(K)	301.9	302.1	300.7	300.3	300.1	300.0

Time = 720.0 seconds.

Upper temp(K)	499.1	418.2	351.1	330.4	313.5	303.0
Lower temp(K)	305.6	306.1	306.2	303.3	300.6	300.0
Upper vol(m**3)	10.9	22.5	77.3	31.5	67.7	526.7
Layer depth(m)	1.2	1.2	1.3	1.3	2.6	3.6
Ceiling temp(K)	332.0	315.9	305.4	302.7	300.9	300.1
Up wall temp(K)	325.2	312.1	304.1	302.0	300.7	300.1
Low wall temp(K)	302.2	302.4	301.0	300.5	300.1	300.0
Floor temp(K)	302.1	302.3	300.8	300.4	300.1	300.0

Time = 780.0 seconds.

Upper temp(K)	503.4	421.4	352.9	331.6	313.7	303.3
Lower temp(K)	305.5	305.6	305.4	302.4	300.2	300.0
Upper vol(m**3)	10.9	22.5	77.3	32.7	72.8	566.3
Layer depth(m)	1.2	1.2	1.3	1.4	2.8	3.9
Ceiling temp(K)	334.8	317.3	306.0	303.0	301.0	300.1
Up wall temp(K)	327.5	313.3	304.5	302.3	300.8	300.1
Low wall temp(K)	302.4	302.7	301.1	300.5	300.1	300.0
Floor temp(K)	302.4	302.6	300.9	300.4	300.1	300.0

Time = 840.0 seconds.

Upper temp(K)	507.1	423.4	354.3	332.2	313.3	303.6
Lower temp(K)	305.1	305.0	304.6	301.6	300.1	300.0
Upper vol(m**3)	11.0	22.9	79.3	35.2	79.1	601.8
Layer depth(m)	1.2	1.2	1.3	1.5	3.0	4.1
Ceiling temp(K)	337.5	318.7	306.5	303.3	301.1	300.2
Up wall temp(K)	329.7	314.4	304.9	302.5	300.9	300.1
Low wall temp(K)	302.7	302.9	301.1	300.6	300.2	300.0
Floor temp(K)	302.6	302.9	301.0	300.5	300.1	300.0

Time = 900.0 seconds.

Upper temp(K)	508.9	423.7	355.3	331.3	312.8	303.7
Lower temp(K)	304.5	304.1	303.5	300.8	300.0	300.0
Upper vol(m**3)	11.5	24.0	84.5	39.5	86.0	633.4
Layer depth(m)	1.2	1.3	1.4	1.7	3.3	4.3
Ceiling temp(K)	340.0	320.0	307.0	303.5	301.2	300.2
Up wall temp(K)	331.8	315.4	305.3	302.7	300.9	300.2
Low wall temp(K)	302.9	303.2	301.2	300.6	300.2	300.1
Floor temp(K)	302.8	303.1	301.1	300.5	300.2	300.1

Time = 960.0 seconds.

Upper temp(K)	507.6	421.5	355.3	330.1	312.3	303.7
Lower temp(K)	303.8	303.1	302.5	300.3	300.1	300.0
Upper vol(m**3)	12.2	26.1	92.9	44.4	92.9	661.6
Layer depth(m)	1.3	1.4	1.6	1.9	3.6	4.5
Ceiling temp(K)	342.1	321.0	307.5	303.7	301.3	300.2
Up wall temp(K)	333.6	316.2	305.6	302.8	301.0	300.2
Low wall temp(K)	303.1	303.4	301.3	300.6	300.2	300.1
Floor temp(K)	303.0	303.3	301.2	300.6	300.2	300.1

Time = 1020.0 seconds.

Upper temp(K)	503.3	418.1	354.8	329.2	312.1	303.7
Lower temp(K)	303.0	302.3	301.7	300.3	300.5	300.0
Upper vol(m**3)	13.3	29.1	103.7	49.6	99.4	686.6
Layer depth(m)	1.4	1.6	1.7	2.1	3.8	4.7
Ceiling temp(K)	343.8	321.8	307.8	303.8	301.3	300.2
Up wall temp(K)	335.0	316.8	305.9	302.9	301.0	300.2
Low wall temp(K)	303.3	303.6	301.4	300.7	300.2	300.1
Floor temp(K)	303.2	303.5	301.3	300.6	300.2	300.1

Time = 1080.0 seconds.

Upper temp(K)	497.7	414.2	354.0	328.6	311.9	303.7
Lower temp(K)	302.4	301.7	301.3	300.8	301.5	300.0
Upper vol(m**3)	14.7	32.4	116.3	55.0	105.5	707.8
Layer depth(m)	1.6	1.7	2.0	2.3	4.0	4.9
Ceiling temp(K)	345.0	322.3	308.2	304.0	301.4	300.3
Up wall temp(K)	336.1	317.3	306.2	303.0	301.0	300.2
Low wall temp(K)	303.4	303.8	301.5	300.7	300.3	300.1
Floor temp(K)	303.4	303.7	301.4	300.7	300.2	300.1

Time = 1140.0 seconds.

Upper temp(K)	488.0	409.1	352.9	327.8	311.7	303.6
Lower temp(K)	302.0	301.6	301.4	302.2	303.3	300.0
Upper vol(m**3)	16.7	37.1	132.1	61.1	111.3	720.3
Layer depth(m)	1.8	2.0	2.2	2.6	4.3	4.9
Ceiling temp(K)	345.8	322.7	308.5	304.1	301.4	300.3
Up wall temp(K)	336.8	317.6	306.4	303.1	301.1	300.2
Low wall temp(K)	303.6	304.0	301.6	300.8	300.3	300.1
Floor temp(K)	303.5	304.0	301.5	300.8	300.3	300.1

Time = 1200.0 seconds.

Upper temp(K)	476.8	404.3	352.1	327.7	311.8	303.6
Lower temp(K)	302.1	302.1	302.3	303.5	303.6	300.0
Upper vol(m**3)	19.3	42.5	148.6	65.5	114.5	730.4
Layer depth(m)	2.1	2.3	2.5	2.8	4.4	5.0
Ceiling temp(K)	346.0	322.9	308.7	304.2	301.4	300.3
Up wall temp(K)	337.0	317.8	306.6	303.2	301.1	300.2
Low wall temp(K)	303.7	304.3	301.7	300.9	300.3	300.1
Floor temp(K)	303.6	304.2	301.7	300.8	300.3	300.1

Time = 1260.0 seconds.

Upper temp(K)	468.7	401.7	351.7	327.5	311.7	303.6
Lower temp(K)	303.0	305.0	306.6	304.2	303.6	300.1
Upper vol(m**3)	22.1	47.9	162.0	68.3	116.9	738.5
Layer depth(m)	2.4	2.6	2.7	2.9	4.5	5.1
Ceiling temp(K)	346.0	323.1	308.9	304.3	301.5	300.3
Up wall temp(K)	337.0	318.0	306.8	303.2	301.1	300.2
Low wall temp(K)	303.7	304.7	301.9	301.0	300.4	300.1
Floor temp(K)	303.7	304.6	301.8	300.9	300.3	300.1

Time = 1320.0 seconds.

Upper temp(K)	463.8	400.8	351.6	327.0	311.5	303.6
Lower temp(K)	306.7	313.4	315.3	304.3	303.5	300.1
Upper vol(m**3)	25.2	52.6	170.7	69.3	118.3	742.9
Layer depth(m)	2.7	2.8	2.9	2.9	4.5	5.1
Ceiling temp(K)	346.0	323.4	309.1	304.4	301.5	300.3
Up wall temp(K)	337.0	318.2	307.0	303.3	301.2	300.3
Low wall temp(K)	303.9	305.2	302.2	301.1	300.4	300.1
Floor temp(K)	303.8	305.1	302.1	301.0	300.4	300.1

Time = 1380.0 seconds.

Upper temp(K)	461.7	400.6	351.8	326.9	311.4	303.5
Lower temp(K)	315.0	320.3	319.8	304.2	303.5	300.1
Upper vol(m**3)	28.4	55.0	174.1	70.0	119.4	746.7
Layer depth(m)	3.1	3.0	2.9	2.9	4.6	5.1
Ceiling temp(K)	346.1	323.7	309.4	304.4	301.6	300.3
Up wall temp(K)	337.2	318.4	307.2	303.4	301.2	300.3
Low wall temp(K)	304.1	305.8	302.6	301.2	300.5	300.1
Floor temp(K)	304.0	305.6	302.3	301.1	300.4	300.1

Time = 1440.0 seconds.

Upper temp(K)	462.6	400.3	351.4	326.7	311.3	303.5
Lower temp(K)	337.4	321.8	321.3	303.9	303.5	300.1
Upper vol(m**3)	30.2	55.4	175.9	70.7	120.4	749.6
Layer depth(m)	3.2	3.0	3.0	3.0	4.6	5.1
Ceiling temp(K)	346.4	324.0	309.6	304.5	301.6	300.3
Up wall temp(K)	337.4	318.7	307.3	303.5	301.2	300.3
Low wall temp(K)	304.6	306.4	302.9	301.3	300.5	300.1
Floor temp(K)	304.2	306.1	302.5	301.2	300.4	300.1

Time = 1500.0 seconds.

Upper temp(K)	463.6	400.5	351.3	326.4	311.2	303.4
Lower temp(K)	358.0	322.4	322.3	303.7	303.3	300.1
Upper vol(m**3)	31.7	55.7	177.2	71.2	121.2	751.5
Layer depth(m)	3.4	3.0	3.0	3.0	4.6	5.2
Ceiling temp(K)	346.9	324.3	309.8	304.6	301.6	300.3
Up wall temp(K)	337.8	319.0	307.5	303.5	301.2	300.3
Low wall temp(K)	305.4	306.9	303.2	301.3	300.5	300.1
Floor temp(K)	304.5	306.6	302.6	301.2	300.5	300.1

Time = 1560.0 seconds.

Upper temp(K)	465.2	400.8	351.2	326.2	311.0	303.4
Lower temp(K)	373.7	322.8	323.2	303.5	303.3	300.1
Upper vol(m**3)	32.7	56.2	178.1	71.7	121.8	752.5
Layer depth(m)	3.5	3.0	3.0	3.0	4.7	5.2
Ceiling temp(K)	347.4	324.6	310.0	304.7	301.6	300.4
Up wall temp(K)	338.3	319.3	307.6	303.6	301.3	300.3
Low wall temp(K)	306.3	307.4	303.4	301.4	300.6	300.1
Floor temp(K)	304.8	307.0	302.8	301.3	300.5	300.1

Time = 1620.0 seconds.

Upper temp(K)	466.1	401.0	351.2	326.1	311.0	303.4
Lower temp(K)	385.7	323.4	324.1	303.3	303.3	300.1
Upper vol(m**3)	34.1	56.3	179.0	72.0	122.3	753.1
Layer depth(m)	3.7	3.0	3.0	3.0	4.7	5.2
Ceiling temp(K)	348.1	325.0	310.2	304.7	301.7	300.4
Up wall temp(K)	338.9	319.6	307.8	303.6	301.3	300.3
Low wall temp(K)	307.3	307.8	303.6	301.5	300.6	300.1
Floor temp(K)	305.1	307.3	302.9	301.4	300.5	300.1

Time = 1680.0 seconds.

Upper temp(K)	466.7	401.1	351.2	326.0	310.9	303.3
Lower temp(K)	392.9	323.2	324.8	303.1	303.3	300.1
Upper vol(m**3)	34.9	56.3	179.9	72.3	122.8	753.3
Layer depth(m)	3.7	3.0	3.0	3.0	4.7	5.2
Ceiling temp(K)	348.7	325.4	310.4	304.8	301.7	300.4
Up wall temp(K)	339.5	319.9	308.0	303.7	301.3	300.3
Low wall temp(K)	308.3	308.2	303.9	301.5	300.6	300.1
Floor temp(K)	305.4	307.7	303.1	301.4	300.5	300.1

Time = 1740.0 seconds.

Upper temp(K)	466.5	400.7	351.0	325.9	310.8	303.3
Lower temp(K)	400.7	321.0	323.6	301.9	301.6	300.1
Upper vol(m**3)	37.1	56.6	180.8	72.6	123.1	753.6
Layer depth(m)	4.0	3.0	3.0	3.0	4.7	5.2
Ceiling temp(K)	349.4	325.7	310.6	304.9	301.7	300.4
Up wall temp(K)	340.0	320.2	308.1	303.7	301.3	300.3
Low wall temp(K)	309.3	308.6	304.1	301.6	300.6	300.1
Floor temp(K)	305.7	308.0	303.2	301.5	300.5	300.1

Time = 1800.0 seconds.

Upper temp(K)	467.5	401.1	351.1	325.9	310.8	303.3
Lower temp(K)	400.7	320.5	323.5	301.4	300.8	300.1
Upper vol(m**3)	36.7	56.5	180.9	72.6	123.1	754.0
Layer depth(m)	3.9	3.0	3.0	3.0	4.7	5.2
Ceiling temp(K)	350.0	326.0	310.7	304.9	301.7	300.4
Up wall temp(K)	340.6	320.4	308.2	303.8	301.3	300.3
Low wall temp(K)	310.2	308.9	304.2	301.6	300.6	300.1
Floor temp(K)	306.0	308.4	303.4	301.5	300.6	300.1

Time = 1860.0 seconds.

Upper temp(K)	468.6	401.8	351.4	326.0	310.9	303.2
Lower temp(K)	401.5	320.7	323.8	301.5	300.7	300.1
Upper vol(m**3)	36.2	56.5	180.9	72.6	123.1	754.0
Layer depth(m)	3.9	3.0	3.0	3.0	4.7	5.2
Ceiling temp(K)	350.7	326.4	310.9	305.0	301.8	300.4
Up wall temp(K)	341.1	320.7	308.4	303.9	301.4	300.3
Low wall temp(K)	310.9	309.2	304.4	301.7	300.7	300.1
Floor temp(K)	306.3	308.7	303.5	301.6	300.6	300.1

Time = 1920.0 seconds.

Upper temp(K)	469.3	402.2	351.7	326.2	310.9	303.2
Lower temp(K)	402.0	321.0	324.0	301.5	300.6	300.1
Upper vol(m**3)	36.7	56.6	180.9	72.6	123.1	754.0
Layer depth(m)	3.9	3.0	3.0	3.0	4.7	5.2
Ceiling temp(K)	351.4	326.8	311.1	305.1	301.8	300.4
Up wall temp(K)	341.7	321.1	308.5	303.9	301.4	300.3
Low wall temp(K)	311.6	309.6	304.6	301.7	300.7	300.1
Floor temp(K)	306.5	309.0	303.6	301.6	300.6	300.1

Time = 1980.0 seconds.

Upper temp(K)	470.3	402.7	352.0	326.4	311.0	303.2
Lower temp(K)	401.8	321.2	324.2	301.5	300.6	300.1
Upper vol(m**3)	36.4	56.5	180.8	72.6	123.1	754.0
Layer depth(m)	3.9	3.0	3.0	3.0	4.7	5.2
Ceiling temp(K)	352.1	327.2	311.3	305.2	301.8	300.4
Up wall temp(K)	342.3	321.4	308.7	304.0	301.4	300.3
Low wall temp(K)	312.3	309.9	304.7	301.8	300.7	300.1
Floor temp(K)	306.8	309.3	303.7	301.7	300.6	300.1

Time = 2040.0 seconds.

Upper temp(K)	471.0	403.4	352.4	326.6	311.1	303.3
Lower temp(K)	403.1	321.5	324.4	301.6	300.6	300.1
Upper vol(m**3)	36.5	56.6	180.9	72.6	123.1	754.0
Layer depth(m)	3.9	3.0	3.0	3.0	4.7	5.2
Ceiling temp(K)	352.8	327.6	311.5	305.3	301.9	300.4
Up wall temp(K)	342.9	321.7	308.9	304.0	301.4	300.3
Low wall temp(K)	312.8	310.2	304.9	301.8	300.7	300.1
Floor temp(K)	307.0	309.6	303.8	301.7	300.6	300.1

Time = 2100.0 seconds.

Upper temp(K)	472.0	404.0	352.7	326.8	311.2	303.3
Lower temp(K)	402.3	321.6	324.6	301.6	300.7	300.1
Upper vol(m**3)	36.1	56.5	180.9	72.6	123.1	754.0
Layer depth(m)	3.9	3.0	3.0	3.0	4.7	5.2
Ceiling temp(K)	353.5	327.9	311.7	305.3	301.9	300.4
Up wall temp(K)	343.6	322.0	309.0	304.1	301.5	300.3
Low wall temp(K)	313.4	310.5	305.1	301.9	300.7	300.1
Floor temp(K)	307.2	309.9	304.0	301.8	300.7	300.1

Time = 2160.0 seconds.

Upper temp(K)	472.5	404.4	353.0	326.9	311.3	303.3
Lower temp(K)	403.7	321.9	324.8	301.7	300.7	300.1
Upper vol(m**3)	36.5	56.6	180.9	72.6	123.1	754.0
Layer depth(m)	3.9	3.0	3.0	3.0	4.7	5.2
Ceiling temp(K)	354.2	328.3	311.9	305.4	301.9	300.4
Up wall temp(K)	344.2	322.3	309.2	304.2	301.5	300.3
Low wall temp(K)	313.9	310.8	305.2	301.9	300.7	300.1
Floor temp(K)	307.4	310.2	304.1	301.8	300.7	300.1

Time = 2220.0 seconds.

Upper temp(K)	472.7	404.5	353.1	327.0	311.3	303.3
Lower temp(K)	403.6	322.1	325.0	301.7	300.7	300.1
Upper vol(m**3)	36.4	56.5	180.9	72.6	123.1	754.0
Layer depth(m)	3.9	3.0	3.0	3.0	4.7	5.2
Ceiling temp(K)	354.9	328.7	312.1	305.5	301.9	300.4
Up wall temp(K)	344.8	322.7	309.3	304.2	301.5	300.3
Low wall temp(K)	314.5	311.1	305.4	302.0	300.7	300.1
Floor temp(K)	307.6	310.4	304.2	301.9	300.7	300.1

Time = 2280.0 seconds.

Upper temp(K)	473.1	404.8	353.3	327.1	311.4	303.4
Lower temp(K)	404.7	322.2	325.1	301.8	300.7	300.1
Upper vol(m**3)	36.2	56.6	180.9	72.6	123.1	754.0
Layer depth(m)	3.9	3.0	3.0	3.0	4.7	5.2
Ceiling temp(K)	355.5	329.1	312.2	305.6	302.0	300.4
Up wall temp(K)	345.3	323.0	309.5	304.3	301.5	300.3
Low wall temp(K)	315.0	311.4	305.5	302.0	300.8	300.1
Floor temp(K)	307.8	310.7	304.3	301.9	300.7	300.1

Time = 2340.0 seconds.

Upper temp(K)	473.5	405.1	353.5	327.2	311.4	303.4
Lower temp(K)	404.8	322.4	325.2	301.8	300.7	300.1
Upper vol(m**3)	36.3	56.7	180.9	72.6	123.1	754.0
Layer depth(m)	3.9	3.0	3.0	3.0	4.7	5.2
Ceiling temp(K)	356.2	329.4	312.4	305.7	302.0	300.4
Up wall temp(K)	345.9	323.3	309.6	304.4	301.6	300.3
Low wall temp(K)	315.4	311.6	305.7	302.0	300.8	300.1
Floor temp(K)	308.0	311.0	304.4	302.0	300.7	300.1

Time = 2400.0 seconds.

Upper temp(K)	473.5	405.1	353.6	327.3	311.5	303.4
Lower temp(K)	405.1	322.6	325.3	301.9	300.8	300.1
Upper vol(m**3)	36.7	56.5	180.9	72.6	123.1	754.0
Layer depth(m)	3.9	3.0	3.0	3.0	4.7	5.2
Ceiling temp(K)	356.8	329.8	312.6	305.7	302.0	300.4
Up wall temp(K)	346.4	323.6	309.8	304.4	301.6	300.3
Low wall temp(K)	315.9	311.9	305.8	302.1	300.8	300.1
Floor temp(K)	308.2	311.2	304.5	302.0	300.8	300.1

Time = 2460.0 seconds.

Upper temp(K)	474.1	405.4	353.7	327.4	311.5	303.5
Lower temp(K)	404.7	322.7	325.5	301.9	300.8	300.1
Upper vol(m**3)	35.9	56.4	180.9	72.6	123.1	754.0
Layer depth(m)	3.9	3.0	3.0	3.0	4.7	5.2
Ceiling temp(K)	357.4	330.1	312.8	305.8	302.1	300.4
Up wall temp(K)	347.0	323.8	309.9	304.5	301.6	300.3
Low wall temp(K)	316.4	312.2	305.9	302.1	300.8	300.1
Floor temp(K)	308.4	311.5	304.6	302.1	300.8	300.1

Time = 2520.0 seconds.

Upper temp(K)	474.4	405.7	354.0	327.5	311.6	303.5
Lower temp(K)	404.9	323.0	325.6	301.9	300.8	300.1
Upper vol(m**3)	36.3	56.7	180.8	72.6	123.1	754.0
Layer depth(m)	3.9	3.0	3.0	3.0	4.7	5.2
Ceiling temp(K)	358.0	330.5	313.0	305.9	302.1	300.4
Up wall temp(K)	347.5	324.1	310.0	304.6	301.6	300.3
Low wall temp(K)	316.8	312.4	306.1	302.2	300.8	300.1
Floor temp(K)	308.6	311.7	304.7	302.1	300.8	300.1

Time = 2580.0 seconds.

Upper temp(K)	474.7	405.9	354.1	327.6	311.6	303.5
Lower temp(K)	405.6	323.1	325.7	302.0	300.8	300.1
Upper vol(m**3)	36.2	56.5	180.8	72.6	123.1	754.0
Layer depth(m)	3.9	3.0	3.0	3.0	4.7	5.2
Ceiling temp(K)	358.6	330.8	313.1	306.0	302.1	300.4
Up wall temp(K)	348.0	324.4	310.2	304.6	301.7	300.3
Low wall temp(K)	317.2	312.7	306.2	302.2	300.8	300.1
Floor temp(K)	308.8	312.0	304.8	302.2	300.8	300.1

Time = 2640.0 seconds.

Upper temp(K)	475.2	406.2	354.2	327.7	311.7	303.5
Lower temp(K)	405.6	323.2	326.0	302.0	300.8	300.1
Upper vol(m**3)	35.5	56.5	180.8	72.6	123.1	754.0
Layer depth(m)	3.8	3.0	3.0	3.0	4.7	5.2
Ceiling temp(K)	359.2	331.1	313.3	306.1	302.2	300.5
Up wall temp(K)	348.5	324.7	310.3	304.7	301.7	300.3
Low wall temp(K)	317.6	312.9	306.3	302.3	300.9	300.1
Floor temp(K)	309.0	312.2	304.9	302.2	300.8	300.1

Time = 2700.0 seconds.

Upper temp(K)	475.0	406.3	354.4	327.8	311.7	303.6
Lower temp(K)	405.9	323.4	326.0	302.1	300.8	300.1
Upper vol(m**3)	36.4	56.6	180.9	72.6	123.1	754.0
Layer depth(m)	3.9	3.0	3.0	3.0	4.7	5.2
Ceiling temp(K)	359.8	331.5	313.5	306.1	302.2	300.5
Up wall temp(K)	349.1	325.0	310.5	304.7	301.7	300.3
Low wall temp(K)	318.0	313.2	306.5	302.3	300.9	300.1
Floor temp(K)	309.2	312.4	305.0	302.3	300.8	300.1

5.0 SUMMARY/CONCLUSIONS

5.1 Summary

As stated in section 3.2, the upper electrical penetration area (Room 6) is considered to be untenable when the temperature of the upper or lower gas layer is greater than 140°F or the concentration of O_2, CO_2, or CO fall below 17%, above 10%, or above 35,000 ppm, respectively. When conditions within room 6 as a result of a fire in Room 1 fall within one of these parameters it is assumed that an operator will be unable to access the area and perform the manual actions necessary to perform safe shutdown functions.

From the output of the FAST routine in Sections 4.1.3 and 4.2.2 the following information is obtained.

TABLE 5.3.1
TIME TO UNTENABILITY - ROOM 6

	POOL FIRE	CABLE TRAY FIRE
TEMPERATURE OF UPPER GAS LAYER	NOT REACHED (Peak at 94.1°F)	NOT REACHED (Peak at 87.1°F)
O_2 CONCENTRATION BELOW 17%	NOT REACHED (Peak at 19.6%)	NOT REACHED (Peak at 17.2%)
CO_2 CONCENTRATION ABOVE 10%	NOT REACHED (Peak at 0.753%)	NOT REACHED (Peak at 2.29%)
CO CONCENTRATION ABOVE 35,000 ppm	NOT REACHED (Peak at 82.8 ppm)	NOT REACHED (Peak at 828ppm)

Note: Table 5.1.3 lists only the upper layer tenability conditions. This is due to the fact that the upper layer is the worst case environment. The conditions tabulated for the upper layer are considered to be the bounding conditions and conditions in the lower layer would be less severe.

5.2 Conclusion

In order to perform manual safe shutdown operations in the upper electrical penetration area due to a safe shutdown fire in the entranceway to the electrical tunnels, a plant operator must be able to access the upper electrical penetration area for 45 minutes after ignition of the fire. In both fire scenarios the fire does not ignite redundant cable tray stacks, therefore operator access into the upper electrical penetration area is not required.

Computer runs were performed to determine tenability conditions in the Electrical Penetration Area (Room 6). The data in Section 4.0 shows that the tenability limits are not reached within the 45 minute time period for these two fire scenarios.

6.0 REFERENCES

6.1 HAZARD I, Version 18, Fire Hazard Assessment Method, NIST Handbook 146, Bukowski, Peacock, Jones, and Faney, 1989.

6.2 FPETOOLS, Version 3.01, Fire Protection Engineering Tools for Hazard Estimation, NISTIR 4380, Nelson, 1993.

6.3 Heat Release Rate Characteristics of Some Combustible Fuel Sources in Nuclear Power Plans, NBSIR 85-3195, Lee, 1985.

6.4 Quantitative Data on the Fire Behavior of Combustible Materials Found in Nuclear Power Plant, NUREG/CR-4679, November, 1987.

6.5 SFPE Handbook of Fire Protection Engineering, 1st Edition, 1988.

6.6 NFPA, Fire Protection Handbook, 17th Edition, 1991.

6.7 New York Power Authority, Indian Point Unit 3 Fire Protection Program Plan.

6.8 ENG-527, Fire Barrier Inspections, Penetration Fire Seal Program, Evaluation No. 5, Rev. 1, 10/26/93.

6.9 NYPA letter to NRC IPN-93-143, Dated 11/17/93, IP3 Request for Exemption from Section 111.G of Appendix R to 10CFR50.

6.10 Review and Evaluation of the Indian Point Probabilistic Safety Study, NUREG/CR-2934, 1982.

6.11 Indian Point Probabilistic Safety Study, 1982.

6.12 ONOP-FP-1A, Safe Shutdown From Outside the Contral Room, Rev. 8, 4/23/93.

6.13 EPRI NP-7332, Design Guide For Fire Protection of Grouped Electrical Cables, EPRI, 1991.

6.14 Modak, A.T., "Thermal Radiation From Pool Fires", Combustion and Flame, 29: 177-192 (1977)

6.15 Combustible Loading Analysis, Indian Point Unit 3, Rev. 0, 1993.

Plant Drawings:

6.16 9321-F-14233, Rev. 5

6.17 9321-F-14223, Rev. 5

6.18 9321-F-14263, Rev. 3

6.19 9321-F-12113, Rev. 6

6.20 9321-F-40673, Rev. 5

6.21 9321-F-12123, Rev. 4

6.22 9321-F-14203, Rev. 4

ATTACHMENT 1
INPUT DATA ROUTINES

1.0 Development of Fire Data Files:

The fire data files for the fires were developed using the MYFIRE subroutine of the MAKEFIRE routine in the FPETOOLS program.

MYFIRE - The individual fire data files were generated under this subroutine, the following inputs were used:

Pool fire mass loss rate = 11.4 g/sec

- heat of combustion = 20,000 BTU/lb

Cable fire

- heat release rate, as described in section 3.1.2
- heat of combustion = 14,000 BTU/lb

The subroutine then generated the data files presented in Attachment 2.

In order to determine if the exposed target is ignited the radiant energy incident on the target must be evaluated and then compared with the critical value below which ignition will not occur.

The incident energy (flux) received by a target can be represented by the relation:

$$q_i = Q_o/4\pi r_c^2$$

where: Q_o = Total radiant flux from the exposing fuel package (kW)

q_i = Incident flux per unit area on unignited fuel package (kW/m^2)

r_c = Distance between the effective center of the fire and the surface of the target fuel package (m)

This relationship approximates the fire as a point source located at the center of an equivalent circular fire. For this analysis, the radiative portion of the fire's heat release rate is assumed to be 35% of the total heat release rate, based on engineering judgment.

Modak has shown that the above relationship is valid for values of r greater than four times the flame diameter. Below that value, the incident energy on the target is overstated. Modak has developed correction factors to compensate for these errors. These are shown graphically in Figure 6 of Modak's paper "Thermal Radiation from Pool Fires" [Combustion and Flame, Volume 29, 177-192 (1977)]. As the separation distance between the source fire and the target is small in both fire scenarios, these correction factors are applied in this analysis.

Pool Fire:

The pool fire has a constant heat release rate of 543 kW. The pool fire has a 2 ft. diameter. The point source is assumed to be located in the center of the pool giving a total separation distance, r, between the point source and the target of 3 ft. (1 ft. radius plus 2 ft. separation). From the reference cited above, for a radius to separation ratio of 3, the factor is 0.85. The incident flux received by the target is constant at 15.199 kW/m^2 for the duration of the pool fire.

Table 3-1 of the EPRI Report NP-7332 "Design Guide for Fire Protection of Grouped Electrical Cables" lists critical values for heat flux and temperature below which piloted ignition can not occur. For silicone, glass braid/asbestos cable, which is the type assumed for use in this report, the critical values are 14 kW/m^2 for critical flux (q_i) and 705 K for critical ignition temperature. These are the lowest values for the types of cables listed in this table.

Since the incident flux is greater than the critical flux, piloted ignition is possible. A further

evaluation is made of the time required for the onset of ignition at this incident flux using Eq. 1 from Section 2.3.1 of the EPRI Report NP-7332. This equation is:

$$t = \frac{E}{q_E - q_{CR}}$$

where: t is the time to either pyrolosis, ignition, or electrical failure

E is the energy required to initiate either pyrolosis, ignition, or electrical failure

q_E is the heat flux received by the cable

q_{CR} is the critical heat flux at or below which either pyrolosis, ignition or electrical failure cannot be initiated

For silicone, glass braid/asbestos cable, from Table 3-1 of EPRI Report NP-7332, E is 778 kJ/m^2 and q_{CR} is 14 kW/m^2 as indicated previously. The above formula yields a time to ignition of 648.87 seconds. For this scenario with the combustibles as described, the target must be exposed to the incident heat flux of 15.199 kW/m^2 for a period of 648 seconds (10.8 minutes) before there is a sufficient flammable vapor/air mixture to allow piloted ignition. The calculations in Section 4.1.1 show that a 2 gallon lubrication oil fire will burn out after 399.7 seconds. Therefore, the cables will not be esposed to the incident flux for a sufficient amount of time to allow piloted ignition to occur.

Cable Fire:

The cable fire in one stack of cable trays has a growing heat release rate history which reaches a maximum, steady value of 352 kW at 2300 seconds. The cable tray is 2' wide and it is assumed that the fire begins in the center of the tray. The heat release curve is shown in Attachment A2. As the fire grows from 0k W the equivalent area and flame radius will also grow. The correction

factor from Modak's paper is dependent on the ratio of the equivalent fire radius to the separation distance. The equivalent flame radius is a function of the heat release rate. In order to determine the equivalent radius, the heat release rate per unit area must be computed so that the fire size can be calculated at each point in time.

NUREG/CR - 4679, Table 4, lists the heat release rates per unit area for the same cable samples used in EPRI Report NP - 7332. Based on these values, a weighted heat release rate per unit area is determined for the cable types and percentages listed in Section 3.0 of this report. The heat release rates per unit area for the cable types are:

PE/PVC	395 kW/m^2
PE,PP/Cl-S-PE	345 kW/m^2
Silicone/Asb	182 kW/m^2

The weighted value from this data is 212.78 kW/m^2. Using this value, an equivalent fire area can be calculated for each point on the fire growth curve from the following relationship:

$$Fire\ Area = \frac{Heat\ release\ rate}{Heat\ release\ rate\ per\ unit\ area}$$

The equivalent flame radius is then computed. This value for the flame radius is added to the original separation distance of 6 ft. to obtain the modified separation distance for the point source calculation. These calculations are shown in Table A1-1.

The maximum incident flux received by the exposed cable tray is 1.307 kW/m^2. This is well below the value of 14 kW/m^2 for critical flux as described under the pool fire discussion above. Therefore, ignition of the exposed cable tray is not expected to occur throughout the 2700 second duration of the cable tray fire scenario.

TABLE A1-1

Source Fire:		Cable						
Separation Distance (ft):		6						
Radiative Fraction:		0.35						
Time	HRR	Fire Area	R	R	Ro	Ro/R	Modak	qi
(sec)	(kW)	(m^2)	(m)	(ft)	(ft)		Factor	(kW/m^2)
0	0.000	0.000	0.000	0.000	6.000	Infinity	1.000	0.000
100	62.000	0.291	0.305	0.999	6.999	7.005	0.950	0.360
200	113.000	0.531	0.411	1.349	7.349	5.448	0.930	0.583
300	156.000	0.733	0.483	1.585	7.585	4.786	0.910	0.740
400	190.000	0.893	0.533	1.749	7.749	4.430	0.900	0.854
500	219.000	1.029	0.572	1.878	7.878	4.195	0.900	0.952
600	243.000	1.142	0.603	1.978	7.978	4.033	0.890	1.019
700	263.000	1.236	0.627	2.058	8.058	3.916	0.890	1.081
800	279.000	1.311	0.646	2.120	8.120	3.831	0.880	1.116
900	292.000	1.372	0.661	2.168	8.168	3.767	0.880	1.155
1000	304.000	1.429	0.674	2.212	8.212	3.712	0.870	1.176
1100	312.000	1.466	0.683	2.241	8.241	3.677	0.870	1.198
1200	320.000	1.504	0.692	2.270	8.270	3.643	0.870	1.220
1300	327.000	1.537	0.699	2.295	8.295	3.615	0.870	1.240
1400	331.000	1.556	0.704	2.309	8.309	3.599	0.870	1.251
1500	336.000	1.579	0.709	2.326	8.326	3.580	0.870	1.264
1600	339.000	1.593	0.712	2.336	8.336	3.568	0.870	1.272
1700	342.000	1.607	0.715	2.347	8.347	3.557	0.870	1.280
1800	344.000	1.617	0.717	2.354	8.354	3.549	0.870	1.286
1900	346.000	1.626	0.719	2.360	8.360	3.542	0.870	1.291
2000	348.000	1.635	0.722	2.367	8.367	3.535	0.870	1.296
2100	350.000	1.645	0.724	2.374	8.374	3.527	0.870	1.302
2200	351.000	1.650	0.725	2.377	8.377	3.524	0.870	1.304
2300	352.000	1.654	0.726	2.381	8.381	3.520	0.870	1.307
2400	352.000	1.654	0.726	2.381	8.381	3.520	0.870	1.307
2500	352.000	1.654	0.726	2.381	8.381	3.520	0.870	1.307
2600	352.000	1.654	0.726	2.381	8.381	3.520	0.870	1.307
2700	352.000	1.654	0.726	2.381	8.381	3.520	0.870	1.307

2.0 Development of Smoke and Hot Gas Layer and Species Production Data:

Data on the smoke and hot gas layer within the electrical tunnel and penetration areas was developed by utilizing the FAST routine within the HAZARD I program. FAST is a model to describe fire growth and smoke transport in multicompartment structures. The implementation consists of a set of programs to describe the structure to be modeled, run the model, and produce usable output. The physical bases of zone models, their limitations and development of the predictive equations are described in Appendix A.

Structures of FAST Model - The primary element of the model is a compartment. The interest in these predictive schemes lies in the environment within the compartments, so the model is structured around variables such as temperature, pressure, etc., in the compartment. Predictive equations for the gas layers in each compartment are derived from conservation of mass, momentum and energy, an equation of state, and the boundary conditions to which each compartment is subject. The term "boundary condition" refers to the transfer points at the boundaries of the compartments; examples are vents, air conditioning ducts, etc. The actual physical phenomena which drive the transport are then couched as source terms. Such a formulation allows the greatest flexibility in adding, modifying, or deleting terms which are appropriate to the problem at hand.

The conservation equations used are for mass, momentum and energy. These equations are fundamental to predictive models, and must hold in all cases. These conservation equations are rearranged to form a set of predictive equations for the sensible variables in each compartment. An important concession which is made for computational speed is that the fluid momentum between the compartments is calculated, but not within a compartment. The work term (volumetric expansion and contraction) is included in the energy equation, however. The result is that the program cannot follow acoustic waves anywhere, or gravitational waves within a compartment. The concomitant improvement is that the program is not limited by the Courant time step condition for wave motion within a compartment.

Each compartment is subdivided into a few "control volumes," which are called zones. The premise is that the details which occur within such volumes are not of concern, but their interaction is. This simplification is based on the observation that when a fire grows and spreads, the gases in a compartment stratify into distinct zones. In the present calculation there are only two zones per compartment. There is reasonably good agreement between theory and experiment for this choice, and there are other phenomena which put a more severe constraint on the validity of the model.

FAST is formulated as a set of ordinary differential equations. It was the first model of fire growth and smoke spread to cast the entire model in this form and was done because of the efficiency of solving the conservation equations this way.

It is important to keep in mind that this model is based on a control volume concept. To that end, one gives up knowledge of some of the details of the internal structure of the problem being modeled, such as temperature variation within a zone.

3.0 Description of the Data File Used by FAST

The computer model requires a description of the problem to be solved. The following description is for the input data used by the model. In general, the order of the data is not important. The one exception to this is the first line which specifies the version number and gives the data file a title.

The data are grouped as:

- Version and title 3.1.1
- Time specification 3.1.2
- Ambient conditions 3.1.3
- Floor plan data 3.1.4
- Connections 3.1.5
- Thermophysical properties of the enclosing surfaces 3.1.6
- Fire specificaitons 3.1.7
- Species production 3.18

The number of lines in a given data set will vary depending for example on the number of openings or the number of species tracked. A number of parameters such as heat transfer and flow coefficients are set within the program as constants.

Each line of input data file begins with a key word which identifies the type of data on the line. The key words are:

CEILI	specify name of ceiling descriptor(s)	(N)
CHEMI	miscellaneous parameters for kinetics	(5)
CO	CO/CO2 mass ratio	(Lfmax+1)
CT	fraction of fuel which is toxic	(Lfmax+1)

CVENT	opening/closing parameter	(Lfmax+4)
DEPTH	depth of compartments	(N)
DUMPR	specify a file name for saving time histories	(1)
EAMB	external ambient	(3)
FAREA	area of the base of the fire	(Lfmax+1)
FHIGH	height of the base of the fire	(Lfmax+1)
FLOOR	specify the name of floor property descriptor(s)	(N)
FMASS	pyrolysis rate	(Lfmax+1)
FQDOT	heat release rate	(Lfmax+1)
FTIME	length of time intervals	(Lfmax)
HCL	hcl/pyrolysis mass ratio	(Lfmax+1)
HCN	hcn/pyrolysis mass ratio	(Lfmax+1)
HCR	hydrogen/carbon mass ration of the fuel	(Lfmax+1)
HEIGH	interior height of a compartment	(N)
HI/F	absolute height of the floor of a compartment	(N)
HVENT	specify vent which connect compartments horizontally	(7)
INTER	initial height of the upper/lower interface	(2)
LFBO	compartment of fire origin	(1)
LFBT	type of fire	(1)
LFMAX	number of time intervals	(1)
LFPOS	position of the fire in the compartment	(1)
OD	C/CO2 mass ratio	(Lfmax+1)
RESTR	specify a restart file	(2)
TAMB	ambient inside the structure	(3)
TIMES	time step control of the output	(5)
VVENT	specify a vent which connects compartments vertically	(3)
VERSN	version number and title	(fixed format 2)
WALLS	specify the name of wall property descriptor(s)	(N)
WIDTH	width of the compartments	(N)

WIND	scaling rule for wind effects	(3)

The number in parenthesis is the maximum number of entries for that line. "N" represents the number of compartments being modeled and "Lfmax" is the number of time intervals used to describe the fire, detailed below in section 3.1.7. The outside (ambient) is designated by one more than the number of compartments, N + 1. So the compartment model will refer to the outside as compartment seven.

Each line of input consists of a label followed by one or more alphanumeric parameters associated with that input label. The label must always begin in the first space of the line and be in capital letters. Following the label, the values may start in any column and all values must be separated by either a comma or a space. Values may contain decimal points if needed or desired. They are not required. Units are standard SI units. Most parameters have default values which can be utilized by oimitting the appropriate line. These will be indicated in the discussion. The maximum line length is 128 characters, so all data for each key word must fit in this number of characters. For each entry which requires more than one type of data, the first entry under the column "parameter" indicates the number of data required.

In the following sections each data input group is described in detail, following each data description is a list of the data that was used as input for this analysis.

3.1.1 Version and Title

This line <u>must</u> be the first line in the file. It is the line that FAST keys on to determine whether it has a correct data file. The format is fixed, that is the data must appear in the columns specified in the text.

Label	Parameter	Comments
VERSN	(2)	The VERSN line is a required input.
	Version Number	The version number parameter specifies the version of FAST for which the input data file was prepared. Normally, this would be 18. It must be in columns 8-9.
	Title	The title is optional and may consist of letters, numbers, and/or symbols that start in column 11 and may be up to 50 characters. It permits the user to uniquely label each run.

ACTUAL

VERSN	**18**	**CABLE TRAYS FIRE**
VERSN	**18**	**2' DIA POOL FIRE SPECIES**

3.1.2 Time Specification

Label	Parameter	Comments	Units
TIMES	(5)	The TIMES line is required data.	

Label	Parameter	Comments	Units
	Simulation Time	Simulation time is the length of time over which the simulation takes place. The maximum value for this input is 84600 seconds (1 day). The simulation time parameter is required.	s
	Print Interval	The print interval is the time interval between each printing of the output values. If omitted or less than or equal to zero, no printing of the output values will occur.	s
	Dump Interval	The dump interval is the time interval between each writing of the output to the dump file. The dump file stores all of the output of the model at the specified interval in a format which can be efficiently retrieved for use by other programs. A zero must be used if no dump file is to be used. There is a maximum of 50 intervals allowed. If the choice of this parameter would yield more	s

	than 50 writes, it is ajdusted so that this limit is not exceeded.
Display	The display interval is the time s interval between each graphical display of the output as specified in the graphics specification. If omitted as in this analyis, no graphical display will occur. There is a limit on the display of 50 for the micro-computer versions and 100 for the mainframe versions of FAST. This parameter is not adjusted; rather graphs will be truncated to the first 50 or 100 points, respectively.
Copy Count	Copy count is the number of copies of each graphical display to be made on the selected hard copy device as specified in the graphics specification, this item is omitted in this anaylsis.

ACTUAL:

TIMES	**2700**	**60**	**60**	**0**	**0**
TIMES	**540**	**60**	**60**	**0**	**0**

3.1.3 Ambient Conditions

The ambient conditions section of the input data allows the user to specify the temperature and pressure and station elevation of the ambient atmosphere, as well as the absolute wind pressure to which the structuure is subjected. There is an ambient for the interior and for the exterior of the building. The key word for the interior of the building is TAMAB and for the exterior of the building is EAMB. The form is the same for both. The key word for the wind information is WIND. The wind modification is applied only to the vents which lead to the exterior. Pressure interior to a structure is calculated simply as a lapse rate based on the NOAA tables. For the exterior, the nominal pressure is modified by

$$\delta(p)=C_w \rho V^2, where V=V_w\left(\frac{H^i}{H_w}\right)^{p_v}$$

This modification is applied to the vents which lead to the exterior ambient. The pressure change calculated above is modified by the wind coefficient for each vent. This coefficient, which can vary from -1.0 to +1.0, nominally from -0.8 to +0.8, determines whether the vent is facing away from or into the wind. The pressure change is multiplied by the vent wind coefficient and added to the external ambient for each vent which is connected to the outside.

Label	Parameter	Comments	Units
TAMB or EAMB	(3)	These data are optional.	
	Ambient Temperature	Ambient temperature is the temperature of the ambient atmosphere. Default is 300.	K
	Ambient	The ambient pressure is the pressure of the ambient atmosphere. Default is 101300.	Pa
	Station Elevation	The station elevation is the elevation of the point at which the ambient pressure and temperature (see above) are measured. The reference point for the elevation, pressure and temperature must be consistent. This is the reference datum for calculating the density of the atmosphere as well as the temperature anad pressure inside and outside of the building as a function height. Default is 0.	m

Label	Parameter	Comments	Units
WIND	(3)	This line is optional.	
	Wind Speed	Wind speed at the reference The default is 0.	m/s
	Reference Height	Height at which the reference wind speed is measured. The default is 10 meters.	m
	Lapse Rate Coefficient	The power law used to calculate the wind speed as a function of height. The default is 0.16.	

The choice for the station elevation, temperature and pressure must be consistent. Outside of that limitation, the choice is arbitrary. It is often convenient to choose the base of a structure to be at zero height and then reference the height of the building with respect to that height. The temperature and pressure must then be measured at that position. Another possible choice would be the pressure and temperature at sea level, with the building elevations then given with respect to mean sea level.. this is also acceptable, but somewhat more tedious in specifying the construction of a building. Either of these choices works though because consistent data for temperature and pressure are available from the Weather Service for either case.

ACTUAL

TAMB	**300**	**101300**	**0**
EAMB	**300**	**101300**	**0**
TAMB	**300**	**101300**	**0**
EAMB	**300**	**101300**	**0**

Both models set the ambient temperature to 300 Kelvin, the ambient pressure at 101300 pascals , and the reference elevation at 0 meters.

3.1.4 Floor Plan Data

The floor plan data section allows the user to portray the geometry of the structure being modeled. The size and location of every room in the structure MUST be described. The maximum number of rooms is dependent upon the local implementation of FAST. Usually a total of 10 rooms (plus the outdoors) is available for a single simulation. For the PC versions, a maximum of six compartments (plus the outdoors) is allowed. The structure of the data is such that the compartments are described as entities, and then connected in appropriate ways. It is thus possible to have a set of rooms which can be configured in a variety of ways. In order to specify the geometry of a building, it is necessary to give its physical characteristics. Thus the lines labelled HI/F, WIDTH, DEPTH and HEIGHT are all required. Each of these lines requires "N" data entries, that is one for each compartment.

Label	Parameter	Comments	Units
HI/F	Floor Parameter	The floor height is the height of the floor of each room with respect to station elevation specified by the TAMB parameter. The reference point must be the same for all elevations in the input data. The number of values on the line must equal the number of rooms in the simulation.	m
WIDTH	Room Width	Room width specifies the width of the room. The number of values on the line must equal the number of rooms in the simulation.	m
DEPTH	Room Depth	Room depth specifies the depth of the room. The number of values on the line must equal the number of rooms in the simulation.	m
HEIGH	Room Height	Room Height specifies the height of the room. The number of values on the line must equal the number of rooms in the simulation.	m

ACTUAL

HI/F	**0.00**	**3.05**	**3.05**	**3.36**	**3.36**	**3.96**
WIDTH	**3.05**	**3.05**	**2.44**	**2.44**	**2.44**	**5.49**
DEPTH	**3.05**	**6.10**	**24.38**	**9.76**	**10.68**	**26.54**
HEIGHT	**6.10**	**3.05**	**3.05**	**3.05**	**4.73**	**5.18**

Data is the same for both fires.

3.1.5 Connections

The connections section of the input data file describes any horizontal or vertical vents between the rooms in structure. These may include doors between rooms in the structure, windows in the rooms (between rooms or to the outdoors), or vertical openings between floors of the structure. Openings to the outside are included as openings to the room with a number one greater than the number of rooms described in the floor plan data section. Doors, windows, and the like are called horizontal vents because the direction of the vent, or vent connection, is in the horizontal direction. The key word is HVENT. Horizontal vents may be opened or closed during the fire with the use of the CVENT key word. For vertical vents, such as scuddles, the key word is VVENT; at present there is not an equivalent mechanism for opening or closing the vertical vents. The form for horizontal and vertical vents is necessarily different.

Label	Parameter	Comments	Units
HVENT	(7)	Required to specify connections between compartments. No openings prevents flow. Each HVENT line in the input file describes one horizontal vent between rooms in the structure (or between a room and the outdoors). The first six entries on each line are required. There is an optional seventh parameter to specify wind coefficient.	
	First Room	The first room is simply the first connection.	
	Second Room	The second room is the room number to which the first room is connected. The order has one significance. The height of the sill and soffit are with respect to the first compartment specified.	
	Vent Number	There can be as many as four vents between any two compartments. This number specifies which vent is being described. It can range from one to four.	

	Width	The width of the opening.	m
	Soffit	Position of the top of the opening above the floor of the room number specified as the first room.	m
	Sill	Sill height is the height of the bottom of the opening above the floor of the room number specified as the first room.	m
	Wind	The wind coefficient is the cosine of the angle between the wind vector and the vent opening. This applies only to vents which connect to the outside ambient (specified with EAMB). The range of values is -1.0 to +1.0. If omitted, the value defaults to zero.	
VVENT	(3)	Required to specify a vertical connection between compartments. Each VVENT line in the input file describes one vertical vent between rooms in the structure (or between a room and the outdoors). There are three parameters, the connected compartments, and the effective area of the vent.	

First Room	The first room is simply the first connection.
Second Room	The second room is the room number to which the first room is connected. The order has one significance. The height of the sill and soffit are with respect to the first compartment specified.
Area	This is the effective area of the opening. For a hole, it would be the actual opening. For a diffuser, then the effective area will be somewhat less than the geometrical size of the opening.

ACTUAL

HVENT	**1**	**2**	**1**	**3.05**	**6.10**	**3.05**
HVENT	**2**	**3**	**1**	**2.44**	**3.05**	**0.00**
HVENT	**3**	**4**	**1**	**2.44**	**3.05**	**0.31**
HVENT	**4**	**5**	**1**	**2.44**	**3.05**	**0.00**
HVENT	**5**	**6**	**1**	**2.44**	**4.73**	**0.61**

Data is the same for both fires.

CVENT is a parameter which is used to open or close vents. It multiples the width in the vent flow calculation. The default is 1.0 which is a fully open vent. A value of 0.5 would specify a vent which was halfway open.

Label	Parameter	Comments	Units
CVENT	(LFMAX+4)	Specify closing value. Each CVENT line in the input file describes one horizontal vent between rooms in the structure (or between a room and the outdoors).	
	First Room	The first compartment.	
	Second Room	The second room is the room number to which the first room is connected.	
	Vent Number	This number specifies which vent is being described. It can range from one to four.	
		These parameters correspond to the first three parameters in HVENT.	
	Width (LFMAX+1)	Fraction that the vent is open. This applies to the width only. The sill and soffit are not changed.	

CVENT has a form similar to HVENT but in addition contains the opening data. The additional data is in the same form as all the time dependent specifications, namely a value for each endpoint in the heat release curve. The form is

CVENT C#1 C#2 V# x x x x, ...

ACTUAL

CVENT	**1**	**2**	**1**	**1.00**	**1.00, ...**
CVENT	**2**	**3**	**1**	**1.00**	**1.00, ...**
CVENT	**3**	**4**	**1**	**1.00**	**1.00, ...**
CVENT	**4**	**5**	**1**	**1.00**	**1.00, ...**
CVENT	**5**	**6**	**1**	**1.00**	**1.00, ...**

Data is the same for both fires.

3.1.6 Thermophysical Properties of Enclosing Surfaces

The thermophysical properties of the enclosing surfaces are described by specifying the thermal conductivity, specific heat, emissivity, density, and thickness of the enclosing surfaces for each room. If the thermophysical properties of the enclosing surfaces are not included, FAST will treat them as adiabatic (no heat transfer). Since most the heat conduction is throught the ceiling and since the conduction calculation takes a significant fraction of the computation time, it is recommended that initial calculations be made using the ceiling only. Adding the walls generally has a small effect on the results and the floor contribution is usally negligible. Clearly, there are cases where the above generalization does not hold, but it may prove to be a useful screening technique. Currently, thermal properties for matierals are read from a thermal database fire unique to FAST. The data in the fire for FAST simply gives a name (such as CONCRETE) which is a pointer to the properties in the thermal database . (For computers which do not

support extensions, the ".DAT" is dropped.) For the PC version, this is an installation parameter. All of these specificaitons are optional. The thermal properties are assumed to be constant that is, we do not account for the variation with temperature or water content.

The thermophysical properties are specified at one condition of temperature, humidity, etc. There can be as many as three layers per boundary, but they are specified in the thermal database itself.

Label	Parameter	Comments	Units
CEILI	(N)	The label CEILI indicates that the names of thermophysical properties on this line describe the ceiling material. If this parameter is present, there must be an entry for each compartment.	
WALLS	(N)	The label WALLS indicates that the names of thermophysical properties on this line describe the wall material. If this parameter is present, there must be an entry for each compartment.	
FLOOR	(N)	The label FLOOR indicates that the names of thermophysical properties on this line describe the floor material. If this parameter is present, there must be an entry for each compartment.	

ACTUAL

CEILI	CONCRETE	CONCRETE	CONCRETE	CONCRETE	CONCRETE	CONCRETE
WALLS	CONCRETE	CONCRETE	CONCRETE	CONCRETE	CONCRETE	CONCRETE
FLOOR	CONCRETE	CONCRETE	CONCRETE	CONCRETE	CONCRETE	CONCRETE

Data is the same for both fires.

3.1.7 Fire Specifications

The fire specifications allow the user to describe the fire source in the simulation. The location and position of the fire is specified along with the chemical properties of the fuel. Finally, the fire is described with a series of mass loss rate, fuel height, and fuel area inputs. All of these specifications are optional and each line requires a single number. The defaults for the fire specification is a methane burner in the center of compartment (1). The defaults shown for each key word reflect the values for methane.

Label	Parameter	Comments	Units
LFBO	Room of Fire Origin	Room of fire origin is the room number in which the fire originates. Default is 1.	
LFBT	Fire Type	This is a number indicating the type of fire.	

Label	Parameter	Comments	Units
		1 Unconstrained fire 2 Constrained fire The default is 1.	
LFPOS	Fire Position	The fire position is the area of the room in which the fire originates and is one of the following values: 1 Center of the room 2 Corner of the room, or 3 Along a wall of the room, but not near a corner of the room. The fire position is used to account for the entrainment rate of the plume, which depends on the location of the fire plume within the compartment.	
CHEMI	(6)	Chemical kinetics and miscellaneous parameters.	
	Molar Weight	Molecular weight of the fuel vapor. This is the conversion factor from mass density to molecular density for "tuhc." Default is 16. It is used only for conversion to ppm, and has no effect on the model itself.	

Label	Parameter	Comments	Units
	Relative Humidity	The intial relative humidity in the system. This is converted to kilograms of water per cubic meter from the table from "Dynamical and Physical Meteorology" by Haltiner and Martin (1957).	%
	Limiting Oxygen Index	The limit on the ratio of oxygen to other gaases in the system below which a flame will not burn. This is applicable only to type (LFBT) 2 or later fires. The default is 10.	%
	Heat of Combustion	Heat of combustion of the fuel. Default is 50000000.	J/kg
	Initial Fuel Temperature	Typically, the initial fuel temperature is the same as the ambient temperature as specified in the ambient conditions section.	K
	Gaseous Ignition Temperature	Minimum temperature for ignition of the fuel as it flows from a compartment through a vent into another compartment. The default is the inital fuel temperature.	K

Label	Parameter	Comments	Units
LFMAX	Number of Intervals	This is the number of time intervals for the mass loss rate, fuel height and specifies inputs. The mass loss rate, fuel height and species are entered as series of points with respect to time. This is referred to in this document as a specified fire. A sufficient number of intervals should be selected to provide a reasonable appoximation (using straight line segments) for the input variables which specify the fire. The number of points specified must be one greater than the number of time intervals. For example, if there are six mass loss points there should be a total of five time intervals (or one interval between every two consecutive points). The maximum number of intervals allowed in version 18 of FAST is 21.	
FTIME	Time Interval (LFMAX)	Time interval is the time between each point (mass loss rate, fuel height and species) specified for the fire. The total duration of the fire is the sum of the time intervals. This time is independent of the simulation time which is specified	s

		for TIMES label. If the simulation time is longer than the total duration of the fire, the final values specified for the fire (mass loss rate, fuel height, fuel area, and species) will be continued until the end of the simulation. The number of values on the line must equal the number of time intervals specified by LFMAX, above.	
FMASS	Mass Loss Rate (LFMAX+1)	The rate at which fuel is pyrolyzed at times corresponding to each point of the specified fire.	kg/s
FHIGH	Fuel Height (LFMAX+1)	The height of the base of the flames above the floor of the room of fire origin for each point of the specified fire.	m
FQDOT	Heat Release Rate (LFMAX+1)	The heat release rate of the specified fire.	W

With the three parameters, the heat of combustion (HOC) from CHEMI, FMASS and FQDOT, the pyrolysis and heat release rate are over specified. The model uses the last two of the three to obtain the third parameter. That is, if the three were specified in the order HOC, FMASS and FQDOT, then FQDOT would be divided by FMASS to obtain the HOC for each time interval. If the order were FMASS, FQDOT and HOC, then the pyrolysis rate would be determiend by

dividing the heat release rate by the heat of combustion. If only two of the three are given, then those two will determine the third, and finally, if none or only one of the parameters is present, the defaults shown will be used.

ACTUAL

Cable tray fire

CHEMI	**16.**	**1.**	**10.0**	**33000000.**	**300.**
LFBO	**1**				
LFBT	**2**				
LFPOS	**3**				
LFMAX	**12**				
FTIME	**100. 100. 100. 100. 100. 100. 100. 200. 200. 500. 500. 600.**				
FMASS	**0.0000 0.0019 0.0035 0.0048 0.0058 0.0067 0.0075 0.0081 0.0089 0.0096 0.0104 0.0107 0.0108**				
FHIGH	**0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00**				
FAREA	**0.029 0.029 0.029 0.029 0.029 0.029 0.029 0.029 0.029 0.029 0.029 0.029 0.029**				
FQDOT	**0.00 6.20E+04 1.13E+05 1.56E+05 1.90E+05 2.19E+05 2.43E+05 2.63E+05 2.92E+05 3.12E+05 3.39E+05 3.50E+05 3.52E+05**				

2 ft. pool fire

CHEMI	**16.**	**0.**	**10.0**	**47450000.**	**300.**
LFBO	**1**				
LFBT	**2**				
LFPOS	**1**				
LFMAX	**1**				
FTIME	**540.**				
FMASS	**0.0114 0.0114**				
FHIGH	**0.00 0.00**				
FAREA	**0.07 0.07**				
FQDOT	**5.43E+05 5.43E+05**				

3.1.8 Species Production

Species production rates are specified in the manner similar to the fire, entering the rates as a series of points with respect to time. The species which are followed by FAST are:

Carbon Dioxide
Carbon Monoxide
Concentration-Time Product
Hydrogen Cyanide
Hydrogen Chloride
Nitrogen
Oxygen
Soot (Smoke Density)
Total Unburned Hydrocarbons
Water

For a type two (LFBT=2) fire, such as those modeled in this analysis, nitrogen, oxygen, carbon dioxide, carbon monoxide, soot, unburned fuel and water are followed. In all casaes, the unit of the production rates is kg/kg. The production rate is specified with respect to the basic carbon production in the form of a ratio with carbon dioxide. For carbon monoxide, for example, the specification will be CO/CO^2.

Label	Parameter	Comments	Units
SPECIES	(LFMAX+1)	For each species desired a series of production rates are specified for each of the time points input	

		for the specified fire. The program performs a linear interpolation between these points to determine the time of interest.	
HCR	Production Rate of the Fuel	The mass ratio of hydrogen to carbon as it becomes available from the fuel. This parameter affects primarily the rate of produciton of water.	kg/kg
OD	Yield	The ratio of the mass of carbon to carbon dioxide produced by the oxidation of the fuel.	kg/kg
CO	Yield	The ratio of the mass of carbon monoxide to carbon dioxide produced by the oxidation of the fuel.	kg/kg

ACTUAL

Cable tray fire

HCR	0.330	0.330	0.330	0.330	0.330	0.330	0.330	0.330	0.330	0.330	0.330	0.330	0.330
CO	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023
OD	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034

2' pool fire

HCR	0.330	0.330
CO	0.007	0.007
OD	0.030	0.030

ATTACHMENT 2

TABLE A2-1 HEAT RELEASE (HRR) AND MASS LOSS RATES (MLR) FOR CABLE TRAY FIRE		
TIME (sec)	**HRR (kw)**	**MLR (g/sec)**
0	0	0
100	62	1.901841
200	113	3.466258
300	156	4.785276
400	190	5.828221
500	219	6.717792
600	243	7.453988
700	263	8.067485
800	279	8.558283
900	292	8.957056
1000	304	9.325153
1100	312	9.570553
1200	320	9.815951
1300	327	10.03067
1400	331	10.15337
1500	336	10.30675
1600	339	10.39877
1700	342	10.49080
1800	344	10.55215
1900	346	10.61350
2000	348	10.67485

TABLE A2-1 HEAT RELEASE (HRR) AND MASS LOSS RATES (MLR) FOR CABLE TRAY FIRE		
TIME (sec)	**HRR (kw)**	**MLR (g/sec)**
2100	350	10.73620
2200	351	10.76687
2300	352	10.79755
2400	352	10.79755
2500	352	10.79755
2600	352	10.79755
2700	352	10.79755

FIGURE A2-1

Heat Release Rate for Cable Tray Fire

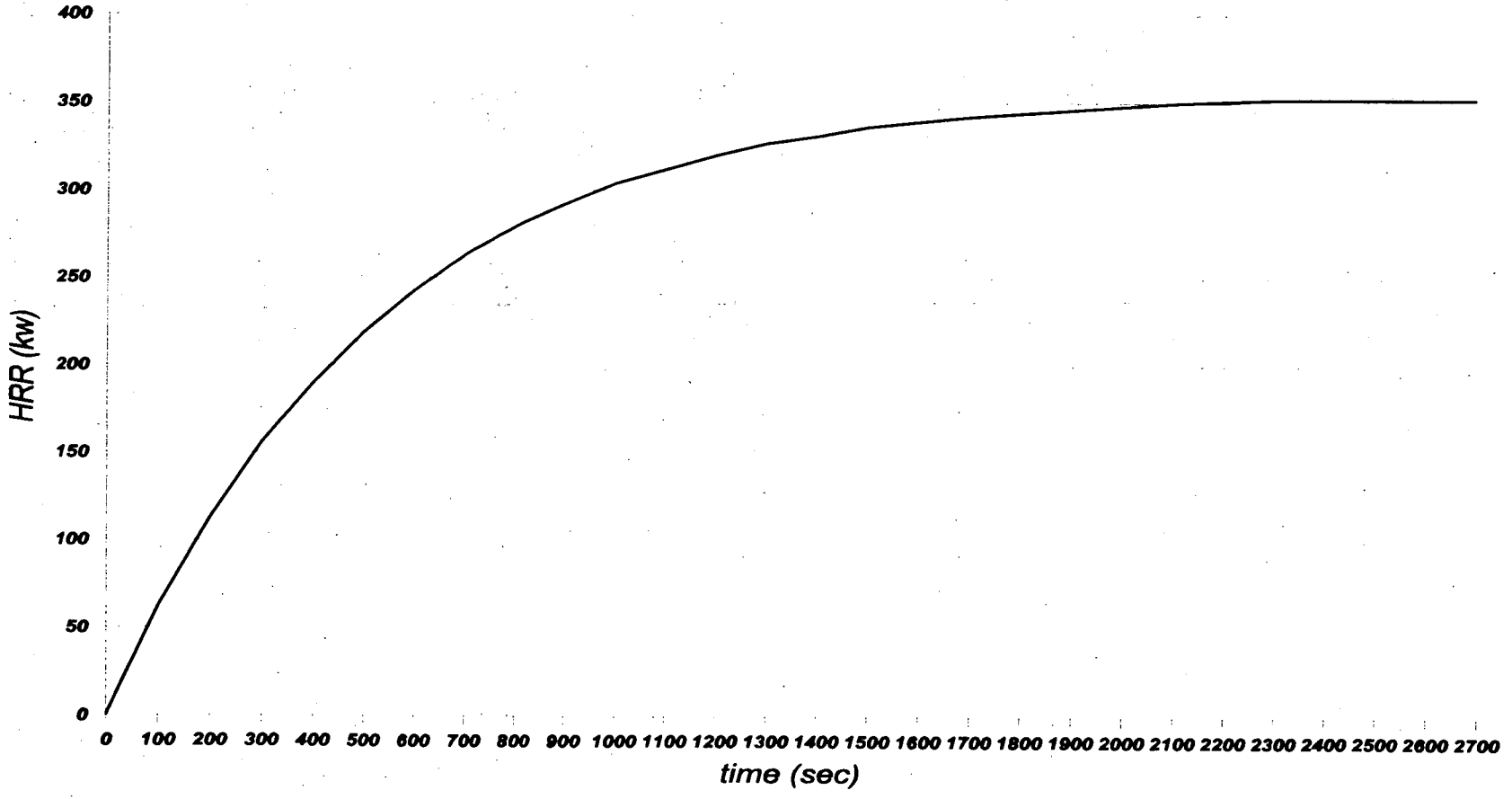
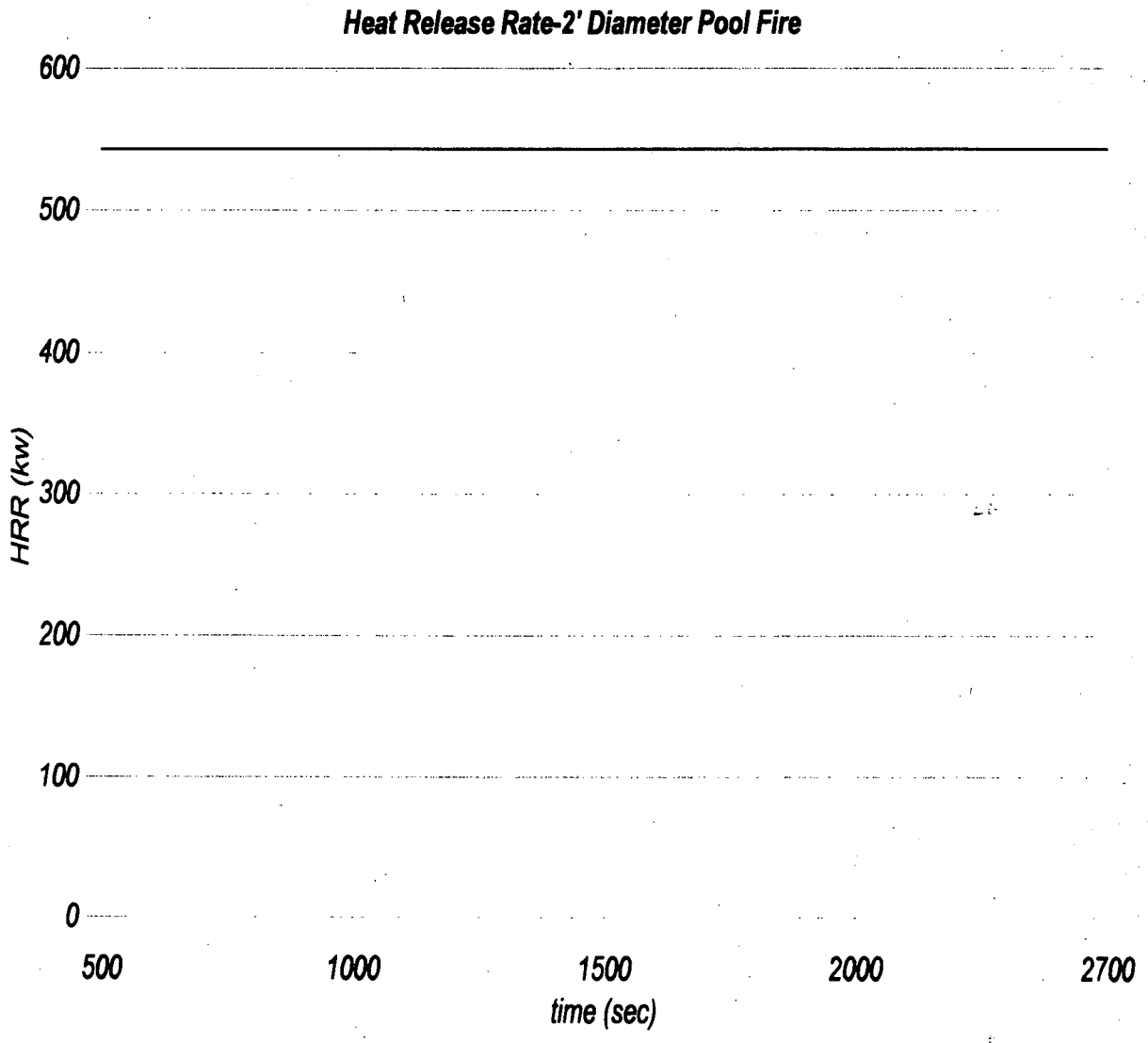


TABLE A2-2 HEAT RELEASE (HRR) AND MASS LOSS RATES (MLR) FOR 2 FOOT DIAMETER POOL FIRE		
TIME (sec)	**HRR (kw)**	**MLR (g/sec)**
0	543.203	11.43516
500	543.203	11.43516
1000	543.203	11.43516
1500	543.203	11.43516
2000	543.203	11.43516
2700	543.203	11.43516

Figure A2-2


Heat Release Rate-2' Diameter Pool Fire
600
500
400
300
200
100
0
HRR (kw)
500
1000
1500
2000
2700
time (sec)

APPENDIX A

TECHNICAL REPORT ON HAZARD 1 PROGRAM

A MULTICOMPARTMENT MODEL FOR THE SPREAD OF FIRE, SMOKE AND TOXIC GASES

Walter W. Jones
Center for Fire Research
National Engineering Laboratory
National Bureau of Standards
U.S. Department of Commerce
Gaithersburg, MD 20899

Reprinted from FIRE SAFETY JOURNAL, Vol. 9, No. 1, 55-79, May 1985.

NOTE: This paper is a contribution of the National Bureau of Standards and is not subject to copyright.

Fire Safety Journal, 9 (1985) 55 - 79

A Multicompartment Model for the Spread of Fire, Smoke and Toxic Gases*

WALTER W JONES

National Bureau of Standards, Washington, DC 20234 (U.S.A.)

1. INTRODUCTION

In recent years there has been considerable research in the area of the spread of fire and smoke from a room of fire origin to connected compartments. The work is motivated by a need to understand and be able to predict the environmental conditions which occur as a fire develops and spreads. Much of the attention has focused on the development of numerical models which are able to make a reasonably accurate assessment of the environment from ignition. The motivation is two-fold. Being able to correlate laboratory scale experiments with full-scale tests is desirable from a cost standpoint. More important, however, from a life-safety and operational standpoint, the ability to make accurate predictions of the spread of fire, smoke and toxic gases opens up many possibilities for combating these problems, as well as taking effective preventive measures. The ability to prevent the hazards from developing becomes especially important as new and exotic materials become available.

This paper describes a model which allows one to predict the evolution of a fire in a room and the subsequent transport of the smoke and toxic gases which evolve from this fire. The numerical implementation improves on previous work, for a review see Jones [1], in particular by retaining the conservation laws in their full differential form and solving them as a set of coupled ordinary differential equations (ODEs). Such a formulation takes advantage of the effort which has gone into solving such systems of equations. The result is a numerical scheme which is considerably faster and much more 'rugged' than previous models.

The model is assumed to be in a world of uniform temperature T_a and reference pressure P_a, with the outside of a wall at T_c which may not be the same as the ambient. The discussion is broken down into the basic structure and fundamental assumptions which go into the model, followed by a derivation of the predictive equations, a discussion of the source terms, the numerical implementation and some calculations and comparisons with experimental data. The notation is given in Appendix A. The numerical implementation of the model is modular and straightforward. It is designed to be transportable.

2. STRUCTURE OF THE MODEL

The primary element of the model is a compartment. The primary interest lies in the composition of the gas layers in each of these compartments. As such, the model is structured around fluid transport phenomena. In this context, the predictive equations for the gas layers in each compartment result from conservation of mass, momentum and energy together with an equation-of-state for each compartment. The actual physical phenomena which drive the transport are then couched as source terms. Such a formulation allows the greatest flexibility in adding, modifying or deleting terms which are appropriate to the problem being solved.

Each compartment is subdivided into one or more 'control volumes'. These control volumes will be of sufficient size that we will require only a few to describe any system of interest. The choice is based on the premise that the details which occur within such a volume do not concern us (at present), but their mutual interaction does. Each of these control volumes is called a zone. The rationale for such a choice arises from the experimental observation that when a fire spreads, the gas

*Contribution of the National Bureau of Standards (U.S.A.). Not subject to copyright.

Elsevier Sequoia/Printed in The Netherlands

layers in the compartments actually stratify into two distinct zones. This is a compromise between a network model and a finite difference model. The former is computationally fast but yields no information on the internal structure whereas the latter yields a great deal of information but requires more computational resources than is warranted. The two zones are referred to as 'upper' and 'lower', respectively. The basic equations describe the mass, momentum and energy transfer from zone to zone in a fire driven environment. A schematic is shown in Fig. 1.

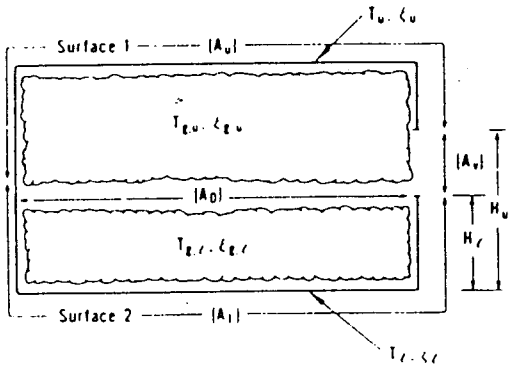


Fig. 1. A schematic of one compartment in the zone model concept. Two layers (u, l) and a single vent are shown.

In considering dynamic systems, it is necessary to solve a problem self-consistently. If such is not done, then some of the dynamics may be obscured or even lost. In particular, discussion of movement of the zone interfaces must be consistent.

The conservation equations for mass and energy can be written in the form

$$\frac{dm}{dt} = \sum_i \dot{m}_i \tag{1}$$

for mass and from the first law of thermodynamics we have

$$\frac{d}{dt}(EV) + p\frac{dV}{dt} = \dot{Q} + \dot{h} \tag{2}$$

together with an equation of state

$$P = \rho RT \tag{3}$$

which closes the set of equations, and with the definitions

$$E = c_v \rho (T - T_R)$$

$$\dot{h} = c_p \sum_i \dot{m}_{i,\,in}(T - T_R) - c_p \sum_i \dot{m}_{i,\,out}(T - T_R) + \sum_i h_{i,\,o}(T_R)$$

$\dot{Q} = \dot{Q}_f + \dot{Q}_R + \dot{Q}_c$ = net energy input

i = index of other compartments

($i \neq$ volume of interest).

The term $h_{i,\,o}(T_R)$ is relative to the temperature from which this mass parcel, $\dot{m}dt$, came. It includes enthalpy of formation. The equation of state for an ideal gas is usually used for closure of the system. More correctly it should be written

$$P = P(\rho, T, \{i\}), \{i\} \equiv \text{set of species} \tag{4}$$

especially for applications to fire problems which are not ideal gas problems. However, for the case of an ideal gas, the derivations and discussion are simplified, and generalizations can be discussed later. The sign convention is that positive fluxes on the right-hand side of an equation will increase the quantity being calculated on the left-hand side, that is, transfer into a volume is indicated by a positive flux on the right-hand side.

The general form of the model is to divide each compartment into two zones: an upper zone which contains a hot layer, and a lower layer which is relatively cool. There may exist one or more fires and plumes in each compartment and these can usually be considered to be part of the upper zone. Mass and energy transfer between the zones is provided by the plumes, mixing at the vents, radiation between layers and flow along the walls. In general a plume, once created, simply transfers mass and energy from one zone to another. Another set of equations could be written for the plume, but as long as it is in quasi-steady equilibrium, considering it to be part of the upper zone is sufficient. Another way of looking at the plume is to consider it so small in mass, energy constant and volume that it can be ignored except as a transfer mechanism. For some problems, however, the plume must be considered a separate zone along with the concomitant conservation equations. An example would be when the rise time of the plume is of interest

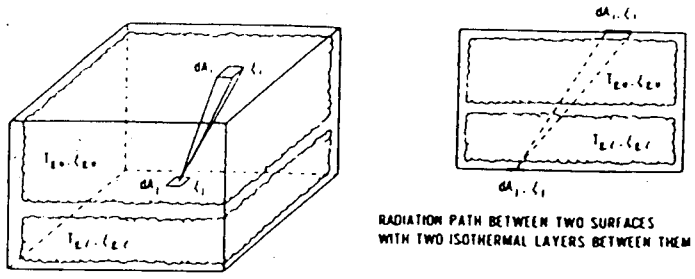


Fig. 2. Radiation transport scheme. Shown is the view factor calculation of surface 'i' as seen by surface 'j', transmitted through both layers.

or when the actual size and composition of the plume is important.

Since the conservation equations are written in terms of the volumes of these entities, a relationship between the height and the volume is needed, such as

$$V_u = \int_{Z_l}^{H_R} ZA(Z)\,dZ \tag{5}$$

to calculate the layer depths. This removes the usual restriction that the compartments be rectangular parallelepipeds, and allows calculations for circular crosssections (aircraft) and trapezoids (atria).

The radiation transport scheme used is fairly simple and derives from the work of Siegel and Howell [2]. The view factors which are used in the calculation of solid angles are concomitant with surfaces which are planes or discs. The relationship is shown schematically in Fig. 2. The simplification used here and discussed in more detail by Jones [1] is retained, but the actual areas are used, and the exact view factors are used wherever possible [3]. For example, in calculating the area of the upper wall, allowance is made for any vents which exist by subtracting their area from the total wall area. In addition, ceiling and upper wall, lower wall and floor are treated separately (as pairs). This is necessitated by the possible use of different materials for the respective surfaces which may have different radiative properties, as well as the different types of convective flow which occur over each of these surfaces. More correctly, we should consider three surfaces, ceiling, wall and floor. This is under development. A problem arises in treating vertical convection as the layer depth tends to zero.

Actual closure of the model is obtained by assuming that the size of the compartment is fixed so that

$$V = V_u + V_l \tag{6}$$

and that there is a single reference pressure

$$P_u = P_l \tag{7}$$

at the boundary (interface) of the zones.

The set of equations which is necessary to describe fully such a physical system can be reduced by considering the physical impact of some of the terms. In particular, the pressure should be a general function of position, $P(X, Y, Z)$, in the compartment, which would require us to include a differential equation for the conservation of momentum explicitly. A general form for the perturbed pressure might be

$$\bar{P}(x, y, t) = P(t) - \int_0^Z \rho(t)\,dz + \delta P(X, Y, Z, t) \tag{8}$$

where P is a reference pressure and is usually the pressure at the base of the compartment. In the spirit of the 'control volume' formulation

$$\delta P \to 0$$

This implies that acoustic waves are filtered out and that internal momentum need not be calculated. The hydrostatic term is small in absolute value in comparison with the reference pressure, so it is not necessary to carry this calculation through the equation of state. Finally, the time dependent portion of the hydrostatic term deals with the movement of the interface, and thus can be ignored if we limit ourselves to problems where the

momentum associated with the discontinuity (alternatively the velocity) is not significant. Dropping the momentum equation for internal waves increases the computational time step a great deal since we are not limited by the Courant time step criterion (time step α grid size/speed of sound). This prohibits us from considering problems such as deflagration waves and explosions. With these considerations in mind, we will assume

$$P_u = P_l = P \tag{9}$$

The pressure in eqn. (9) is the reference pressure at the floor. This simplification is carried through the conservation equations and greatly simplifies the resulting predictive equations. However, it is necessary to retain the hydrostatic term for the flow field calculations at vents. As we are considering only small changes in the absolute pressure, differences of these terms will be comparable to the hydrostatic pressure change, eqn. (8).

For example, for eqn. (22)

$$\delta P \sim 1 - 1000 \text{ Pa}$$

whereas

$$\int (\rho_1 T_1 - \rho_2 T_2)\, dz \sim 100 \text{ Pa}$$

where the integration is over a vent opening. So the flow can be dominated by the hydrostatic term whereas the $\delta P/P < 1\%$.

3. DERIVATION OF THE CONSERVATION EQUATIONS

A zone model describes a physical situation in terms of integrals of extensive physical quantities. Thus we deal with total mass rather than mass density, total energy rather than energy density but temperature is used as before (an intensive quantity). The integrals are volume integrals whose boundary surfaces enclose the Euclidean space of interest. The space with which we are concerned usually is a compartment with zones including a hot upper gas, a cool (relatively) lower layer, objects, plumes and fires. The connections occur at the boundary of these zones. Examples of possible connections are the vents connecting compartments, the radiation from a fire to the compartment walls, etc. With this basis we can make the conservation equations into a form which describes a fire in terms of the quantities which are appropriate to the control volume approach, intuitively understandable and lend themselves to measurement.

3.1. Fluid transport

The conservation equations for each compartment of a two layer model are

$$\frac{dm_u}{dt} = \sum_i \dot{m}_{u,i} \longrightarrow \dot{m}_u \tag{10}$$

$$\frac{dm_l}{dt} = \sum_i \dot{m}_{l,i} \longrightarrow \dot{m}_l \tag{11}$$

$$\frac{d}{dt}\{c_v m_u (T_u - T_R)\} - V_u \frac{dP_u}{dt} = \dot{Q}_u + \dot{h}_u \tag{12}$$

$$\frac{d}{dt}\{c_v m_l (T_l - T_R)\} - V_l \frac{dP_l}{dt} = \dot{Q}_l + \dot{h}_l \tag{13}$$

In writing these equations, we will make two assumptions. First, that the fire will not feed mass directly into the lower layer. Second, we will write the upper layer equation as if there is only one fire. If more than one fire exists, then a sum over such sources is necessary and if none are present, then this term vanishes. The source term $\dot{Q}$ includes all energy transfers due to radiation and convection and $\dot{h}$ includes the enthalpy flow. We can rewrite the energy conservation equations as predictive equations for temperature, in which case they become

$$m_u c_p \frac{dT_u}{dt} - V_u \frac{dP_u}{dt} = \dot{Q}_u + \dot{h}_u - c_p T_u \frac{dm_u}{dt} + c_v T_R \frac{dm_u}{dt} \longrightarrow \dot{E}_u \tag{14}$$

and

$$m_l c_p \frac{dT_l}{dt} - V_l \frac{dP_l}{dt} = \dot{Q}_l + \dot{h}_l - c_p T_l \frac{dm_l}{dt} + c_v T_R \frac{dm_l}{dt} \longrightarrow \dot{E}_l \tag{15}$$

The right-hand side of eqn. (14) [illegible] can be

temperature (T_R) is chosen arbitrarily. If the only phase change occurs in pyrolysis of the fuel, then we can set the reference pressure to zero and include the pyrolysis energy as a sink term in the energy release rate. As $T_R \to 0$ we obtain

$$\dot{E}_u = \dot{Q}_f(u) + \dot{Q}_R(u) + \dot{Q}_c(u) - Q_p\dot{m}_f + \\ + c_p\dot{m}_p(T_v - T_u) + c_p\sum_i \dot{m}_{i,u}(T_i - T_u) \quad (16)$$

and

$$\dot{E}_l = \dot{Q}_f(l) + \dot{Q}_R(l) + \dot{Q}_c(l) + c_p\sum_i \dot{m}_{i,l}(T_i - T_l) \quad (17)$$

The equations and assumptions necessary to close this set are

$$P = \rho RT \quad (18)$$

$$\rho_u RT_u = \rho_l RT_l \quad (19)$$

with

$$m = \rho V \quad (20)$$

and $V = V_u + V_l = \text{constant}$ (21)

The energy source terms $\{\dot{E}_l, \dot{E}_u\}$ are shown schematically in eqns. (16, 17) but can be much more complex and depend upon the configuration. Combining eqns. (10 - 11) and (14 - 17), together with the closure relations, we obtain

$$\frac{dP}{dt} = \frac{\dot{s}}{(\beta - 1)V} \quad (22)$$

$$\frac{dT_u}{dt} = \frac{1}{\beta}\left(\frac{T_u}{PV_u}\right)\left(\dot{E}_u + \frac{V_u}{(\beta - 1)V}\dot{s}\right) \quad (23)$$

$$\frac{dT_l}{dt} = \frac{1}{\beta}\left(\frac{T_l}{PV_l}\right)\left(\dot{E}_l + \frac{V_l}{(\beta - 1)V}\dot{s}\right) \quad (24)$$

$$\frac{dV_u}{dt} = \frac{1}{P\beta}\left(c_p\dot{m}_u T_u + \dot{E}_u - \frac{V_u}{V}\dot{s}\right) \quad (25)$$

where

$$\dot{s} = c_p\dot{m}_u T_u + c_p\dot{m}_l T_l + \dot{E}_u + \dot{E}_l \quad (26)$$

and $\beta = c_p/R = \gamma/(\gamma - 1)$ (27)

It should be pointed out that the equations are written in this form for the sake of clarity and simplicity. In a numerical implementation there are better ways to express the source terms which minimize the problem of the small difference of large numbers.

4. SOURCE TERMS

Equations (22 - 25) are written so that physical phenomena which affect the environment are source terms and appear on the right-hand side. Sources which appear directly are:

1. radiation between the gas layers and walls, fires and other objects,
2. convective heating,
3. flow in plumes,
4. flow in vent jets,
5. mixing at vents.

Phenomena which are included but do not show up explicitly are:

1. radiation between objects,
2. conduction through walls and objects.

4.1. Source terms: radiation

In order to calculate the radiation absorbed in a zone, a heat balance must be done which includes all objects which radiate to the zone. Clearly, in order for this calculation to be done in a time commensurate with the other sources, some approximations are necessary.

The terms which contribute heat to an absorbing layer are the same (in form) for all layers. Essentially we assume that all zones in these models are similar, so we can discuss them in terms of a general layer contribution.

Radiation can leave a layer by going to another layer, to the walls, exiting through a vent, heating up an object or changing the pyrolysis rate of the fuel source. Similarly a layer can be heated by absorption of radiation from these surfaces and objects as well as from the fire itself. The formalism which we will employ for the geometry is that used by Siegel and Howell [2] and is shown in Fig. 2. The radiative transfer can be done with a great deal of generality; however, as with most models we assume that zones and surfaces radiate and absorb like a grey-body with some constant emissivity ($\epsilon \leq 1$).

A further assumption consonant with the stratified zone assumption is that emission and absorption are constant throughout a gas layer. In application to a growing fire, a

further assumption is made that the lower layer is mostly diathermous. Although not a necessary assumption, this reduces the computation time for this term by 50%. For smoke propagation some distance from the fire(s) such an assumption will not be valid, but the temperature will be so low that radiation will not be the dominant mechanism for heat loss. Flames, plumes, fires, objects and bounding surfaces have some average shape from which the view factors can be calculated. The walls of compartments are usually flat and rectangular. The gas layers are spheres with an equivalent radius of

$$L = 4V/A \tag{28}$$

and an effective emissivity of

$$\epsilon_g = 1 - \exp(-\alpha L). \tag{29}$$

The terms which contribute to heating of a layer are:

1. fires and plumes,
2. walls,
3. other layers,
4. vents (radiation from other compartments),
5. nonburning objects.

The radiation balance of items 2 - 5 can be dealt with using the following notation:

F_{jk} — geometrical view factor of surface (j) by surface (k)

σ — Stephen-Boltzman constant = 5.67×10^{-8} W/m^2 K^4

α — absorption coefficient of the upper gas layer m^{-1}

L — mean beam length of the equivalent sphere (m), defined in eqn. (28)

$\epsilon_{u,l}$ — emissivity of the upper/lower walls

ϵ_g — emissivity of the upper gas layer

Using the formalism of Siegel and Howell [2] we have

$$D = \{1 - (1 - \epsilon_u)(1 - \epsilon_g)F_{uu}\}\{1 - (1 - \epsilon_l)F_{ll}\} - \{(1 - \epsilon_u)(1 - \epsilon_l)(1 - \epsilon_g)^2 F_{ul}F_{lu}\} \tag{30a}$$

$$\Pi_u = [\{1 - (1 - \epsilon_g)F_{uu}\}\{1 - (1 - \epsilon_l)F_{ll}\} - \{(1 - \epsilon_l)(1 - \epsilon_g)^2 F_{ul}F_{lu}\}]\sigma T_{uw}^4 - (1 - \epsilon_g)F_{ul}\epsilon_l\sigma T_{lw}^4 - [1 + (1 - \epsilon_l)\{(1 - \epsilon_g)F_{ul}F_{lu} - F_{ll}\}]\epsilon_g\sigma T_g^4 \tag{30b}$$

$$\Pi_l = [\{1 - (1 - \epsilon_u)(1 - \epsilon_g)F_{uu}\}(1 - F_{ll}) - (1 - \epsilon_u)(1 - \epsilon_g)^2 F_{ul}F_{lu}]\sigma T_{lw}^4 - (1 - \epsilon_g)F_{lu}\epsilon_u\sigma T_{uw}^4 - [\{1 - (1 - \epsilon_u)(1 - \epsilon_g)F_{uu}F_{lu} + (1 - \epsilon_u)(1 - \epsilon_g)F_{lu}]\epsilon_g\sigma T_g^4 \tag{30c}$$

Finally,

$$\dot{Q}(\text{upper}) = A_u\epsilon_u\Pi_u/D$$

$$\dot{Q}(\text{lower}) = A_l\epsilon_l\Pi_l/D$$

To this must be added the energy radiated by the fire. A heat transfer balance with the fire is not necessary simply because the amount of heat radiated by the fire is usually much greater than that absorbed by the fire. In order to investigate flashover, however, this calculation must be generalized to include the fire and lower layer absorption in the radiative heat balance equation rather than relying on the postulate that superposition of the terms is sufficient.

A simple example of the results can be given for the case

$$\epsilon_u = \epsilon_l = 1,$$

for which we have

$$\dot{Q}_g = -\sigma[\epsilon_g T_u^4 A + (1 - \epsilon_g)T_{uw}^4(A_u + A_{uv}) - T_{uw}^4 A_u - \epsilon_g T_{lw}^4 A_d - T_g^4 A_{uv}] + F_f\dot{Q}_f \tag{31}$$

where

A_d = area of the upper/lower layer discontinuity

A_{uv} = area of vents which the gas layer 'sees'

A_u = area of the upper wall (including ceiling)

F_f = fraction of the fire which radiates times its view factor for the gas layer

$A = A_u + A_d$

4.2. Source terms: convective heating

Convection is the mechanism by which the gas layers lose (or gain) energy to walls or other objects. Conduction is a process which is intimately associated with convection but as it does not show up directly as a term for

heat gain or loss, it will be discussed here.

Convective heat flow is energy transfer across a thin boundary layer. The thickness of this layer is determined by the relative temperature between the gas zone and the wall or object surface, see Schlichting [4] and Turner [5]. We can write the heat flux term as

$$\dot{Q}_c = h_c(T_g - T_w)A_w \tag{32}$$

where the transfer coefficient can be written as

$$h_c = \frac{k}{l} C_v(\mathrm{Gr} \times \mathrm{Pr})^{1/3}$$

The terms are:

A_w = area of wall(s) in contact with the zone

Gr = Grashoff number = $gl^3|T_g - T_w|/\nu^2 T_g$

Pr = Prandtl number ≈ 0.7

k = thermal conductivity of the gas

$$= 2.7 \times 10^{-7}\left(\frac{T_g + T_w}{2}\right)^{4/5}$$

l = length scale ≈ $\sqrt{A_w}$

C_v = coefficient which depends on orientation [5]

Nu = Nusselt number

$$\nu = 7.18 \times 10^{-10}\left(\frac{T_g + T_w}{2}\right)^{7/4}$$

For the cases of interest

Orientation	*Coefficient*	*Condition*
Vertical	0.130	$\mathrm{Gr} \times \mathrm{Pr} > 10^8$
Horizontal	0.210	$T_g > T_w$
Horizontal	0.012	$T_g < T_w$

The coefficients for horizontal surfaces apply to a slab over the zone. For the inverse of this situation the coefficients should be reversed.

4.3. Source terms: plumes

A fire generates a plume which transports mass and energy from the fire into the upper layer. In addition, the plume entrains mass from the lower layer and transports it into the upper layer. The former generally increases the upper zone internal energy whereas the latter will have a cooling effect. For a fire which is consuming mass at a rate $\dot{m}_f$, heat addition will be

$$\dot{Q} \cong \chi_c \dot{m}_f \cdot H_c$$

Some fraction, χ_R, will exit the fire as radiation and the remainder will be left to drive the plume. We can empirically divide the heat transfer into actual combustion and simple gasification. The former, denoted by χ_c, is the relative fraction of pyrolysate which participates in the combustion. Also, once combustion occurs, a fraction of the energy leaves the fire as radiation ($\chi_R \dot{Q}$) and convective energy ($(1 - \chi_R)\dot{Q}$). The former is a function of such external effects as radiation, e.g., other fires, and vitiation. The latter efficiencies relate to sootiness and Froude number. The mass flow in a plume comes from a correlation of experimental data given by McCaffrey [6]. This correlation divides the flame/plume into three regions:

$$\left.\begin{aligned}
&\text{flaming:}\\
&\dot{m}_p = 0.011Q(Z/Q^{2/5})^{0.566} \qquad Z/Q^{2/5} < 0.08\\
&\text{intermittent:}\\
&\dot{m}_p = 0.026Q(Z/Q^{2/5})^{0.909} \qquad 0.08 \leqslant Z/Q^{2/5} < 0.20\\
&\text{plume:}\\
&\dot{m}_p = 0.124Q(Z/Q^{2/5})^{1.895} \qquad 0.20 \leqslant Z/Q^{2/5}
\end{aligned}\right\} \tag{33}$$

Entrainment in the intermittent region agrees with the work of Cetegen *et al.* [7] but yields greater entrainment in the other two regimes. This difference is particularly important for the initial fire as the upper layer is far removed from the fire. In this formulation, the total mass flow in the plume is given by the above correlation and the fuel pyrolysis is related to it by

$$\dot{m}_p + \dot{m}_v = f(mz, Q) \tag{34}$$

given above.

4.4. Source terms: door jets

Flow at vents is governed by the pressure difference across a vent. In the control volume approximation the general momentum equation for the zones is not solved. Instead,

the momentum transfer at the zone boundaries is included by using Bernoulli's solution for forced flow. This solution is augmented for restricted openings by using 'flow coefficients'. The modification deals with the problem of constriction of velocity streamlines at an orifice.

There are two cases which apply to these models. The first, and most usually thought of in fire problems, is for air or smoke which is driven from a compartment by buoyancy. The second type of flow is due to a piston effect which is particularly important in the early stages of a fire. Rather than depending on density difference between two gases, the flow is forced, for example, by volumetric expansion when combustion occurs.

The results used for this model are those of Bodart and Jones [8] and will not be duplicated here. The notation used is:

S = smoke
A = air
ij = flow from compartment (i) to (j)
P = floor pressure (reference)

The order of the letters indicate the type of atmosphere from which the fluid is coming and to which it is going. As many as three neutral planes can exist for such flows. Two mixing phenomena which occur at vents are similar to entrainment by plumes. For the case when hot gas leaves a compartment and is driven by buoyancy into the upper layer of a second compartment, a door jet exists which is analogous to a normal plume. Mixing of this type occurs for flow

$SA_{ij} > 0$

and is discussed in detail by Cetegen *et al.* [7] and Tanaka [9]. The other is much like an inverse plume and causes contamination of the lower layer as cold gas from a compartment flows through a hot layer in a second compartment and is driven by buoyancy (negative) into the lower layer. Quintiere *et al.* [10] discuss this phenomena for the case of crib fires in a single room and deduce the relation

$$SA_l(\mathrm{u} \rightarrow \mathrm{l})/AS_{ji} = 0.5\left(\frac{T_{\mathrm{l}i}}{T_{\mathrm{u}i}}\right)\left(\frac{N - Z_l}{N}\right) \qquad (36)$$

This term is predicated on the Kelvin–Helmholz shear flow instability and requires shear flow between two separate fluids. The instability is enhanced if the fluids are of different density since the equilibration distance is proportional to $\nabla\rho$. A schematic of this type of flow is shown in Fig. 3. As can be seen, mixing into the lower layer of a room occurs under the same conditions for which the 'door-jet' mixing to the upper layer occurs.

4.5. Source terms: fire

Currently we can deal with two types of fires. The first is a specified fire. Then the mass pyrolysis rate is specified and the heat release rate becomes

$$\dot{Q}_f = h_c\dot{m}_f - c_p(T_u - T_f)\dot{m}_f - Q_p\dot{m}_f \qquad (37)$$

whereas the mass loss rate, $\dot{m}_v$, is related to the pyrolysis rate by

$$\dot{m}_v - \dot{m}_f = (1 - \chi_f)\dot{m}_v$$

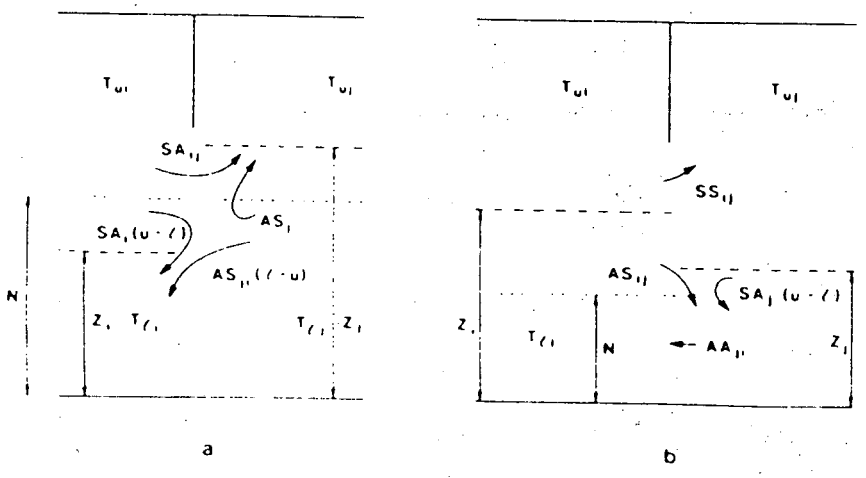


Fig. 3. Possible upper/lower mixing mechanisms which [illegible]

As the burning efficiency becomes 100%, all of the volatiles are burned, and nothing remains for sooting. The heat release goes into radiation and enthalpy flux

$$\dot{Q}_R(\text{fire}) = \chi_R \dot{Q}_f$$

$$\dot{Q}_c(\text{fire}) = (1 - \chi_R)\dot{Q}_f$$

The term $\dot{Q}_c(\text{fire})$ then becomes the driving term in the plume flow equation (see eqns. (33, 34)).

This approach is extended for a pool fire. A pool fire is basically the same except that it is driven self-consistently by reradiation from the compartment and the flame itself. From Rockett [11] we have

$$\dot{Q}_f = \dot{Q}_R(\text{ext}) + \dot{Q}_{\text{flame}} - \dot{Q}_{RR} + \dot{Q}_{\text{conv}} - \dot{Q}_{\text{cond}} \tag{38}$$

where

$\dot{Q}_R$ = external radiation to the fuel source
$\dot{Q}_{\text{flame}}$ = radiation from the flame back to the fuel
$\dot{Q}_{RR}$ = fuel surface reradiation
$\dot{Q}_{\text{conv}}$ = enthalpy flux away from the fire
$\dot{Q}_{\text{cond}}$ = conductive heat loss from the fuel to the surroundings

4.6. Source terms: conduction

Conduction of heat through solids is not a source term in the sense mentioned earlier. That is, loss or gain of energy from solids occurs by convective heating, which in turn is influenced by subsequent gain or loss through the solids. However, as much of the net heat loss from a compartment occurs through loss to the walls, as well as heating of interior objects, the form of heat propagation in solids will be discussed here.

The equation which governs the heat transfer in solids is

$$\frac{\partial T}{\partial t} = \frac{k}{\rho c} \nabla^2 T \tag{39}$$

and is a linear parabolic equation [12]. As such, it must be solved by a different technique than is used for the ordinary differential equations which describe mass and enthalpy flux. In order to couple these systems in a reasonable way, we appeal to the principle of time splitting. Simply stated, we have two systems of equations which are decoupled as long as the time step used is short compared to the characteristic time scale for either set of equations. Wall temperatures change and the characteristic time for energy flux through a solid is characteristically on the order of minutes. By using a time step of no more than one second the applicability of time splitting is assured.

Currently the model assumes two walls, the upper wall (and ceiling) which is in contact with the upper layer, and the lower wall (and floor) which is in contact with the lower layer. A refinement will be to separate the ceiling and upper wall, and the lower wall and floor. This will be useful since walls are generally constructed of materials whose thermal properties are different than the ceiling and floor. A futher assumption is that conduction is one dimensional only. That is, the heat equation is

$$\frac{\partial T}{\partial t} = \frac{k}{\rho c} \frac{\partial^2 T}{\partial x^2} \tag{40}$$

and the solid behaves as an infinite slab in the other two space dimensions. A corollary to this is that the wall in contact with the gas layer changes temperature instantaneously as the layer interface moves up and down. Such a formulation is not entirely satisfactory as there is a finite equilibration time for the solid. An additional refinement will be to extend this equation to two dimensions to track the layer as it moves up and down. So far, the only zone model to attempt to include this effect is discussed by Jones [1] and Mitler and Emmons [13]. Even in this case the attempt was made only to include heat loss from the upper layer as it moves down and comes in contact with cool lower walls. However, the phenomenon is important, as is discussed by Quintiere *et al.* [14], especially as the thermocline in the wall will influence the direction in which the wall boundary flow propagates.

Conduction through solids occurs in two places: the compartment walls and interior objects. The technique used is the same in both cases, although the boundary conditions on the equation may be different. Generally a slab is cut into N intermediate slices ($N + 1$ nodes). Then eqn. (40) is solved for each slice. The actual finite difference used is a time centered, implicit scheme which is symmetric about the nodes. For the interior nodes we have

$$T_i'[1+\eta] = \frac{\eta}{2}[T_{i+1}' + T_{i-1}'] + \left\{T_i + \frac{\eta}{2}[T_{i+1} - 2T_i + T_{i-1}]\right\} \tag{41a}$$

where

$$\eta = \frac{\Delta t}{\Delta x}\frac{k}{\rho c}$$

and for the edge nodes

$$T_i'\left[1+\frac{\eta}{2}\right] = \frac{\eta}{2}\left[T_{i+1}' \pm \frac{\dot{Q}_c}{k}\right] + \left\{T_i + \frac{\eta}{2}\left[T_{i+1} - T_i \pm \frac{\dot{Q}_c}{k}\right]\right\} \tag{41b}$$

The temperature at the starting time at node 'i' is T_i and at time $t + \delta t$ it is T_i'. The number of nodes is chosen to reduce the residual error to some reasonable value, say less than 1%. Use of $N > 20$ will improve precision with no concomitant increase in accuracy. This technique would allow one to use different constituents for each slab, although such is not done in the current implementation. Each time step requires both an initial condition and one boundary condition. We start with the internal temperatures in each case, and the flux on the 'hot' side. The usual scheme is to set the far side boundary condition to zero heat flux (which allows heat build up in the interior) or to approximate the far side exterior as a constant temperature bath. Either technique is satisfactory unless this far side happens to be the interior boundary for another compartment.

5. NUMERICAL INTEGRATION

The problem of the spread of fire, smoke, etc. has been formulated as a set of differential equations. These equations are derived from the conservation of mass and energy. As a result, most of the equations are non-linear and first order ordinary differential equations (ODE). The exception to this rule is the heat conduction equation which is a linear parabolic equation, in one or two dimensions. The former can be solved using implicit predictor-corrector methods [15], and the latter by successive over-relaxation (SOR) [16].

In the numerical implementation, we have relied on the validity of a technique called time splitting. Simply stated, we have decoupled equations which have greatly differing relaxation times, that is

$$\frac{1}{n}\frac{dn}{dt} = L_n$$

where L_n varies by more than an order of magnitude for each process. Except for the driving program which invokes the hydrodynamics, species transport and thermal conductivity, the various modules which incorporate the physical processes are exercised separately and interact as source terms. This splitting technique is standard but the inherent assumptions should be checked when implementing a new numerical model. In addition, a check should be made at each time step to insure that the relevant stability criterion (similar to a Courant condition for fluid flow) is not violated.

For both types of equations the solution at each time step is found by an implicit scheme. The implicit method allows us to implement the numerical solution as a time centered algorithm. This insures reversibility in the physical phenomenon, at least for non-diffusive systems. A test of this assertion is to exclude thermal conduction, integrate from an initial condition to some final time, and subsequently, by changing the sign of the time step, we should be able to return to the starting position. A time reversal calculation is an important step in assuring ourselves that the integration scheme itself is not dissipative and thus will not relax to an incorrect final state. This is a real property in non-dissipative physical systems and should be mirrored as closely as possible in a numerical model. When conductivity is included, such reversibility ceases to be strictly valid, of course.

An additional virtue of the time centered scheme is avoiding the bifurcation which can occur in pure leapfrog schemes. The disadvantage is the one additional source calculation required at each time step. This time appears to be short. However, [illegible]

with the 'corrector' phase of the implicit scheme.

The order of the integration is as follows:

(1) Estimate the values for pressure, etc. at $t_0 + \delta t$.

(2) Find the source terms for eqns. (22 - 25) based on the time centered values ($t_0 + 1/2\delta t$).

(3) Integrate eqns. (22 - 25) using the source terms defined at the time centered positions.

(4) Repeat steps (2) and (3) until convergence is reached.

(5) Integrate the conduction equation using the SOR technique.

The following illustration shows where each of these time-step points is, in relation to steps (1 - 5):

(1) $t_0 \longrightarrow t_0 + \delta t$
estimate values at $(t_0 + \delta t)$

(2) $t_0 \longrightarrow x \longleftrightarrow t_0 + \delta t$
find sources at $(t_0 + \delta t)$

(3) $t_0 \longrightarrow t_0 + \delta t/2 \longrightarrow t_0 + \delta t$
integrate from (t_0) to $(t_0 + \delta t/2)$

(4) $t_0 \longrightarrow t_0 + \delta t$
repeat steps (2) and (3)

(5) $t_0 \longrightarrow t_0 + \delta t$
integrate conduction equation

Since each step is of at least second order accuracy, the overall scheme will also be second order accurate ($0(\delta t^3)$). The relative error allowed at each time step is $\sim 10^{-3}$. Thus the precision is greater than the precision of the computer being used (at least as long as these calculations are being done in single precision).

As for the integration scheme itself, it is derived from an Adam–Bashford backwards difference scheme [15], of order $k = 1$. This yields a single step predictor and second order corrector, $0(\delta t^3)$. These equations become 'stiff' if the individual source terms are large, which leads to a short time step, yet the total source function may be tightly coupled if the solution is being approached asymptotically. Another possibility is that the source terms for the various equations differ by more than an order of magnitude. In either case, the usual time step criterion would require a time step which is prohibitively short. It is possible to modify the Taylor expansion used in obtaining the predictor–corrector scheme to use the asymptotic nature of the equations to enhance the speed of the solver [17].

The general form of an equation is

$$\frac{dn}{dt} = q - ln \equiv f$$

Using the notation $n(0)$, $q(0)$, $l(0)$, $f(0)$ are the initial values at time (t_0), and $n(1)$, $q(1)$, $l(1)$, and $f(1)$ are the values at the new time $(t_0 + \delta t)$, we obtain first for the normal equations

$$\text{predictor } n(1) = n(0) + \frac{\delta t}{2} f(0) \tag{42a}$$

$$\text{corrector } n(1) = n(0) + \frac{\delta t}{2} (f(0) + f(1)) \tag{42b}$$

and for the stiff equations

$$\text{predictor } n(1) = n(0) + \frac{\delta t}{1 + \delta t l(0)} f(0) \tag{43a}$$

$$\text{corrector } n(1) = n(0) + \frac{2\delta t}{1 + \delta t\{l(0) + l(1)\}} \times \{f(0) + q(1) - l(1)n(0)\} \tag{43b}$$

The corrector must be iterated until some specified error criterion is reached. If the specified error cannot be reached in a small number of iterations, say two or three, then the time step must be reduced. It turns out to be advantageous to halve the time step for each instance that a reduction is required, and increase it by only 10% for each subinterval that the error criterion is satisfied.

One technique which has been used in previous work to reduce the solution time for these equations is to convert them to an algebraic form. The conversion is done by noting that the final state of the equations at each time step is a pseudo equilibrium. Thus the transient term can be dropped. For a number of reasons, simultaneous ODEs are generally easier to solve than the corresponding algebraic equations unless one is exceedingly close to the solution. Such an assertion is difficult to prove in the general case but two examples should suffice to indicate the

difference in the nature of the root finding procedure. One of the simplest nonlinear algebraic equation is

$$AB = C$$

with A, B, and C being integers. Until recently this nonlinear decomposition was thought to be unsolvable (in finite time) for an arbitrary value of C. Also, a straight comparison of this method (embodied in a model) with other models using the algebraic scheme, has shown a reduction by at least a factor of ten in the time required for a given calculation. A detailed timing comparison of several models is given elsewhere [18].

6. COMPARISON WITH EXPERIMENTAL DATA

The series of tests which serve as a database for this analysis are based on a two-room fire scenario by Cooper *et al.* [19] and an ongoing series of full-scale validation tests at the National Bureau of Standards. The former was a two-room configuration, consisting of a burn (or fire) room and a corridor. It is referred to as the 'Nike Site' in later discussions. The latter is a three-room configuration with the additional room being a target room for testing high density occupancy, referred to as 'Building 205'. The geometry of each of these configurations is shown in Table 1.

Comparisons between the model and experimental data are for fires of 100 kW. Figures 4 and 5 show the comparison for the Nike Site tests for the upper layer temperatures in the burn room and corridor, and the interface height in the corridor. Figures 6 and 7 show a similar comparison to the current experiments in B205, a full scale facility at NBS. It is apparent from a comparison of Figs. 4 - 7 that plume entrainment is estimated very well but that the door jet entrainment is underestimated. We can see this from the good agreement between experiment and theory in any compartment which contains a primary plume whereas in other compartments the predicted temperature is too high and the layer depth too small in comparison with experimental values. This underestima-

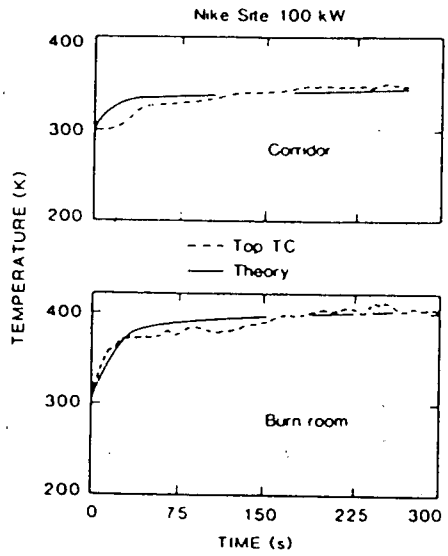


Fig. 4. Comparison of experimental and calculated temperature profiles for the upper layer in the burn room and corridor in the 'Nike Site' experiments (Table 1).

TABLE 1

Geometry data for validation calculation

		Burn	Vent	Corridor	Vent	Target
Nike Site	Depth*	4.3	—	11.1 - 20.2	—	
	Width	3.3	1.07	2.4	0.95	
	Height	2.3	2.00	2.3	0.15	
	Area	14.2	2.14	26.6 - 48.4	0.14	
	Volume	32.2	—	61.2 - 112.3	—	
Bldg 205	Depth	2.3	—	12.2	—	2.3
	Width	2.3	1.0	2.4	1.0/1.0**	2.3
	Height	2.2	1.9	2.4	1.9/2.0	2.2
	Area	5.5	1.9	29.7	1.9/2.0	5.5
	Volume	11.8	—	72.6	—	11.8

*Lengths are in meters, areas in square meters and volumes in cubic meters

**V1/V2: V1 is from corridor to target room and V2 is from corridor to [illegible]

tion occurs in the regions which McCaffrey [16] calls the flaming and far field regions. In the intermittent region, where the results of McCaffrey [6] and Cetegen *et al.* [7] agree, the entrainment rate appears to be correct.

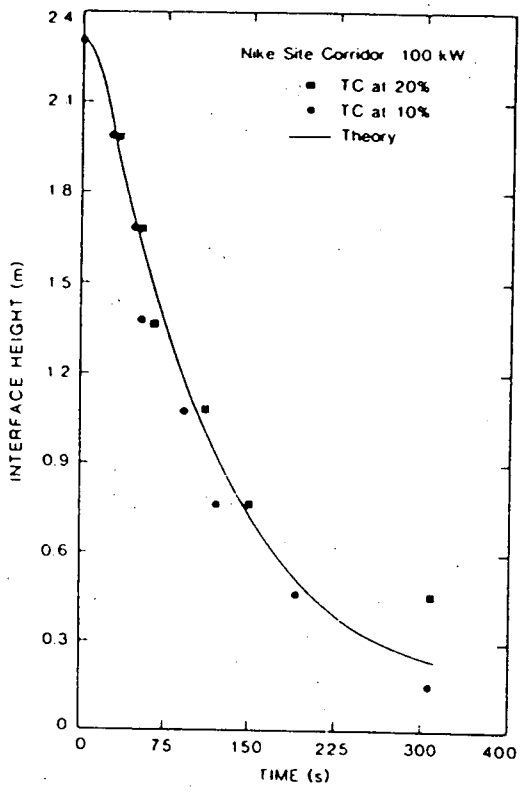


Fig. 5. Comparison of experimental and calculated interface height in the corridor of the 'Nike Site' experiments (Table 1). See refs. 14 and 19 for an explanation of the criteria (10%, 20%) used to determine the experimental interface height.

Another factor which gives rise to disparity between theory and experiment is the assumption, in the model, of known and uniform wall materials. In the experiments, walls consist of several materials in a composite such as calcium-silicate board over gypsum. Allowing for these factors, the agreement seems quite good. As research continues, these discrepancies will be resolved.

7. STABILITY AND COMPLETENESS

There are a number of phenomena which are either not included or need additional work. They are:

1. Wall effect — two dimensional, unsteady heat flow
2. Separation of flow — vents
3. Ceiling jet — transit time

The first refers to the finite thermal inertia of the wall as the hot layer moves down (or possibly up). There will be a two dimensional thermocline in the wall which differs from that in the compartment. Although this has only a small direct effect, it can lead to flow along the walls which can subsequently contribute to contamination of the lower layer. Such effects become particularly important as the smoke travels further from the fire source and temperature differentials become small.

The second problem is quite important for asymptotic predictions, especially near the room of fire origin. Currently we assume that hot gas mixes with hot gas or cold with cold

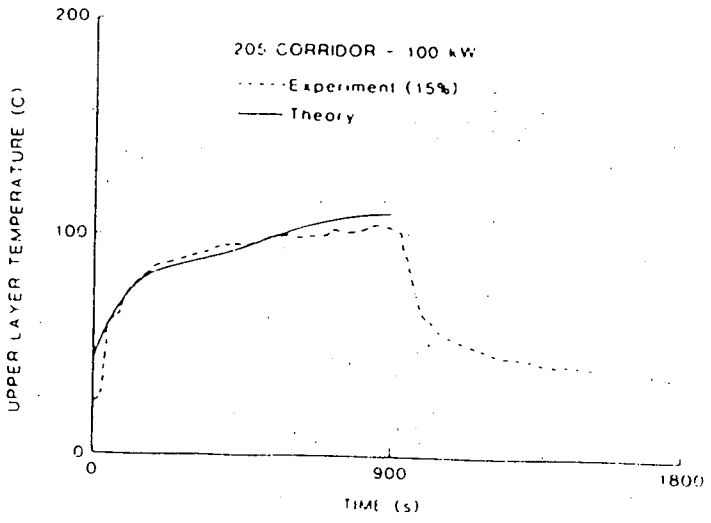


Fig. 6. Comparison of experimental and calculated upper layer temperature in the corridor of 'B205' experiments (Table 1)

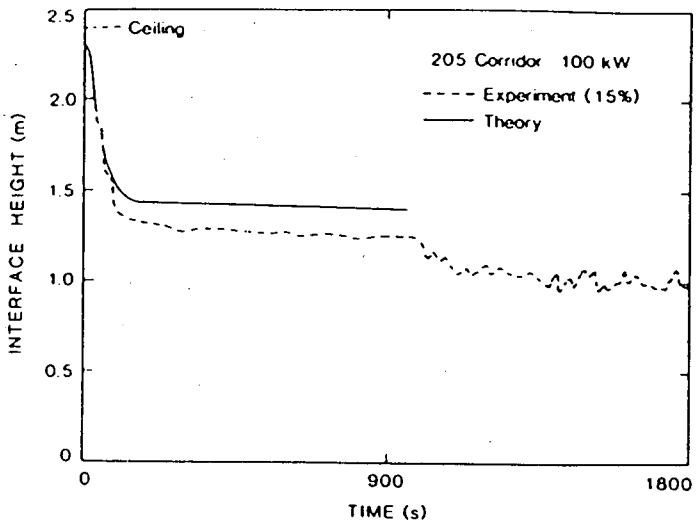


Fig. 7. Comparison of experimental and calculated interface height in the 'B205' experiment (Table 1)

gas as it traverses a vent. This was a reasonable approximation while the lower layer was assumed to be ambient. Now that we calculate the lower layer temperature, we find that the recirculating gas may have a temperature of the order of the lower layer of the room into which it enters. A particular example will demonstrate the effect. In a two-compartment calculation, Jones and Quintiere [20] found that the layer outside of the burn room is lower than that in the compartment of fire origin. As there is no source of heat in this second compartment and cooling occurs due to mixing, the upper layer in this adjacent space is cool relative to the upper layer in the fire room, and even comparable in temperature with the lower layer. Currently we assume all of the hot gas in the adjacent room, which flows into the fire room, will be deposited in the fire room upper layer. As can be seen in Fig. 8 (Evans [21]), this assumption leads to discrepancies in prediction versus experiment. A better approach is to divide the incoming flow into two components: for flow into compartment (i) from compartment (j), we have a component into the upper layer

$$= \left(\frac{T_{uj} - T_{lj}}{T_{ui} - T_{li}}\right)\dot{m}_{j\to i},$$

with the remainder going into the lower layer. This occurs only after an interface discontinuity has been established.

The third problem will only be important for very long corridors (20 m) or very tall

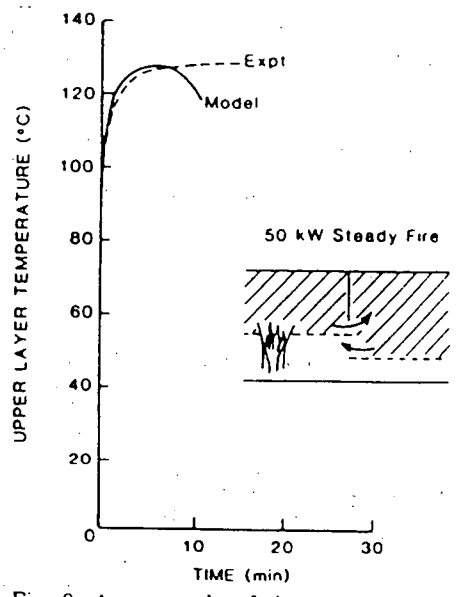


Fig. 8. An example of the upper layer separation which occurs in actual flows.

transient phenomenon. For purposes of siting smoke detectors, for example, this transient may be important.

8. CONCLUSIONS

The fire and smoke transport model, as described in this paper, is quite detailed and complete as far as our current understanding of fire phenomenology is concerned. It draws on a great deal of the research into fires which have occurred over the past ten years, pulling together much of the best work which has

implementation is of particular interest because it is extremely durable. The problems discussed in Section 7 'Stability and Completeness' need to be addressed if we are to carry this work further, such as to fires in high rise hotels or on aircraft carriers.

ACKNOWLEDGEMENTS

Two NBS cooperative students, Alicia Fadell and Charles DeWitt have contributed to this effort. Ms. Fadell was instrumental in implementating the 'BUILD' program which generates the configuration and description files for the 'FAST' model. Mr. DeWitt is responsible for 'FASTPLOT', a routine which enables one to analyze rather easily the extensive output available from 'FAST'.

A machine readable copy of the model is available through NTIS. The tape includes the data file listed in the appendices.

REFERENCES

1 W. W. Jones, *A Review of Compartment Fire Models, IR 83-2684*, National Bureau of Standards, Washington, DC, 1983.
2 R. Siegel and J. R. Howell, *Thermal Radiation Heat Transfer*, McGraw-Hill, New York, 1981.
3 T. Kusada, *NBSLD, The Computer Program for Heating and Cooling Loads in Buildings, BSS 69*, National Bureau of Standards, Washington, DC, 1976.
4 H. Schlichting, *Boundary Layer Theory*, Pergammon Press, New York, 1955, (translated by J. Kestin).
5 J. S. Turner, *Buoyancy Effects in Fluids*, Cambridge University Press, 1973.
6 B. J. McCaffrey, Momentum implications for buoyant diffusion flames, *Comb. Flame, 52* (1983) 149.
7 B. M. Cetegen, E. E. Zukoski and T. Kubota, Entrainment and Flame Geometry of Fire Plumes, Ph.D. Thesis of Cetegen, Cal. Tech., 1982.
8 W. W. Jones and X. Bodart, On a proof of the solvability of the conservation equations which describe the transport of fire and smoke, *Fall Technical Meeting of the Combustion Institute, Clearwater, 1984*.
9 T. Tanaka, *A Model of Fire Spread in Small Scale Buildings, RP #84*, Building Research Institute, Japan, 1980; T. Tanaka, *A Model of Multiroom Fire Spread, IR 83-2718*, National Bureau of Standards, Washington, DC, 1983.
10 J. G. Quintiere, K. Steckler and B. J. McCaffrey, A model to predict the conditions in a room subject to crib fires, *First Specialists Meeting (Int.) of the Combustion Institute, Talence, France, 1981*.
11 J. A. Rockett, Experimental determination of the heat flux to a burning surface, private communication (to be published).
12 H. S. Carslaw and J. C. Jaeger, *Conduction of Heat in Solids*, Oxford University Press, London, 1959.
13 H. E. Mitler and H. W. Emmons, Documentation for CFC V, The Fifth Harvard Computer Fire Code, *Home Fire Project Tech. Rep #45*, Harvard University, 1981.
14 J. G. Quintiere, K. Steckler and D. Corley, An assessment of fire induced flows in a compartment, *Fire Sci. Technol., 4* (1984) 1.
15 S. D. Conte, *Elementary Numerical Analysis*, McGraw-Hill, New York, 1965.
16 A. R. Mitchell and P. F. Griffiths, *The Finite Difference Method in Partial Differential Equations*, Wiley, New York, 1980.
17 T. R. Young and J. P. Boris, A numerical technique for solving stiff ordinary differential equations associated with the chemical kinetics of reactive flow problems, *J. Phys. Chem., 81* (1977) 2424.
18 W. W. Jones, An improved numerical method for fire models, *Fall Technical Meeting of the Eastern Section of the Combustion Institute, Atlantic City, 1982*.
19 L. Y. Cooper, M. Harkleroad, J. Quintiere and W. Rinkinen, *An Experimental Study of Hot Layer Stratification in Full Scale Multiroom Fire Scenarios, ASME 81-HT-9*, Milwaukee, 1981.
20 W. W. Jones and J. G. Quintiere, Prediction of corridor smoke filling by zone models, *Comb. Sci. Technol., 11* (1983) 111.
21 D. Evans, private communication, 1983
22 W. W. Jones and A. Fadell, *A Device Independent Graphics Kernal*, to be published

APPENDIX A – NOTATION

A area (m^2); A_u, A_l, A_d are the upper and lower compartment surface areas in contact with the upper and lower gas layer, Fig. 1, respectively. A_d is the interface area between the upper and lower layers. In Section 4.4, 'A' is used as a variable in the flow equations to indicate air.

B width of a vent (m)

C, C' flow coefficient ≈ 0.6 - 0.7 for both smoke and air

c specific heat – c_p, c_v (J/kgK)

$\dot{E}$	energy release rate (J/s)
E	internal energy of the gases — see eqn. (2)
F_{ij}	view factor — relative area of 'i' as seen by 'j' (dimensionless)
g	acceleration of gravity (9.8 m/s^2)
H	height (m), H_u, H_l, are the upper and lower limits of a vent — Fig. 1
h	enthalpy (J/kgK)
h_c	heat of combustion — theoretical (J/kg)
i, j	compartment indices
k	thermal conductivity (J/smK)
L	mean beam length (m) equivalent opaque sphere
m	mass (kg)
$\dot{m}$	mass flow (kg/s):
	$\dot{m}_v$ — rate of release of volatiles
	$\dot{m}_e$ — entrained into a plume
	$\dot{m}_f$ — fuel burning rate = $\chi_e \dot{m}_v$
	$\dot{m}_{ij}$ — mass entering room 'i' from room 'j'
	$\dot{m}_p$ — flow rate in plume ($\dot{m}_p = \dot{m}_v + \dot{m}_e$)
N	height of the neutral plane (m)
P	pressure (Pa):
	$\bar{P} \rightarrow P$ — floor reference pressure
	P_a — outside ambient pressure
$\dot{Q}$	rate heat is added or lost (J/s):
	$\dot{Q}_u$, $\dot{Q}_l$ — upper, lower zones, respectively
	$\dot{Q}_f$ — fire ($h_c \dot{m}_v$)
	$\dot{Q}_o$ — objects
	$\dot{Q}_R$ — radiation
	$\dot{Q}_c$ — convection by walls
	$\dot{Q}_g$ — radiation added to upper gas layer
	$\dot{Q}_k$ — radiation from surface 'k'
	$\dot{Q}_p$ — combustion energy lost by formation of volatiles
R	gas constant for specific mixture
S	smoke — Section 4.4
t	time (s)
T	temperature (K):
	T_a — ambient
	T_c — external wall
	T_u — upper wall
	T_l — lower wall
	T_R — reference temperature for enthalpy flow
	T_g — upper zone temperature
	T_v — pyrolysis temperature
V	volume (m^3)
Z	layer thickness (m) — Z_i = interface height in compartment (i)
α	absorption coefficient of upper gas layer (m^{-1}), thermal diffusivity (m^2/s)
γ	ratio of specific heat (c_p/c_v)
ϵ	emissivity (dimensionless):
	ϵ_i — surface 'i'
	ϵ_g — upper gas layer
	ϵ_u — upper compartment surface
	ϵ_l — lower compartment surface
ρ	mass density (kg/m^3); ρ_{ui} — density of the lower layer in compartment (i)
κ	thermal conductivity (J/msK)
δ_{ij}	Kronecker delta = 0 $i \neq j$
	= 1 $i = j$

Δt time step (s)
Δx spatial discretization

Subscripts — In general 'u' and 'l' indicate upper and lower gas layer, respectively. For area and emissivity variables, reference is to the compartment itself.

APPENDIX B

Shown in Table 2 is a sample input for FAST. The organization is that control is at the beginning, followed by component information, connections, wall properties, a description of the fire, species generation information and finally file descriptors for graphics and the dump file.

TABLE 2

```
VERSION 16 Toxic hazard evaluation
Timesteps   600  120  000    0    0
NFLOR     1 NUMBER OF FLOORS IN THE CALCULATION
NROOM     4 TOTAL NUMBER OF ROOMS
NMXOP     1
TAMB   300.
HI/F    0.0   0.C   0.0   0.0
WIDTH   3.3   2.4   2.9   2.4
DEPTH   4.3  18.8   9.9   9.9
HEIGH   2.3   2.3   2.3   2.3
HVENT     1     2       1.07  2.0   0.0
HVENT     2     3       1.07  2.0   0.0
HVENT     3     5       0.95  .15   0.0
HVENT     2     4       1.07  2.0   0.0
HVENT     4     5       .95   .10   0.0
WALLS     2
COND   .0012  .0012  .0012  .0012
SPHT   .840   .840   .840   .840
DNSTY 2000.   2000.  2000.  2000.
THICK 0.50    0.50   0.50   0.50
EMISS 0.8     0.8    0.8    0.8
COND   .0012  .0012  .0012  .0012
SPHT   .840   .840   .840   .840
DNSTY 2000C.  2000.  2000.  2000.
THICK 0.50    0.50   0.50   0.50
EMISS 0.8     0.8    0.8    0.8
LFBO      1 ROOM OF FIRE ORIGIN
LFBT      1 TYPE OF FIRE (GAS BURNER)
LFMAX     6 NUMBER OF INTERVALS OF FIRE GROWTH
LFPOS     1 POSITION OF THE FIRE (CENTER)
        1.0  0.0       .750 .250  .00      49758 300.    .0
FMASS   .002 .002 .002 .002 .002 .002 .002
FAREA     .5   .5   .5   .5   .5   .5   .5
FHIGH     .0   .0   .0   .0   .0   .0   .0
FTIME     60.  60.  60.  60.  60.  60.
SPECI    3 1.0    1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0
SPECI    7 1.0    .025 .025 .025 .025 .025 .025 .025 .025
SPECI    9 3500. .02  .02  .02  .02  .02  .02  .02  .02
SPECI   10 31.2    1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0
ENDSP
```

In general, the first word in each line is a key word and must be included. The explanation of this file will be by example:

Line	*Meaning*
1	version and title
2	time step information
	600 → number of seconds for the calculation
	120 → print interval

	120 → dump interval (requires files)
	1 → graphics interval (requires files)
	0 → hard copy counter
3	Number of floors — not used with this version, but retained for compatibility
4	Total number of compartments
5	Maximum number of openings between compartments (≤4)
6	ambient temperature,
7 - 10	compartment geometry, $W \times L \times H \times$ Floor (1 → NROOM)
11 - 16	connection configuration (outside is compartment NROOM + 1)
17	number of walls used in the calculation[1]
18 - 27	thermophysical properties of the upper and lower walls respectively (units are SI except energy (kJ) and power (kW).
28	which compartment the fire is in
29	type of fire (currently only a gas burner is allowed)
30	number of intervals for production rate[2]
31	interior position of the fire to establish entrainment rate (1 → center)
32	fuel properties necessary for partial combustion
	1.0 → fraction of pyrolysis which burns
	0.0 → fraction of water in the fuel
	0.750 → fraction of carbon in fuel by weight
	0.25 → fraction of hydrogen in fuel by weight
	0.00 → fraction of oxygen in fuel by weight
	49758 heat release rate (kJ/kg)
	300.0 fuel inlet temperature
	0.0 fraction of heat which exits the fire plume in the lower layer as radiation
33	mass loss rate at each end point (kg/s), LFMAX + 1.
34	area of the fire at each end point (m^2)
35	height of the base of the flame (m)
36	duration of each time interval (LFMAX)
37 - 40	fractional production rate of species 3, 7, 9 and 10[3]
	first number is species (1 → 12)
	second number is a conversion factor
	third through LFMAX + 3 are fractional production rates[4]
41	termination label (required)
42 - 44	file descriptors
	DISFG = plan view[5]
	CONFG = layer information[5]
	DUMPR = dump file for FASTPLOT

There are two primary output files for the model. The first is binary (UNIT = 9) and is used by the routine 'FASTPLOT' described in Appendix D. The other is an ASCII file (UNIT = 6) and usually is displayed on the printer. Units are SI (MKS) except for energy which is in kJ. The meanings of the symbols, in the order which they appear, are:

[1]Currently an upper and lower wall are used. This will change shortly to four walls to reflect the physical difference among the ceiling, walls and floor.

[2]Figure 9 shows a sample fire production curve.

[3]Species 1 - 12 are N_2, O_2, CO_2, CO, HCN, HCL, ThHC, H_2O, smoke density, total % LC_{50}, smoke number density and HCL number density.

[4]Fraction of the mass burning rate at the corresponding endpoint (see line 33 and Fig. 9)

[5]Format for the graphics files is given in the NBSIR [illegible] and Fadell (19[illegible])

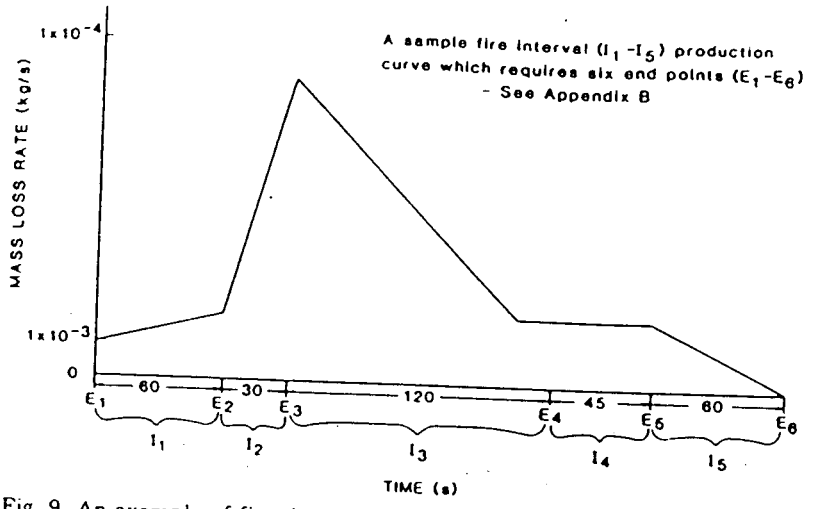


Fig. 9. An example of fire size specification through mass loss data.

Initial	— reiterate the input parameter, generally in the order of input
Timestep output	—
TIME	— simulated time (s)
U. TEMP	— upper layer temperature (K)
L. TEMP	— lower layer temperature (K)
U. VOLUM	— upper layer volume (m^3)
U. DEPTH	— vertical thickness of the upper layer (m)
C. TEMP	— ceiling temperature at the surface (K)
F. TEMP	— floor temperature (K)
EMS	— flow into the upper layer from the plume (kg/s)
EMP	— pyrolysis rate (kg/s)
ADS	— area of the fire (m^2)
QF	— enthalpy release rate of the fire (kW) to the upper and lower layer
QR	— total radiant energy to the upper and lower layers (kW)
QC	— total convective heating of the upper and lower layers (kW)
Pres	— floor reference pressure (Pa)
mass	— vent flow from $i \rightarrow j$ (kg/s) - sec (Section 4.4)

Species concentrations listed by species:

mass	— total mass of that species in the layer (kg)
M/V	— mass per unit volume multiplied by the conversion factor shown in line 37 - 40 of the input fuel. Unity leaves this value in (kg/m^3)[6].
PPM	— parts per million of the total molecules present
PPM-M	— dosage which is an integral of (PPM) over time (PPM — minutes)

APPENDIX C

The program BUILD is used to construct data files for configuration display. These files can then be used by FAST to display a decision tree either interactively or as a graphics streaming file. Both the configuration file for display as well as information on position and type of display for the decision tree are built by this program. The commands are:

[6]This conversion factor allows the user to convert this output to an optical density, LC_{50} or whatever

ADD [VERTEX, EDGE, POLYGON] (default = VERTEX)

add vertex	— create vertices by specifying three (x, y, z) coordinates; add vertices to the work file
add edge	— create edges by specifying two vertices; add edges to work file
add polygon	— create polygons by correcting vertices. A minimum of three vertices are required to define a polygon, and there is an internal maximum specified by NPVERT.

DELETE [VERTEX, EDGE, POLYGON] (default = VERTEX)

delete vertex	— delete vertices and any edges or polygons which are connected to the deleted vertices
delete edge	— delete edges
delete polygon	— delete polygons

DISPLAY [ALL, VERTEX, EDGE, POLYGON] (default = ALL)

display all	— display all edges and polygons in graphics mode
display vertex	— display all vertices and their line numbers in graphics mode
display edge	— display all edges in graphics mode
display polygon	— display all polygons in graphics mode

DUPLICATE

Duplicate a polygon at another location — asks for a displacement vector.

END

End the program.

ERASE

Erase the display screen.

GET [filename] (default = INFILE)

Open an existing file and assign the filename to INFILE; the elements of this file make up the new work file.

HELP

List all the BUILD commands, their corresponding options, and the default values.

LIST [VERTEX, EDGE, POLYGON] (default = VERTEX)

list vertex	— list the world coordinates, window coordinates, and the vertices of the work file on the display screen
list edge	— list the edges of the work file on the display
list polygon	— screen list work file's polygons on the display screen

MOVE [VERTEX, POLYGON] (default = VERTEX)

move vertex	— move a vertex from its present location to a new location — asks for a displacement vector
move polygon	— move a polygon from its present location to a new location — asks for a displacement vector

PRINT [ALL, VERTEX, EDGE, POLYGON] (default = ALL)

print all	— list the work file's world and window coordinates, vertices, edges, and polygons on the printer
print vertex	— list the world coordinates, window coordinates, and vertices of the work file on the printer
print edge	— list the work file's edges on the printer
print polygon	[illegible]

SAVE [filename]

(default = OUTFILE)

Save the current file under the specified filename; assign the filename to OUTFILE.

STATUS

List the filenames stored in INFILE and OUTFILE; indicate the current number of vertices, edges, and polygons and the maximum number of each element allowed.

WINDOW

Create the work file's window space by specifying minimum and maximum x and y coordinates for display. Defaults to WORLD.

WORLD

Create the work file's three-dimensional world space by specifying x, y, and z coordinates. All structures must be contained in this cartesian coordinate system.

APPENDIX D

FASTPLOT is a data analysis program which runs in conjunction with 'FAST'. The results for 'FAST' are dumped to a data file after each prescribed desired time step. FASTPLOT has the capability to form a list of variables, read in their values at each time interval, list out the values in tabular form, graph the values (hard copy or screen), and save the variables in a file for future reference.

The FAST model models a fire in one of several compartments, or rooms, and follows smoke and toxic gases from one compartment to another. We are concerned with variables in both the upper and lower layers.

The list of variables presently available through FASTPLOT are:

AREA	burning area of the fire (m^2)
CONCENTRATION	species density in parts per million
CONVECTIVE	heat loss from layer to solid surface due to convection (kW/m^2)
DOORJET	buoyant mass flow through a vent (kg/sec)
DOSE	species concentration integrated over time (ppm-min)
ENTRAINED	mass entrained by a plume (from lower layer to the upper layer)
INTERFACE	height of the two-zone discontinuity (m)
MASS	mass density in a layer (kg/m^3)
MDOTFIRE	mass loss rate of the fire source (kg/sec)
NEUTRAL 1, NEUTRAL 2, NEUTRAL 3	neutral planes (maximum of three) for each vent
PLUME	total mass flow into the plume (kg/sec)
PRESSURE	reference pressure at the floor of the compartment (Pa)
QC	total convective heat gain by a layer
QF	total enthalpy increase from the fire source
QR	total radiative heat gain by a layer
RADIATION	heat loss from layer due to radiation (kW/m^2)
TEMPERATURE	temperature of the layer (C)
VENTFLOW	mass flow through a vent (kg/sec) — bidirectional
VOLUME	volume of the upper zone (m^3)
WALLTEMP	temperature of the wall (C)

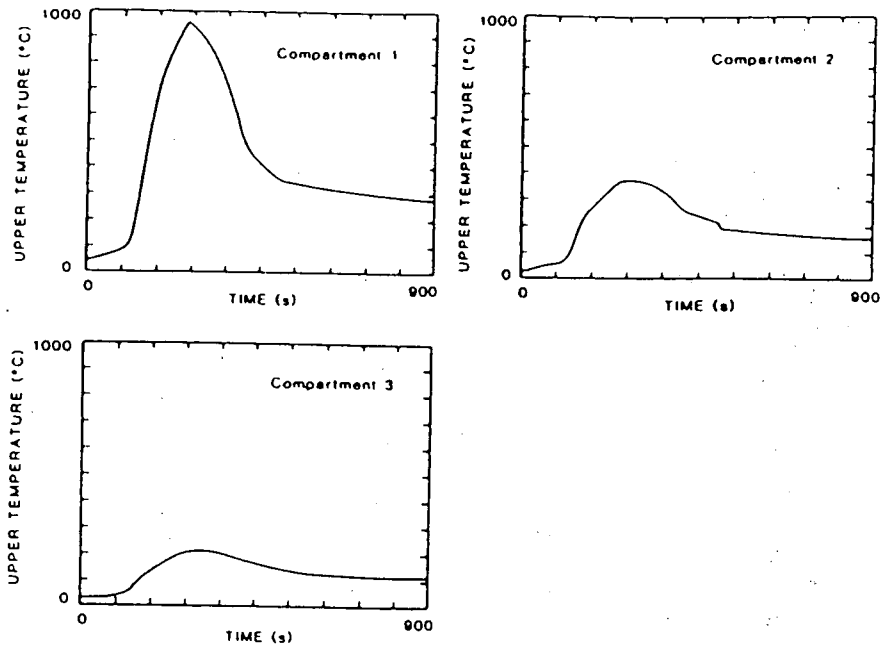


Fig. 10. Sample output from 'FASTPLOT'. Shown is one of the 100 kW calculations for the 'B205' experiments in the three compartment configuration.

The CONCENTRATION, DOSE, and MASS also have associated with them a species number.

The main control of the program is carried out in the subroutine WHICHONE. It does the actual building of a list and the processing of the options. The possible options available to the user are:

ADD
CHANGE
CLEAR
DEFAULT
DELETE
END
HELP
LIST
PLOT
REVIEW
SAVE

Upon running the program, the first input encountered will be that of the dump file generated by FAST. Most of them will be of the form:

filename.DMP

Next, the user will be asked to input the option which he wishes to have performed. The following is a description of each of the options available. They are in the order that they usually will be encountered. However, some may be executed before the others without any problems. The minimum number of characters required to recognize an option is enclosed in the parenthesis at the beginning of each word.

1. (DE)FAULT

This enables the user to set his own default parameters for the following:

COMPARTMENT #
VENTFLOW DESTINATION
LAYER

SPECIES #
CHARACTER SET FOR PLOTTING

This option may be done at any time and if it is not done the defaults are set to '1, 2, upper, 9, and 4' respectively. The purpose of this option is to change the defaults available for other commands and data input.

2. (VA)RIABLES

The purpose of this option is to allow the user to recall the possible variables that are available for use. They will be listed on the screen.

3. (AD)D

This command is used to build a list of variables. When an option is requested ADD may be entered by itself or together with a list of variables that are to be added. If it is entered alone a message will be printed asking for the variables that are to be added to the list. For example:

) ADD
— INPUT VARIABLES TO BE ADDED)
or
) ADD TEMP, PRES, ...

For each variable selected there is a series of questions that will be asked as to the type of that variable wanted. Questions asked about all variables are:

WHICH COMPARTMENT? —)
WHICH LAYER? —)

If VENTFLOW is chosen the compartment origin and destination will be requested; if CONCENTRATION, MASS, or DOSE are selected the species number of each will be requested.

The maximum number of variables allowed on the list at any one time is 25. If the list is full or the variable is presently on the list the addition will be disallowed and another option requested.

4. (DEL)ETE

When this option is entered the present list of variables will be printed out to the screen and the user will be asked to input the variables to delete by the number associated with them on the list. They must be entered on a single line separated by commas or blanks.

If the variable number that is input does not correspond to one that is currently on the list it will be skipped. After the deletions have been processed a new list is presented and another option requested. If the list is presently empty then that fact will be stated in an error message.

5. (HE)LP

This command may be input at any time that the user is asked for an option. Its purpose is to simply list out to the console a list of the available commands and a brief explanation after which another option will be asked for.

6. (RE)VIEW

At times the user may wish to see what is presently on his list before entering a command. This may be done with the REVIEW command. It will print out the current list along with the compartment number, species, and layer of each of the variables. After the printing of the entire list the option request is again displayed.

7. (LI)ST

After variables have been added to the list and their data values read in, the user may list out the values of any of the variables on the list to either the printer or the console. The user will input the device number (5 = CONSOLE, 6 = PRINTER), and the list of variables presently on the list will be displayed. He will then be asked to input the corresponding number(s) of the variable(s) to be listed out. They must be entered on a single line separated by commas or blanks. The maximum number of variables able to be listed at one time is 8 for the printer and 5 for the console.

8. (PL)OT

This option is central to the data analysis. After entering this command the current list of variables will be displayed along with their numbers. The user will be asked to input the number of the variable(s) to be plotted from the list. They should be entered in a string separated by a comma or a blank space. For example:

ENTER VARIABLES TO BE PLOTTED —) 1,2,3,4
or
ENTER VARIABLES TO BE PLOTTED —) 1 2 3 4

After entering the variable numbers, the number of the device which the graph is to be plotted on will be asked for.

The possible devices are:

1. CALCOMP
2. PRINTER
3. LEXIDATA
4. SCREEN

The maximum number of plots per call to PLOT is limited to 4. They will be printed in the following order on the device depending on the number of graphs per page:

If more than 4 variables are input only the first four will be accepted and the remaining ones disregarded. If a variable number not on the list is entered, an error message will appear, the list will be reprinted and the input will be asked for again. This will continue until all variables entered are currently on the list.

Before the graphing is done the user is given the opportunity to change the range of the X and Y axes. The maximum and minimum values of the X and Y axes will be displayed, followed by a request for a change in each, which will be of the form:

CHANGE (X or Y) AXIS TO? —)

If no change is desired simply enter a ⟨RETURN⟩ and the next axis change will be displayed. If a change is made the value will be entered and the same change request will be made again. This will be repeated until a ⟨RETURN⟩ is entered.

When all the changes have been made, if any, the graph of that particular variable will be plotted. After it has been completed the next variable's maximum and minimum will appear and their changes input as before.

After the final graph has been completed the option request will be displayed and a new option may be entered.

9. (SA)VE

This option allows the user to save the values of the variables on the list in a file. The format used will make the data compatible with an experimental data processing program designed for

The user will be asked for the name to be used for the file. A check will be made to see whether that file presently exists or not. If it does the user will be asked if he wants to write over the old file with this new data. If his answer is NO, nothing will be placed in the file and another option requested. If, however, he does want the file rewritten, or the file does not already exist, the new file will be created and the data stored in it.

Each variable on the list will be dumped with the following format at the beginning of each block of data:

I6,I6,A6, * --------- COMMENT ---------

The first I6 will be for the number of data points for that variable, the next I6 is for the number given to that variable on the list, and the A6 is for the actual variable name. Everything after the * is a comment block and will be filled with information relevant to that particular variable, such things as species number, compartment number, layer, etc. The actual numerical data will be dumped using the format 7E11.5.

10. (CL)EAR

The input of this command empties the variable list.

11. (CH)ANGE

This option restarts the program by asking for a new file and resetting all variable lists.

12. (EN)D

This function terminates the execution of the FASTPLOT program.