NIST-GCR-92-612

User's Guide for the Fire Demand Model; A Physically Based Computer Simulation of the Suppression of Post-Flashover Compartment Fires

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United States Department of Commerce
Technology Administration
National Institute **of** Standards and Technology

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Issued July 1992

Sponsored by:
U.S. **Department of Commerce**
Barbara Hackman Franklin, ***Secretary***
Technology Administration
Robert **M.** White, ***Under Secretary for Technology***
National Institute of Standards and Technology
John W. Lyons, ***Director***

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This report was prepared for the Building and Fire Research Laboratory of the National Institute of Standards and Technology under grant number 60NANBOD1050. The statements and conclusions contained in this report are those of the authors and do not necessarily reflect the views of the National Institute of Standards and Technology or the Building and Fire Research Laboratory.

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MRC-R-1364
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USER'S GUIDE FOR THE FIRE DEMAND MODEL

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Grant No.: NIST 6ONANBOD1050

April 1992

Prepared for: U.S. Department of Commerce
National Institute of
Standards and Technology
Gaithersburg, MD 20899

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ABSTRACT

The Swedish Fire Research Board and the U.S. Federal Emergency Management Agency, with the cooperation of the U.S. National Institute of Science and Technology, supported the development of a computerized Fire Demand Model (FDM). The FDM simulates the suppression of post-flashover charring and non-charring solid fuel fires in compartments using water sprays from portable hose-nozzle equipment used by fire departments. The output of the FDM shows the extinguishing effects of water sprays at various flow rates and droplet sizes. The calculations are based on a heat and mass balance accounting for gas and surface cooling, steam-induced smothering, direct extinguishment of the fuel and water spray induced air inflow and venting of heat and products of combustion.

This document provides instruction on how to execute the FDM on a Personal Computer (PC). This includes a description of the required input parameters and instructions for producing three different types of graphical plots: **(1)** time-temperature histories, **(2)** volume-median-drop-size verses water application rate defining combinations where fire control is and is not possible, and **(3)** cross plots to facilitate comparison between different cases.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

Section **Page**

LIST OF ILLUSTRATIONS

LIST OF TABLES

SECTION 1

INTRODUCTION

1.1 Background.

The Swedish Fire Research Board and the U.S. Federal Emergency Management Agency, with the cooperation of the U.S. National Institute of Science and Technology, have sponsored the development of a computer simulation of fire suppression for post-flashover compartment fires called the Fire Demand Model (FDM). This document provides a User's Guide for running this model.

The development of the FDM was undertaken to further the Understanding of the basic mechanisms involved, as well as to support the development of standards for and to seek ways of improving the performance of fire suppression systems. The overall goals are to reduce economic losses and enhance life safety by improving the protection of residential and industrial buildings as well as fire fighting and civilian personnel from major fires.

Despite the almost universal use of plain water dispersed by hydraulic nozzles and sprinklers, there is still considerable uncertainty in quantifying its effects as a suppression agent. One would like not only to estimate the total quantity of water and its application rate which would effectively suppress a given structural fire, but one would also like to identify and quantify the factors which influence suppression effectiveness. These are the major objectives in the development and use of the FDM.

Over the years, there have been numerous fireground operational data and experimental test programs conducted to establish fire suppression data for a variety of building and fuel characteristics as well as suppression agents. Operational and test data currently exist in reports published by many organizations. Such data gathering and experimental testing is very expensive and time consuming. Furthermore, such data has not lead to an understanding of the basic phenomena and mechanisms involved and ultimately to establishing performance based fire control standards. Increased understanding could lead to improvements in the effectiveness of fire suppression.

The current effort is following a broader approach looking closely at the theoretical aspects of the problem and making best use of physical-mathematical modeling in addition to experimental work to establish those physical properties of fire suppression systems that determine improved effectiveness for a variety of fire situations. **A** broader scientific approach involving both experimental and computer modeling work is being followed to better understand the phenomena, as well as to guide the development of new and to improve conventional suppression systems.

The FDM developed to date focuses on the manual suppression of post-flashover charring and non-charring solid fuel fires using water spray from portable hose-nozzle equipment used by Fire Departments. Pre-flashover fires, fixed in-place suppression systems, and suppression agents other than water remain for future work. A detailed R&D plan for these cases is provided in an earlier report (Reference **1**).

The output of the current post-flashover FDM shows the extinguishing effects of hose-nozzle systems emitting water spray at various flow rates and droplet sizes. The calculations are based on a heat and mass balance accounting for gas and surface cooling, steam-induced smothering, direct extinguishment of the fuel and water spray induced air inflow and venting of heat and products of combustion. A discussion of the physical basis and computer details of the FDM is presented in Reference 2 and results from the model in Reference **2, 3, 4** and **5.** Reference 6 summarizes several full scale fire suppression tests completed at the Building and Fire Research Laboratory at NIST (BFRL-NIST) comparing fire conditions before and during suppression to FDM predictions. Appendix **A** of this document provides an overview of the FDM and how one can interpret its results. This User Guide presumes the reader is well grounded in this earlier documentation.

1.2 Organization of User's Guide.

This document provides instruction on how to execute the FDM on an IBM compatible personal computer (PC). Section **2** describes the FDM Controller and Section **3** explains the general features of FDM operation. Section 4 provides a guide for running the FDM including descriptions of the input parameters. Finally, Sections **5,** 6, and **7** provide instructions for producing three different types of graphical plots: **(1)** time-temperature histories, **(2)** volume-median-drop-size verses water application rate defining combinations where fire control is and is not possible, and **(3)** cross plots to facilitate comparison between different cases. Appendix **A** provides a brief overview of the FDM and how to interpret its output results.

1.3 FDM Hardware/Software Requirements.

The FDM has the following hardware/software requirements:

- An 8086-, 8088-, 80286-, or 80386-based IBM compatible computer with at least 447KB of RAM and DOS Version **2.0** or higher.
- An EGA or VGA compatible graphics card and monitor.
- A Tektronix, HPGL-Plotter, PostScript, or QMS-Lasergrafix format printer for publication-quality plots or an Epson-compatible printer for PC screen "dumps" of plots created by the Volksgrapher[1] plot software package.

1.4 FDM Software Installation.

The procedure to install the Fire Demand Model on a hard disk from the provided floppy disk is as follows (note: the installation instructions assume that the model is to be installed in the directory "\FDM" on drive "C:" and that the floppy disk containing the files to be installed is in drive **"A:")**:

1. If the directory "C:\FDM" does not exist, create it using the DOS "MD" command.
2. Copy the files from the floppy disk to the FDM directory using the command,

   ```
   COPY A:*.*  C:\FDM
   ```

   The FDM directory should contain the following files:

README	–	File that describes the installation process.
FIRE.BAT	–	Batch file that controls execution of the Fire Demand Model.
FDM.EXE	–	Fire Demand Model main program.
SETUP.EXE	–	Input parameter setup program for Fire Demand Model main program FDM.EXE.
TTPLOT.EXE	–	Time/Temperature history plot program.

[1] **Kahaner, D.K. and W.E. Anderson, "Volksgrapher: A FORTRAN Plotting Package User's Guide, Version 3.0," National Institute of Standards and Technology, NISTIR 90-4238, February** 1990.

FLPLOT.EXE	–	Fire control failure line plot program.
XPLOT.EXE	–	Fire control failure lines cross-plot program.
SETUPX.EXE	–	Input file setup program for fire control failure lines cross-plot program XPLOT.EXE.
ASK.COM	–	Public domain assembly language key'board input utility (PC Magazine DOS Power Tools[2]).
BATCHMAN.COM	–	Public domain assembly language multifunction batch utility (PC Magazine DOS Power Tools).
OPTION2.COM	–	Public domain assembly language program that provides tools for IF ERRORLEVEL tests (PC Magazine DOS Power Tools).

3. Add the directory name "C:\FDM" to the DOS directory PATH contained in the file "AUTOEXEC.BAT".
4. Re-boot the machine.

If the model has been installed in the default directory location "C:\FDM", then no further steps are necessary. If the model is to be installed in a directory other than "C:\FDM", then substitute the desired directory name for "C:\FDM" in the above steps. The following step is also required:

5. Edit the file "FIRE.BAT" in the directory in which the model is installed, replacing the directory name "C:\FDM" with the name of the directory in which the model is installed on the following lines:

```
SET FIRE=C:\FDM
SET BIN=C:\FDM
```

[2]Somerson, Paul, "PC Magazine DOS Power Tools, 2nd Edition," Bantam Books, 1990.

SECTION 2

FDM MAIN MENU CONTROLLER

The FDM Controller is a file which contains operating system commands. These commands provide the user a display of menu choices as shown in Figure 2.1.

```
FDM Main Menu:
   1. Run Fire Demand Model
   2. Plot Time/Temperature History
   3. Plot Fire Control Failure Line
   4. Cross-Plot Fire Control Failure Lines
   5. Exit
Enter Choice:
```

Figure 2.1. FDM controller main menu choices.

Choices 1 through 4 in Figure 2.1 provide a step by step sequence for running the main PROGRAM FDM and then producing plots using PROGRAMS TTPLOT, FLPLOT and XPLOT. Choice 5 is to exit the Controller.

The Main Menu provides the following:

1. **Run Fire Demand Model.** This provides setup of the input parameters and execution of a FDM case. Tabular printout of time/temperature history results can be requested, or alternatively, specification of the plot option produces files for subsequent plotting.
2. **Plot Time/Temperature History.** This choice provides time/temperature histories in graphical form as illustrated in Figure 2.2. Parameters controlling the plotting are setup and the plots are produced.
3. **Plot Fire Control Failure Line.** This choice plots a "fire control failure line" (Figure 2.3) giving water application rates (per unit total interior area of a compartment) verses the volume-median-drop-size of the spray where fire control is and is not possible (Appendix A.3 explains the significance of this plot). Parameters controlling the plot are set-up and the plots are reproduced.

4. **Cross-Plot Fire Control Failure Lines.** This choice allows the user to create cross-plots of fire control-failure lines from various FDM runs as shown in Figure 2.4. Parameters controlling the plotting are setup and the plots are produced.

5. **EXIT.** This command exits the user from the FDM Controller.

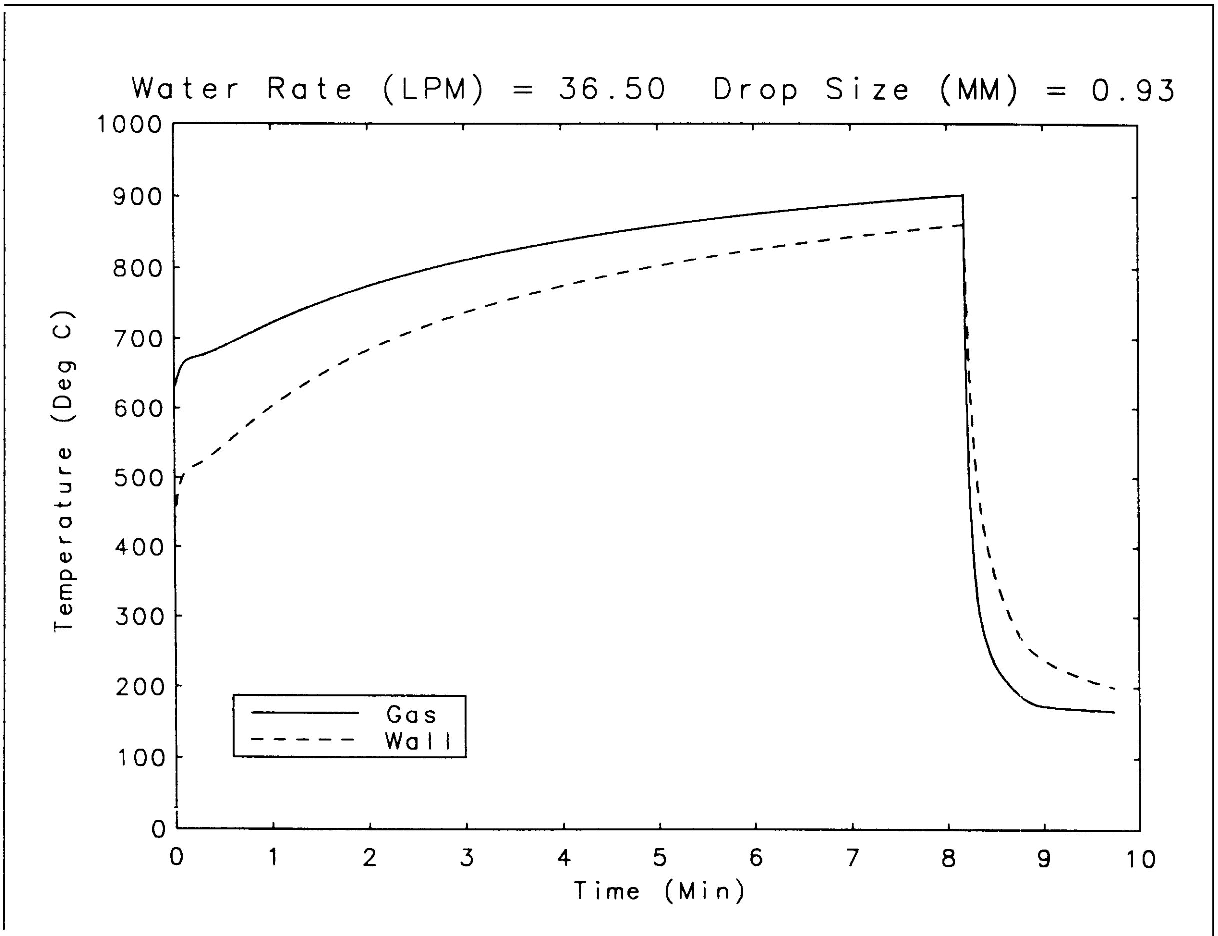

Figure 2.2. Example time/temperature history plot.

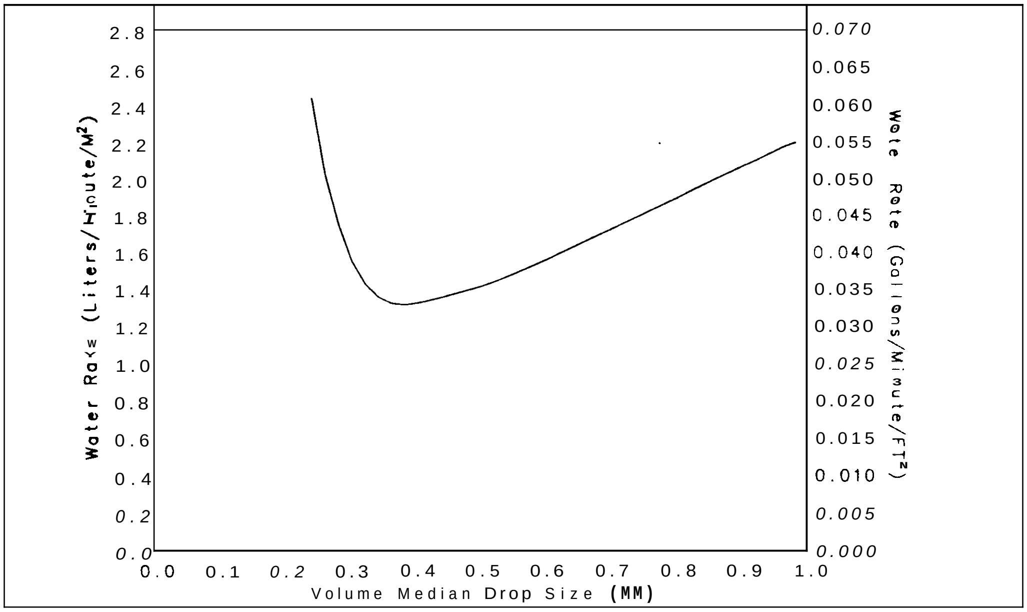

Figure 2.3. Sample failure line plot for 25% water exposed fuel fraction.

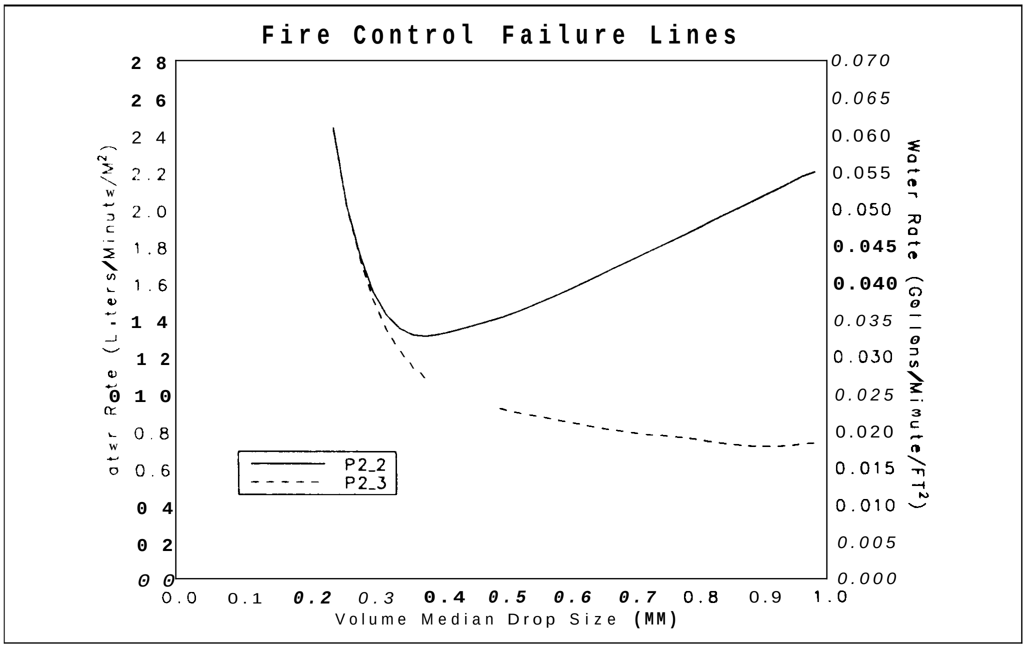

Figure 2.4. Sample failure line cross-plot for 25% (upper line) and 75% (lower line) water exposed fuel fraction.

SECTION 3

GENERAL FEATURES OF FDM DATA INPUT/OUTPUT OPERATION

3.1 Introduction.

This section describes general features of the FDM which affect the imputing of data into the model and the output created. Specifically, Section **3.2** describes the FDM input/output file naming conventions and Section 3.3 describes the definition of list parameters associated with the input.

3.2 Input/Output File Handling.

A uniform process is used to name the input/output files for the four main FDM programs. The input files store the data required to run each program. The file name identifies the data established by the PROGRAM FDM user-friendly setup process, and subsequently the case to run. The file naming conventions are flexible allowing the user to specify the file names, or allowing the system to automatically generate them when the user specifies a file version number only. During the setup mode for PROGRAM FDM, a file is identified and named for input and later for output. PROGRAM FDM can also produce a data file of output results for use with the plot programs.

A file may be identified by simply specifying a version number (greater than 0) without any other non-numeric characters. This version number must be less than 9999 for PROGRAM FDM input files. The version number is attached to the default file name **as** follows: The suffix is always .INP and the prefix is the program name. For example, the Version 1 input file generated for PROGRAM FDM is FDM_1.INP.

A file may also be named directly by the user. The file name, file type, and version number must be separated by a period (.). The filename part cannot exceed 8 characters; and no non-alphanumeric characters may be used except underline (_). For example, an acceptable user specified file name might be CASE_1.INP.

When a file is identified by version number only, the system automatically generates the file name of any plot data output files. Fire control failure line plots are automatically named P2_N, and time/temperature history plots are automatically named P1_N, where N is the version number. The plot programs identify the plot data input file, using a version number which matches the FDM program case run.

3.3 Definition of List Parameters.

Several input parameters are defined as LISTS because a variable number of them may be used to setup any particular case. Specifically, PROGRAM FDM lists a variable number of wall and roof vents and the cross-plot PROGRAM XPLOT lists a variable number of fire control failure lines to be plotted.

A LIST is defined and maintained during a setup session. A LIST begins with the first entry and is successive up to the last entry. A LIST entry is made by adding, inserting or replacing in the LIST. When entered, the appropriate set of parameters must be defined. For wall and roof vents, the parameters defining them are prompted for input. For the failure line cross-plot list, the plot data input file name is requested. For example, when roof vents are closed, the following sample display and menu is used:

```
ROOF VENTS LIST (TIME STARTED OPEN/RATE/FINAL AREA):
    1.          0.000       1.000       10.000

ROOF VENTS MENU:
    A. ADD A ROOF VENT
    I. INSERT A ROOF VENT
    D. DELETE A ROOF VENT
    R. REPLACE A ROOF VENT
    M. MOVE A ROOF VENT
ENTER CHOICE:
```

The above is an existing LIST involving one roof vent. If there were more, they would be listed in succession 1, 2, 3, etc.

Entering a carriage return only exits the menu and continues the setup of other parameters. The following three roof vent parameters are displayed in the roof vent list (see above) whenever a choice to ADD (A), INSERT (I) or REPLACE (R) is made:

TIME AT WHICH ROOF VENT IS STARTED (MINUTES):

RATE AT WHICH ROOF VENT IS OPENED (M2/MIN OR FT2/MIN):
FINAL AREA OF ROOF VENT (M2 OR FT2):

These three parameters are required for each roof vent and define the simulation time when the vent opening is started, the rate the opening is increased, and the final vent size.

For an existing LIST, maintenance of the entries is done using various standard functions. For example, DELETE removes an entry from the list and MOVE changes the order of the entries. If no entries exist in the LIST, an ADD function is used to define the first entry. Thereafter a display of the LIST entries and a menu giving the function choices is displayed, and a request for a choice is made. Each LIST has its own unique display of entries.

The LIST function menu is generic in terms of function choices., Specifically:

ADD – – This function adds an entry into the LIST.

INSERT – – This function adds an entry at a specified position in the LIST. The position must be from 1 to the number of entries, and the new entry will precede the entry currently at the position specified, and become that LIST position. If the position desired is after the last entry, then the ADD function must be used.

DELETE – – To delete an entry in the LIST, its position must be specified. Valid positions can only be 1 to the number of entries. Once specified, any entries after it on the LIST are moved up one position and the number of LIST entries is reduced by 1.

REPLACE – – To replace an entry on the LIST, its position on the list must be specified as a number from 1 to the number of entries. The entry is defined to overwrite the previous entry. This function may be used to edit one parameter of an entry, since just carriage returns to any prompt leaves the value unchanged. Not changing any of the parameters requested will leave the LIST entry unchanged.

MOVE – – This function allows moving an entry from one position on the LIST to another. The position of the entry to be moved must be identified, and also the position to where it is to be moved. Both positions must be from 1 to the number of entries on the LIST. If both positions specified are the same, the entry remains where it is. Otherwise the entry is moved up or down the LIST and the other entries are shuffled appropriately. For failure line plot data files, the order may determine what type line is used to plot each failure line.

SECTION 4

GENERAL MENU CHOICE 1 – RUN THE FIRE DEMAND MODEL

4.1 Overview.

On executing General Menu Choice **1** "Run the Fire Demand Model" (Figure **2.1)** the Program Menu shown in Figure **4.1** appears. The **Setup Input Parameters** choice **"A"** provides a user-friendly series of prompts for creating the FDM input file shown in Figure **4.2.**

```
FDM Program Menu:
   A. Setup Input Parameters
   B. Run Program
   C. Print Log File
   D. Return to Main Menu
Enter Choice:
```

Figure 4.1. Sample FDM program menu.

The **Run Program** choice "B" requests the input file version number or name and executes PROGRAM FDM. The **Print Log File** choice **"C"** outputs tabular results if desired. Finally, the **Return to Main Menu** choice "D" exits to the Program Menu.

4.2 Choice A – – Setup Input Parameters.

4.2.1 File Name and SETUP Menu.

Executing the **Setup Input Parameters** choice **"A"** in Figure **4.1** causes the system to prompt the user for the required information and also to check for correct values, i.e., certain parameters are not allowed to have values outside a range acceptable to the FDM.

```
       1       ! ECHO INPUTS FLAG (0-NO, 1=YES)
  0.0000000    ! START WRITE TIME.  ROUTINES TO OUTPUT DEBUG WRITE STATEMENTS:
********************************************************************************
       1       ! SIMULATION NUMBER
       0       ! OUTPUT TABULAR TIME/TEMPERATURE RESULTS (0=NO, 1=YES)
       1       ! PLOT OUTPUT DATA (0=NO, 1=TIME/TEMP, 2-FAILURE LINE)
 P1_1
       0       ! ENGLISH UNITS(1) OR METRIC UNITS(0)
   29.75000    ! INITIAL WALLS/CEILING AREA (M2 )
   5.950000    ! FLOOR AREA (M2 )
   2.440000    ! ROOM HEIGHT (M )
       1       ! NUMBER OF WALL VENTS
  0.0000000    ! TIME AT WHICH WALL VENT IS OPENED (MINUTES)
   25.00000    ! TIME AT WHICH WALL VENT IS CLOSED (MINUTES)
   1.515000    ! HEIGHT OF WALL VENT (M )
  0.7570000    ! WIDTH OF WALL VENT (M )
   1.515000    ! HEIGHT OF TOP OF WALL VENT ABOVE FLOOR (M )
       0       ! NUMBER OF ROOF VENTS
  2.5300000E-02 ! WALLS/CEILING/FLOOR THICKNESS (M )
      20       ! WALLS/CEILING/FLOOR SEGMENTS
  1.7200000E-03 ! WALLS/CEILING/FLOOR THERMAL CONDUCTIVITY (KCAL/M_MIN_DEG C)
   210.0000    ! SPECIFIC HEAT OF WALLS/CEILING/FLOOR (KCAL/M3_DEG C)
  0.1000000    ! WALL/CEILING-GAS HEAT CONVECTION COEFFICIENT CONSTANT
(KCAL/M2_MIN_(DEG C)**1/3)
   32.95000    ! FUEL LOAD (KG/M2 )
   36.81000    ! FUEL SURFACE AREA (M2 )
   4.920000    ! AIR/FUEL RATIO
   2210.000    ! EFFECTIVE HEAT OF COMBUSTIOI OF FUEL (KCAL/KG)
  0.5000000    ! WALL/CEILING-GAS EMISSIVITY
       0       ! FUEL PLASTIC(1) OB NON-PLASTIC(0)
   425.0000    ! WALL TEMPERATURE AT AT FLASHOVER (DEG C)
   625.0000    ! GAS TEMPERATURE AT AT FLASHOVER (DEG C)
   200.0000    ! WALL TEMPERATURE AT FIRE CONTROL (DEG C)
   200.0000    ! GAS TEMPERATURE AT FIRE CONTROL (DEG C)
   36.50000    ! WATER APPLICATION RATE (L/MIN  )
  0.9300000    ! VOLUME MEDIAN DROP SIZE (MILLIMETERS)
   8.180000    ! TIME WATER APPLIED (MINUTES)
   75.00000    ! WATER EXPOSED FUEL AREA FRACTION (PERCENT)
   5.976000    ! NOZZLE PRESSURE (KG/CM2)
  0.0000000    ! DISTANCE OF NOZZLE FROM VEIT (M )
   60.00000    ! FULL CONE ANGLE OF STREAM (DECREES)
   1.000000    ! SWEEP TIME OF COVERAGE (SECONDS)
       0       ! WATER SPLATTERS FROM CEILING (0-NO, 1-YES)
   20.00000    ! SIMULATION TIME LIMIT (MINUTES)
```

Figure 4.2. Sample FDM parameters input file.

The input sequence begins with the user defining the file name of any preexisting file that is to be edited. If no input file name is provided or an error is detected in attempting to open or read the specified input file, some of the parameters will be initialized to default values as described below. Otherwise the data in the specified input file is read in and are available for editing. Errors in opening or reading the file should be evaluated so that the problems in the data can be corrected. The request for a file name is made by the following prompt.

```
ENTER INPUT PARAMETER FILE VERSION NUMBER OR FILE NAME:
```

If there is no preexisting file to be edited, a carriage return will suffice as a response. After inputting the data for a new file, a file name is requested when the SETUP program is terminated by an END command. A carriage return can also be a response to this request, but the response returns the user to the SETUP menu described below. If an existing file had been previously named, its version number or name is displayed as a reminder. An attempt is then made by the SETUP routine to open the file named for output. If the output name matches the input name, the earlier file is first deleted and a new one opened. If the named output file already exists but doesn't match the input file named, then the following message is displayed:

```
ERROR -- FILE NAMED FOR OUTPUT ALREADY EXISTS
AND DOES NOT MATCH INPUT FILE NAME
```

The named file is not used for the output file and return is to the main SETUP menu.

As noted in Section 3.2, parameter data files may be specified by version number or name. If a number is entered, it is attached to the default prefix FDM_ and the suffix .INP to form the file name. For example, entering version number 1 will form the file FDM_1.INP. Version numbers must be greater than 0 and less then 100,000. Any non-numeric character will indicate that the file is to be named completely by the user. Only alphabetic characters and "_" (underline) may be used and "." (period) used to delimit filename, file type and version number. The filename can not exceed 9 characters. Using version numbers simplifies the naming of FDM input files. Also, plot data files created by PROGRAM FDM are also automatically named. This means that one number can be used to identify a case to be run and any plots produced based on its results.

Once the file name has been specified, the following SETUP Menu appears presenting choices related to parameter definition.

```
TYPE F TO RE-SELECT FDM SETUP FILE
     E TO EDIT FDM PARAMETER DATA
     S TO EDIT SUBSET OF FDM PARAMETER DATA
     R TO REVIEW FDM PARAMETER DATA
     Q TO QUIT FDM PARAMETER DATA ACCESS
ENTER CHOICE:
```

If an invalid choice is entered, the following message is displayed and the menu repeated.

```
*** INVALID CHOICE - TRY AGAIN ***
```

The above **SETUP** menu is also repeated after **EDIT** and **REVIEW** choices are completed. The **QUIT** option terminates the program requesting an output file name to store the parameter data as described above.

The **RE-SELECT FILE** option **(F)** is used to select a different **FDM** parameters input file from the one originally requested. Choosing the **F** option results in the program prompting the user for a new parameters input file version or name.

The **EDIT** option **(E)** sequences through the required parameters providing prompts identifying each. If any user response entered is invalid or out of range, a message will so indicate, and the item will be requested again.

The **EDIT SUBSET** option **(S)** allows for editing a subset of the parameters by specifying a character string contained within the names identifying each of the parameters. The following prompt requests the character string after the S option is selected.

```
ENTER SUBSET CHARACTER(S):
```

A carriage return only causes a return to the above SETUP menu without effecting any changes. Otherwise each parameter in the normal edit sequence is automatically tested by the system, and if its name contains the characters entered, it is prompted for. If the subset brought to the screen results in parameters not desired, they can be skipped by entering a carriage return. Entering the entire name for a prompt guarantees it will be the only name prompted. On the other hand, entering a common letter such as "A", may result in the entire edit sequence of parameters to be prompted. If no parameter names contain the character string entered, then no parameters are prompted, and the following message is displayed, where **CHARSTRING** is the character string entered.

```
NO PARAMETER PROMPTS FOUND WITH CHARACTERS:  CHARSTRING
```

The use of the **S** option implies familiarity with the parameter names. These can be displayed by the selecting complete **EDIT** option or the **REVIEW** option.

The **REVIEW** option **(R)** displays the parameter values in the same sequence as they were defined in the **EDIT** option.

4.3 PROGRAM FDM Setup Prompts and Definitions.

4.3.1 Input Error Checking.

As part of the SETUP sequence, it is desirable to do error checking to validate the input values. Error checking includes general input errors (e.g. entering a non-numeric character), distinguishing integer and real number values, and out-of-range testing.

Each input parameter is prompted for interactively at a terminal one item at a time. The prompt includes the identifying name of the item and its units or valid range of values. The units appear parenthetically in the prompt. Uniform recovery from any input errors is provided by appropriate messages informing of the error and reprompting for the item. This is repeated until a valid value is entered. Typically, a set of parameters are involved so that the same sequencing through the items, changing the items desired by entering values and leaving other items unchanged by just entering a carriage return. However, even when just a carriage return is entered, range testing may be done. Therefore, if a value is entered out-of-range, a carriage return thereafter will not suffice since the value will remain out-of-range. The item will then be repeatedly prompted for until a valid value is entered.

A general input error cause one of the following messages to be displayed:

```
*** ERROR - INVALID INTEGER INPUT ***
*** ERROR - INVALID REAL NUMBER INPUT ***
```

If a valid number is entered, but is out of range, then an appropriate range error message will be displayed, e.g.

```
*** INPUT OUT OF RANGE
*** VALID RANGE IS >= 0 AND <= 1
```

The test for a valid range for the input value can be for a value less than. or equal to, or greater than or equal to a given range, or between two ranges. Equality may be optionally allowed or disallowed. The “between range” check assumes the first range limit is less than the second range limit.

Which type of range test to be done is specific to a parameter entered. In some cases, no range testing is done on the value input.

4.3.2 Overview of Input Prompts.

The following prompts (appearing in capital bold letters) are described in the order they are requested by the **SETUP** routine. Each prompt (or set of prompts) is followed by a discussion of its meaning and use, acceptable range of values, and any default values. Note: A default value is a value a parameter is set to if no input file was named for editing; not the value to which a parameter is set if none is input to a particular prompt.

The prompts are divided as follows: general parameters associated with simulation case identification and output control (Section 4.3.3); description of the compartment (Section 4.3.4), description of the fuel (Section 4.3.5); simulation initialization and termination (Section 4.3.6); description of the water application (Section 4.3.7); and simulation run time control (Section 4.3.8).

4.3.3 General Parameters for Case Identification and Output Control.

ECHO INPUTS FLAG (0=NO, 1=YES):

This flag controls whether a hard copy printout of the user inputs are output to the **LOG** file during a run.

SIMULATION NUMBER:

The simulation number is used when a tabular time-temperature output file (shown in Figure 4.3) is produced. It appears in the printout to identify the run.

OUTPUT TABULAR TIME/TEMPERATURE RESULTS (0=NO, 1=YES):

```
FIRE DEMAND MODEL RUN NUMBER     1

INPUT DATA IS IN METRIC UNITS

COMPARTMENT RELATED DATA:
   ROOM HEIGHT ..............................   2.44     M
    FLOOR AREA          ........ ...........    5.95     M2
   WALL/CEILING AREA .............. .........   29.75    M2
   WALL/CEILING/FLOOR THICKNESS  . .........    0.03     M
   WALL/CEILING/FLOOR              .........
      THERMAL CONDUCTIVITY ....................    0.002   KCAL/M_MIN_DEG C
   WALL/CEILING/FLOOR SPECIFIC HEAT ..........  210.000   KCAL/M3_DEG C
   WALL/CEILING-GAS HEAT
      CONVECTION COEFFICIENT CONSTANT ........    0.100   KCAL/M2_MIN_(DEG C)**4/3
   WALL VENT NUMBER:      1           .......
      TIME OPENED ............     .....  .......    0.00    MIN
      TIME CLOSED ............     ...... .......   30.00    MIN
      VENT HEIGHT          ...     ....  .......    1.515   M
      VENT WIDTH .............     .... .......    0.757   M
      VENT AREA ...............     ... ........    1.515   M

FUEL RELATED DATA
   EFFECTIVE HEAT OF COMBUSTION                  2210.000   KCAL/KG
   FUEL LOAD ................     ...  .......    32.95    KG/M2
   AIR/FUEL RATIO ...........     ...  .......     4.92
   FUEL SURFACE .............     ...  .......    36.810   M2
   FUEL IS WOOD

WATER RELATED DATA
   INITIAL TIME WATER IS APPLIED ............     8.2     MIN
   WATER APPLICATION RATE         ............    36.500   L/MIN
   EFFECTIVE WATER APPLICATION RATE ..........    36.500   L/MIN
   MEDIAN DROP SIZE       .......... ..........    0.930   MILLIMETERS
   REACH ..................... .........    1.220   M
   CONE ANGLE .................. .........   60.0      DEG
   SWEEP TIME                         . .........    1.000   SEC
   VIEWABLE FUEL SURFACE .      .... .........   27.608   M2
   NOZZLE PRESSURE .......      .... .........    5.98    KG/CM2
   DISTANCE OF NOZZLE FROM VENT   .. .........    0.00    M

SIMULATION TIME LIMIT =    9 0 0 MINUTES
TIME STEP DIVISOR =      5 0
```

Figure 4.3.   Sample tabular time-temperature output.

TIME (MIN)	GAS TEMP (DEG C)	W/C TEMP (DEG C)	FL TEMP (DEG C)	RET HEAT (KCAL)	FUEL FRAC	W+1 B-1	TOT WTR APP (L)	TOT WTR ACC (L)	TOT WTR VAP (L)	ETA COST	ETA V GS	ETA V WC	ETA S FU	ETA V FL	ETA V SP
0.0	625.0	425.0	425.0	2838.	0.993	1	0.0000	0.0000	0.0000	0.00	0.00	0.00	0.00	0.00	0.00
0.0	643.5	474.9	453.4	7015.	0.992	1	0.0000	0.0000	0.0000	0.00	0.00	0.00	0.00	0.00	0.00
0.1	657.7	495.6	463.6	7320.	0.991	1	0.0000	0.0000	0.0000	0.00	0.00	0.00	0.00	0.00	0.00
0.1	665.3	505.3	466.9	7621.	0.989	1	0.0000	0.0000	0.0000	0.00	0.00	0.00	0.00	0.00	0.00
0.1	669.1	510.3	467.5	7919.	0.988	1	0.0000	0.0000	0.0000	0.00	0.00	0.00	0.00	0.00	0.00
0.2	671.2	513.4	467.4	8216.	0.986	1	0.0000	0.0000	0.0000	0.00	0.00	0.00	0.00	0.00	0.00
0.2	672.7	516.0	467.3	8513.	0.985	1	0.0000	0.0000	0.0000	0.00	0.00	0.00	0.00	0.00	0.00
0.2	673.9	518.5	467.7	8808.	0.984	1	0.0000	0.0000	0.0000	0.00	0.00	0.00	0.00	0.00	0.00
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.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
8.0	900.0	858.3	851.6 0	8 5E+9	0≤64	1	0.0000	0.000 0	0.0000	0.00	0.00	0.00	0.00	0.00	0.00
8.1	900.3	858.7	852.0 0	97 6E 05	0≤63	1	0.0000	0.000 0	0.0000	0.00	0.00	0.00	0.00	0.00	0.00
8.1	900.6	859.1	852.4 0	587≤+05	0≤62	1	0.0000	0.000 0	0.0000	0.00	0.00	0.00	0.00	0.00	0.00
8.1	900.9	859.4	852.8 0	99 8E 05	0≤61	1	0.0000	0.000 0	0.0000	0.00	0.00	0.00	0.00	0 00	0.00
8.2	901.2	859.8	853.2 0	90 9E 05	0≤60	1	0.0000	0.000 0	0.0000	0.00	0.00	0.00	0.00	0 00	0.00
8.2	901.4	860.2	853.6 0	92 0E 05	0≤59	1	0.0000	0.000 0	0.0000	0.00	0.00	0.00	0.00	0 00	0.00
8.2	901.4	860.2	853.6 0	82 0E+9	0≤59	1	0.0000	0.000 0	0.0000	0.00	0.00	0.00	0.00	0 00	0.00
0.49 FRACTION FUEL REMOVED AT 8.2 MINUTES BY EXTINGUISHMENT								0.0 GOAL							
8.2	892.8	859.0	852.6 0	94 1E 05	0659	1	0.3388E-01	0.000 0	0.3017E-01	0.11	0.40	0.23	0.21	0.05	0.89
8.2	881.5	857.8	849.7 0	93 0E+9	0165	-1	0.5197E-01	0.000 0	0.4401E-01	0.24	0.33	0.21	0.00	0.23	0.76
8.2	871.5	856.5	846.8 0	62 9E 05	0165	-1	0.6951E-01	0.000 0	0.5727E-01	0.24	0.32	0.21	0.00	0.23	0.76
8.2	861.9	855.1	843.8 0	92 8E 05	0165	-1	0.8722E-01	0.135 4E09	0.7072E-01	0.24	0.32	0.21	0.00	0.23	0.76
8.2	852.7	853.6	840.7 0	92 7E+9	0165	-1	0.1050	0.000 0	0.8430E-01	0.24	0.32	0.21	0.00	0.24	0.76
8.2	843.8	852.0	837.6 0.5	2≤+05	0165	-1	0.1230	0.218 3E09	0.9800E-01	0.24	0.32	0.21	0.00	0.24	0.76
8.2	835.2	850.4	834.4 0	92 4E 05	0165	-1	0.1410	0.000 0	0.1118	0.23	0.32	0.21	0.00	0.24	0.77
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
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.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
9.4	68.4	211.5	109.2	0.4112E+05	0.143	-1	46.34	16.10	27.55	0.03	0.14	0.24	0.[illegible]	0.04	0.43
9.5	167.6	209.2	109.0	0.4086E+05	0.142	-1	48.21	17.11	28.35	0.03	0.14	0.24	0.[illegible]	0.04	0.42
9.5	167.6	29 0	109 0 0	08 5E 05	0.142	-1	48.33	17.18	28.40	0.03	0.14	0.24	0.[illegible]	0.04	0.42
9.6	167.8	26 9	108 7 0	0≤ 6 05	0.141	-1	50.21	18.22	29.18	0.03	0.14	0.23	0 [illegible]	0.04	0.41
9.6	167.6	24 8	1[illegible] 5 0	03 6E 05	0.140	-1	52.10	19.27	29.95	0.03	0.14	0.23	0 [illegible]	0.04	0.41
9 7	[illegible] 1	22 [illegible]	108 2 0	0 13E 05	0.139	-1	54.00	20.34	30.71	0.03	0.14	0.22	0.[illegible]	0.04	0.40
9.7	166.5	20 9	108 0 0	99 6 +9	0.138	-1	55.90	21.42	31.47	0.03	0.14	0.22	0.[illegible]	0 03	0.40

FIRE CONTROL AT 9.7 MINUTES, 13.748 % OF FUEL LEFT
56 8 LITERS OF WATER APPLIED, 31.8 LITERS VAPORIZED
END SIMULATION

Figure 4.3. Sample tabular time-temperature output (continued).

This controls whether tabular time-temperature output (Figure 4.3) is provided. Table 4.1 describes the column headings for interpreting the data shown in Figure **4.3.**

PLOT OUTPUT DATA (0=NO, 1=TIME/TEMP, 2=FAILURE LINE):

This parameter stores FDM results in an output file for later use by one of the plotting programs. A ***0*** value means that no output plot data is required. Setting the plot flag to 1 means data will be generated and stored to produce a time temperature plot (Figure 2.1). Setting the Plot Flag to **2** means that the FDM run will loop on water application rates and volume median drop sizes to produce data for a fire control-failure line plot (Figure **2.2).** These plots are produced from the FDM output data using the programs described in Sections ***5***, 6, and **7.** If a plot is desired (a 1 or 2 value) the plot output data file must be identified. If an input file name and version number has not been previously specified, then the following request is made.

ENTER PLOT DATA OUTPUT FILE NAME:

A carriage return only leaves the filename **as** previously entered, or blank. If still blank when the SETUP is ended, the setup case will not be saved until the plot file is specified. If the output file is named by a version number only, one of the following default file names is used, where N is the file version number:

P1_N (Plot Type = 1)
P2_N (Plot **Type = 2)**

This allows one to use the same setup file to produce plot data for the time/temperature history plots (Plot Type 1) or the fire control failure line (Plot Type **2).** The plot data filename will be set automatically if a version number was used for the input file. However, if an output file is named without a version number, the plot data file must be named.

ENGLISH UNITS (1) OR METRIC UNITS (0):

The units for the input data items which follow must all be consistent, i.e., either English, indicated with a 1, or metric, indicated by 0. English units are feet (ft), gallons (gal), BTUs, and degrees Fahrenheit (°F) or Rankine (°R). Metric units are meters (m), liters (ℓ), kilocalories (Kcal), and degrees Centigrade (°C) or Kelvin (°K).

Table 4.1. Column legend for interpreting sample tabular fire time-temperature history (Figure 4.3).

column	Description
TIME	Time after flashover.
GAS TEMP	Average gas temperature in compartment.
W/C TEMP	Average wall/ceiling temperature on interior surfaces of compartment.
FL TEMP	Average floor temperature on interior surface of compartment.
RET HEAT	Total energy retained in compartment gases and interior surfaces.
FUEL FRAC	Fraction of initial fuel load remaining.
VT + 1	Burning is vent controlled = +l.
FU - 1	Burning is fuel controlled = -1.
TOT WTR APP	Total water applied.
TOT WTR VAP	Total water vaporized.
ETA LOST	Fraction of applied water lost or blown away with vented gases.
ETA V GS	Fraction of applied water vaporized in compartment gases.
ETA V WC	Fraction of applied water vaporized on wall/ceiling surfaces.
ETA V FU	Fraction of applied water vaporized on fuel.
ETA V FL	Fraction of applied water vaporized on floor.
ETA V SM	Total fraction of applied water vaporizing.

4.3.4 Compartment Description.

```
INITIAL WALLS/CEILING AREA (M2 OR FT2):
FLOOR AREA (M2 OR FT2):
```

The walls/ceiling area is the total surface area (including vents) of the walls and ceiling. The walls/ceiling area is labeled "initial" because at various times during the simulation, the walls/ceiling area can be reduced (or increased) by the area of any wall opened (or closed). The units are square meters or square feet. The values must be greater than 0.

```
ROOM HEIGHT (M OR FT):
```

The compartment room height is specified in either meters or feet and must be greater than 0.

```
DEFINE/EDIT WALL VENTS (Y/N)?
```

This prompt initiates the definition of wall vents. If no wall vents are required simply enter a "N" with a carriage return. The wall vents are maintained as LISTS (see Section 3.3). A display of any previously defined LIST and a menu to edit this LIST is provided as described in what follows.

Wall vents include doors and windows. Their entire area is considered to be opened immediately at a user specified time. When wall vents are defined, the following display and menu is provided (for this example, the list shows a previously defined vent which is to be edited).

```
WALL VENTS LIST (HEIGHT/WIDTH/TOP/TIME OPENED):
    1.         1.120      1.608      2.000      0.000

WALL VENTS MENU:
    A.  ADD A WALL VENT
    I.  INSERT A WALL VENT
    D.  DELETE A WALL VENT
    R.  REPLACE A WALL VENT
    M.  MOVE A WALL VENT
ENTER CHOICE:
```

Entering a carriage return only exits the menu and continues the setup of the other parameters. The following four wall vent parameters are displayed in the wall vent list (see above). Whenever a choice to ADD (A), INSERT (I), or REPLACE (R) is made:

```
TIME AT WHICH WALL VENT IS OPENED (MINUTES):
TIME AT WHICH WALL VENT IS CLOSED (MINUTES):
HEIGHT OF WALL VENT (M OR FT):
WIDTH OF WALL VENT (M OR FT):
HEIGHT OF TOP OF WALL VENT ABOVE FLOOR (M OR FT):
```

These four parameters are required for each wall vent. They define the simulation time in minutes after fire flashover at which the vent is open, the vent dimensions, and the location of the vent as measured from top of the vent to the floor. The top of the vent must be greater than or equal to the height of the vent and less than or equal to the height of the room (previously specified).

```
DEFINE/EDIT ROOF VENTS (Y/N)?
```

If "Y" is entered, the following sample display and menu occurs. Again, for the example, the list shows a previously defined vent which is to be edited.

```
ROOF VENTS LIST (TIME STARTED OPEN/RATE/FINAL AREA):
    1.        0.000      1.000      10.000

ROOF VENTS MENU:
    A.  ADD A ROOF VENT
    I.  INSERT A ROOF VENT
    D.  DELETE A ROOF VENT
    R.  REPLACE A ROOF VENT
    M.  MOVE A ROOF
ENTER CHOICE:
```

entering a carriage return only exits the menu and continues the setup of other parameters. The following three roof vent parameters are displayed in the roof vent list (see above) whenever a choice to ADD (A), INSERT (I) or REPLACE (R) is made, as follows:

TIME AT WHICH ROOF VENT IS STARTED (MINUTES):
TIME AT WHICH ROOF VENT IS CLOSED (MINUTES):
RATE AT WHICH ROOF VENT IS OPENED (M2/MIN OR FT2/MIN):
FINAL AREA OF ROOF VENT (M2 OR FT2):

These three parameters axe required for each roof vent. They define the time after flashover when the vent opening is started, the rate the opening is increased, and the final vent size[1].

WALLS/CEILING/FLOOR THICKNESS (M OR FT):
WALLS/CEILING/FLOOR SEGMENTS:

The first parameter is the thickness of the compartment enclosure. It is taken as the same for the walls, ceilings and floors. The second parameter controls the grid interval using in the solid surface heat conduction calculations for the walls, ceiling and floor. The grid interval is established by taking the value of this parameter and dividing it into the walls/ceiling/floor thickness input above. A nominal value of at least 20 is recommended unless the cross-section is particularly thin ($< 0.02m$) in which case a lower value may be more appropriate.

WALLS/CEILING/FLOOR THERMAL CONDUCTIVITY
(KCAL/M_MIN_DEG C OR BTU/FT_MIN_DEG F):
SPECIFIC HEAT OF WALLS/CEILING/FLOOR (KCAL/M3_DEG C OR BTU/FT3_DEG F):

These parameters define the thermal properties of the compartment surfaces. They effect the rate of heat loss by conduction through these surfaces.

4.3.5 Fuel Description.

WALL/CEILING-GAS HEAT CONVECTION COEFFICIENT CONSTANT
(KCAL/M2_MIN_(DEG C)**1/3 OR BTU/FT2_MIN_(DEG F)**1/3):

Related to the above, the following equation is used in the FDM in calculating the heat convection coefficient α (Reference 6)

[1]Unlike wall vents, roof vents may be opened gradually, i.e., a firefighter chopping a hole in the roof to vent heat and smoke.

$$\alpha = C * (T_1 - T_{WC})^{0.33} \tag{4.1}$$

The constant C is the "Heat Convection Coefficient Constant" requested. The above prompt C can be parametrically varied in the simulation. For undisturbed boundary layer flow over infinite vertical or horizontal plates, McAdams recommends a value of $C = 0.022$ to 0.018 Kcal/m^2-min-°$C^{1/3}$ for horizontal and vertical surfaces respectively (Reference 7). On the other hand, for post-flashover fire conditions, C may be much greater due to destruction of the boundary layer flow under actual fire conditions (Reference 9). A nominal value of 0.1 Kcal/m^2-min-°$C^{1/3}$ may be used in the simulation.

FUEL LOAD (KG/M2 OR LB/FT2)

This defines the initial amount of fuel in the compartment. It should be noted that when a failure to control the fire occurs the simulation will go to burnout. This parameter can therefore effect the required running time.

FUEL SURFACE AREA (M2 OR FT2):

This defines the total burning fuel surface area exposed to the air.

AIR/FUEL RATIO:
EFFECTIVE HEAT OF COMBUSTION OF FUEL (KCAL/KG OR BTU/LB):

The above fuel related parameters, are described in detail in Reference 2. In general the "Air/Fuel Ratio" is the mass of air required to burn a unit mass of fuel. The "Effective Heat of Combustion of Fuel" is a value less than the calorimetric which accounts for the fact that all the pyrolysis products from the fuel may not be burned within the enclosure. For example, a cellulosic fuel such as fire wood has a Air/Fuel Ratio of 4.92 and an Effective Heat of Combustion of about 2200 Kcal/kg (Reference 6). Values of the above parameters for some typical plastics fuels are given in Table 4.2.

WALL/CEILING-GAS EMISSIVITY:

The emissivity, ε, required is a combined value given by,

$$\varepsilon = \frac{1}{\frac{1}{\varepsilon_f} + \frac{1}{\varepsilon_w} - 1} \tag{4.2}$$

where, ε_f is the emissivity of the fire gases and e, is the emissivity of the walls. The value of ε_f is typically in the range $0.3 < \varepsilon_f < 0.9$ depending on the specifics of the fuel burning and its smokiness (Reference 9). The lower value is applicable to non-smoky transparent flames in small volumes, with the higher value applicable to smoky opaque flames in larger spaces (> 2 meters) (Reference **9). A** reasonable value of ε_w is 0.5 (Reference **7).** Substituting $\varepsilon_f = 0.9$ and e, $= 0.5$, we obtain e ≈ 0.5 which can be used in the FDM **as** a nominal value. e might also be varied parametrically.

FUEL PLASTIC(1) OR NON-PLASTIC(0):

This defines the fuel type **as** plastic or non-plastic (cellulosic or wood). If plastic, then the following additional inputs are required.

IS PLASTIC FUEL CHARRING(1) OR NON-CHARRING(2):

Plastic fuels burn with or without a char layer. The more typical plastic solid fuels are natural or synthetic organic resins made of long hydrocarbon chains bound together by one of a number of possible polymerization process. From the point of view of thermal response, one can divide plastics into two general types: (1) thermoplastics which include various polyolefins (e.g., polyethylene), styrene polymers (e.g., polystyrene), polyvinyl chloride (PVC), and acrylics (e.g., polymethyl methacrylate or **PMMA),** and (2) thermosetting plastics which include various phenolics (e.g., pheno-formaldehyde) and polyurethanes.

In general thermoplastics soften or melt at temperatures low relative to their pyrolysis temperature. Consequently, these plastics burn or pyrolyze from a soft solid or liquid layer on their surface. As an example, polystyrene softens at a temperature of about 100°C, melts at about 240°C and pyrolyzes between 300°C and **400°C.** Another example is polymethyl methacrylate **(PMMA)** which softens at about 50°C and pyrolyzes at between 180°C and 280°C. In the first case, the plastic burns from a liquid layer and in the later from a softened solid layer.

Thermosetting plastics, on the other hand, maintain a permanent "set" even at high temperatures and, in general, pyrolyze or vaporize directly from the solid state. Many thermosets such **as** the phenolic resins produce a char layer on burning but others such **as** the styrenated polystyrene resins do not form a char layer.

Table 4.2. Typical burning characteristics of plastic fuels.

Fuel	Vaporization Temporature (°C)	Increase in Vaporization Temperature With Water (°C/gal/kg)	Effective Heat of Vaporization (Kcal/kg)	Net Heat of Combustion (Kcal/kg)	Air/Fuel Ratio	Density kg/m^3	Specific Heat Kcal/kg-°C	Conductive Heat Transfer Coefficient Kcal/min-m-°C
Polymethyl Methacrylate (PMMA)	2 0	0	36	802	8 2	2 0	0 3	8x 0-C
Polyethylene	400	0	555	7648	14.78	970	0.55	60x10-4
Polyvinyl Chloride (PVC) with Plasticizers	2 0	3 [illegible]	42	3 00	5 5	100	0 2C	0 x 0-4

If the plastic forms a char layer (e.g. a thermoset such as the phenolic resins), then the following parameters must be input[2].

```
CHARRING FUEL BURN RATE CONSTANT (KG/M2_MIN OR LB/FT2_MIN):
CHARRING FUEL FRACTION BURNED BY PYROLYSIS:
CHARRING FUEL FRACTION BURNED BY CHARRING:
CHARRING FUEL PYROLYZING MASS LOSS RATE FRACTION:
CHARRING FUEL CHARRING MASS LOSS RATE FRACTION:
HEAT OF COMBUSTION OF CHAR LAYER (KCAL/KG OR BTU/LB):
```

The charring fuel burn model is based on approximations developed by Harmathy (Reference 8) to determine whether the fire is fuel controlled or ventilation controlled. For fuel controlled,

$$\dot{R}_F = C_1 A_{FU}$$

where A_{FU} is the total surface area of the fuel and C_1 is the "charring fuel burn rate constant" required above. For charring plastic fuels, the user must input a value for C_1. Also in Harmathy's model, the burning is separated into combustion of pyrolysis volatiles and combustion of solids (charring). If M_T is the total initial mass of the fuel, the potential mass of fuel which produces volatiles M_P and the potential mass of fuel which chars, M_C, are given by[2]

$$M_P = C_2 M_T$$

$$M_C = C_3 M_T$$

where C_2 is the above "Charring Fuel Fraction Burned By Pyrolysis" and C_3 is the "Charring Fuel Fraction Burned By Charring." The user is required to input values to C_1, C_2 and C_3 for charring plastic fuels.

The burning rate of volatiles and char respectively is also given by Harmathy's model by,

[2] **Experimental work appears necessary to obtain appropriate values of the empirical constants for char-forming plastic fuels (see Reference 2). For cellulosic fuels that burn with a char layer, the sequence of parameters defining the char layer constants are automatically set to values recommended by Harmathy (Reference 8) ($C_1 = 0.372$ kg/m^2/min, $C_2 = 0.872$, $C_3 = 0.128$, $C_4 = 0.932$, $C_5 = 0.068$, and $C_6 = 8000$ kcal/kg). The user is not prompted for them**

$$\dot{M}_p = C_4\dot{R}$$

$$\dot{M}_C = C_5\dot{R}$$

where C_4 is the above "Charring Fuel Pyrolyzing **Mass Loss** Rate Fraction" and C_5 is the "Charring Fuel Charring **Mass Loss** Rate Fractions." Again, the user is required to input values to C_4 and C_5 for charring plaster fuels[3].

Finally, between the time when pyrolysis is complete and final burnout of the fuel, when no char remains, the heat generated in the compartment is produced by char combustion alone. The "Combustion Heat of the Char Layer" above must be input by the user for charring plastic fuels.

If the fuel is a non-charring plastic, additional inputs are required to characterize its burning. Unlike fuels with an oxidizing char layer, the mass loss rate due to the pyrolysis or vaporization of plastic fuels that burn without a char layer depends strongly on the degree of thermal heat transfer to the fuel bed from the hot or burning gases and surfaces in the compartment. For these materials, fuel-thermal coupling effects are considered in the FDM.

PLASTIC FUEL BURNS AS SOLID(2) OR MOLTEN NON-POLAR(3) OR MOLTEN POLAR(4):

In the FDM model, the non-charring burning plastic fuel surface is categorized into one of three states: **Case 1:** a rigid solid state (e.g., a thermosetting plastic) or a soft or plastic state (i.e., some thermoplastics such as PMMA); **Case 2:** a molten state where the liquid has a *non*-polar molecular structure (i.e., other thermoplastics such as polyethylene); or **Case 3:** a molten state where the liquid has a polar molecular structure (e.g., polyvinyl chloride). In the first case, the impacting water will accumulate on the burning surface and act both as a vaporizing thermal barrier that limits radiative heating of the fuel from above as well as a coolant that cools the hot fuel from below, i.e., the water acts simultaneously as a thermal barrier and as a hot surface coolant.

Water droplets reaching a molten liquid burning surface, (Cases 2 and 3 above) on the other hand, may also penetrate the surface and have an interior cooling effect as well. Whether or not the droplets actually penetrate the surface though,

---

[3] See Footnote 2.

depends on a number of factors including for example: the impacting niomentum of the droplets relative to the resisting viscosity of the liquid, the density of the water (i.e., if the water is heavier than the molten liquid it will sink), and the solubility of the water in the molten fuel. In the latter case, plastic materials having polar molecular structures (Case 3) may dissolve in the water before significant vaporization occurs. For all three cases, the following input parameters are required:

```
NON-CHARRING FUEL FRACTION EXPOSED TO FIRE PLUME:
NON-CHARRING FUEL EMISSIVITY TO FIRE PLUME:
TEMPERATURE RATIO OF PLUME TO BULK COWARTMENT GASES:
NON-CHARRING FUEL FUEL DENSITY (KG/M3 OR LBS/FT3):
NON-CHARRING FUEL THICKNESS (M OR FT):
NON-CHARRING FUEL HEAT OF GASIFICATION (KCAL/KG OR BTU/LB):
NON-CHARRING FUEL TEMP OF VAPORIZATION/PYROLYSIS (DEG C OR DEG F):
NON-CHARRING FUEL SPECIFIC HEAT (KCAL/KG_DEG C OR BTU/LB_DEG F)
FUEL CONDUCTIVE HEAT TRANSFER COEFFICIENT (KCAL/M_MIN_DEG C OR
                                          BTU/FT_MIN_DEG F):
```

The above parameters are required to account for fuel-thermal coupling effects in the FDM. This includes the radiation from the hot gas layer, walls and ceiling and the fire plume as well as the conductive flux density from the vaporizing surface to the interior of the fuel.

Values of the "Heat of Gasification," "Temperature of Vaporization," "Specific Heat" and "Conductive Heat Transfer Coefficient" for some typical plastic fuels are given in Table 4.2. The reader is referred to References 12, 13 and 14 for other fuels.

The remaining non-charring fuel related parameters in the above list are associated with the fire plume radiation model on the fuel bed. This model is based on Harmathy (Reference 10), who suggests that the presence of the enclosure and the location of the vent therein limits the direction and amount of air reaching the plume to that side of the fuel closest to the vent. Consequently, the flame envelope is not necessarily symmetrical and may not extend over the whole fuel bed. His model for local plume radiation is,

$$\dot{q}_p = C_6 A_{FU} C_7 \sigma (C_8 T_1)^4$$

C_6	=	user input empirical "Fraction of the Fuel Exposed to the Fire Plume."
C_7	=	user input empirical "Fuel Emissivity to Fire Plume."
C_8	=	user input "Ratio of the Plume to the Bulk of the Compartment Gases."
σ	=	Stephan-Boltzman constant.
A_{FU}	=	area of the fuel bed.

Although A_{FU} and C_6 are actually variable as the fire progresses, Harmathy takes them as constant during quasi-steady state fire conditions. He also assumes the following values for the various factors,

$$C_6 = 6.0/F_{LD} \leq 1$$
$$C_7 = 0.9$$
$$C_8 = 1.4$$

where F_{LD} is the fuel load in kg/m^2.

Finally, the "Fuel Thickness" above, is used in estimating the conductive flux density from the vaporizing surface to the interior of the fuel. This is the initial thickness of the fuel assuming it is in a horizontal slab configuration.

For non-polar (Case 2) and polar (Case 3) molten plastic fuels the following parameter is also required:

NON-CHARRING MOLTEN FUEL ENHANCED BURN RATE DUE TO WATER (KG/M2_MIN OR LB/FT2_MIN):

As noted by Magee and Reitz in Reference 15, water droplets impacting molten liquid fuels may not only cool the surface, but also act to enhance the burning effect. Two factors appear to cause this: (1) large massive water drops striking molten fuels having relatively low viscosity may "splash" droplets of fuel out of the surface, and (2) water droplets vaporizing within the interior of the fuel creates steam that bubbles to the surface spewing forth molten fuel. In both cases, burning may continue to occur even as the fuel temperature is reduced below that required for vaporization. This enhanced burning effect was observed by Magee and Reitz for polyethylene, a plastic which burn in a liquid molten state. Their results show that applying water at a rate of $0.250\ \ell/\mathrm{min}-\mathrm{m}^2$ increases the burning rate between 0.42 and 0.72×10^8 kg/min-m^2.

For polar (Case 3) molten plastic fuels the following addition parameter is required:

NON-CHARRING MOLTEN POLAR FUEL VAPORIZATION TEMP INCREASE DUE TO WATER (DEG C/LITERS OF WATER ADDED/KG MOLTEN PLASTIC OR DEG F/GALLON OF WATER ADDED/LB MOLTEN PLASTIC):

Molten plastic materials having a **polar** molecular structures (Case 3) may dissolve the water before significant vaporization occurs. In this case extinguishment by diluting may dominate where the volatilization temperature of the combined solution is increased sufficiently to prevent further gas emission. This is particularly true if the melting temperature of the plastic is lower than the boiling point of water (100°C). On the other hand, if the melting temperature of the plastic is greater then **100°C,** it is not presently clear whether vaporization cooling, diluting or both are significant factors to be considered. This depends on whether the water vaporizes quicker than it dissolves on hitting the hot liquid or visa versa. Experiments are needed to see which of these phenomena, if any, dominates. The current model assumes dilution dominates (Reference **2).** For this case there may also be a slight fuel splashing effect, but it is assumed to be of lesser magnitude than for the water immiscible molten plastics discussed above. The major extinguishment effect here is assumed to be the dilution of the surface layers of the molten plastic until the gasification temperature of the solution becomes sufficiently high that feedback radiation does not cause further volatile gas emission.

The effect of adding the water to increase the gasification temperature is expressed in terms of an empirical constant β. $\boldsymbol{\beta}$ is the above "Non-Charring Molten Polar Fuel Vaporization Temperature Increase Due to Water." In metric units, $\boldsymbol{\beta}$ is expressed in degrees centigrade per liter of water added for each kilogram of molten plastic material. A review of the literature found no available data for $\boldsymbol{\beta}$ for burning plastics. Experiments appear necessary to establish values of $\boldsymbol{\beta}$ for the plastics of interest.

4.3.6 Simulation Initialization and Termination.

Parameters required to initialize and terminate a simulation run are,

WALL/CEILING TEMPERATURE AT FLASHOVER (DEG C OR DEG F):
GAS TEMPERATURE AT FLASHOVER (DEG C OR DEG F):

WALL/CEILING TEMPERATURE AT FIRE CONTROL (DEG C OR DEG F):
GAS TEMPERATURE AT FIRE CONTROL (DEG C OR DEG F):

One initializes a FDM simulation by specifying the average compartment gas and wall/ceiling temperatures at which flashover is assumed to occur. 'To illustrate, Figure 4.4 shows the effect of initial wall/ceiling and gas temperature conditions of 425°C and 625°C verses 250°C and 350°C on the time temperature plots for the walls/ceiling and gas temperatures. The initial conditions within this range have little impact on the fire temperatures at the time of water application or the failure-control line. Specifying reasonable values is all that is required since the FDM energy and mass balance calculations quickly stabilizes the temperatures to about the same end value.

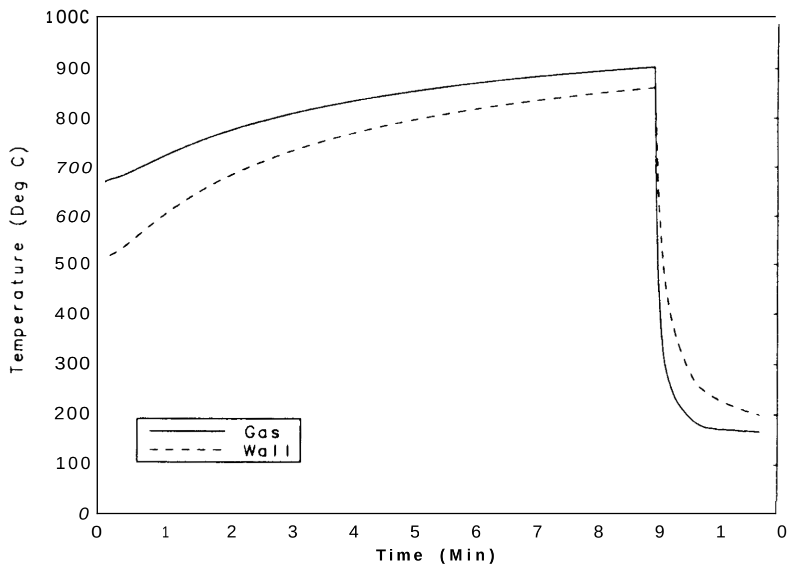
A FDM simulation run is terminated by specifying the gas and wall/ceiling when it is assumed fire control is achieved by water suppression as shown in Figure 4.5. If these criteria are not achieved, the simulation is terminated or burn out of the fuel occurs. What constitutes a reasonable temperature criteria for fire control depends strongly on the firefighter's perception of when fire control occurs. Discussions with firefighter's suggest that from a tactical viewpoint, fire control occurs only when they can begin to advance into an enclosure, even though the actual flames of the fire may have been knocked down earlier. In general, fire fighters will continue to cool the enclosure until that time when they can advance closer and finish off the fire by direct extinguishment. The FDM shows that if the fire-fighter can tolerate a higher temperature, the water flow rates required to achieve fire control are nominal.

4.3.7 Water Application Parameters.

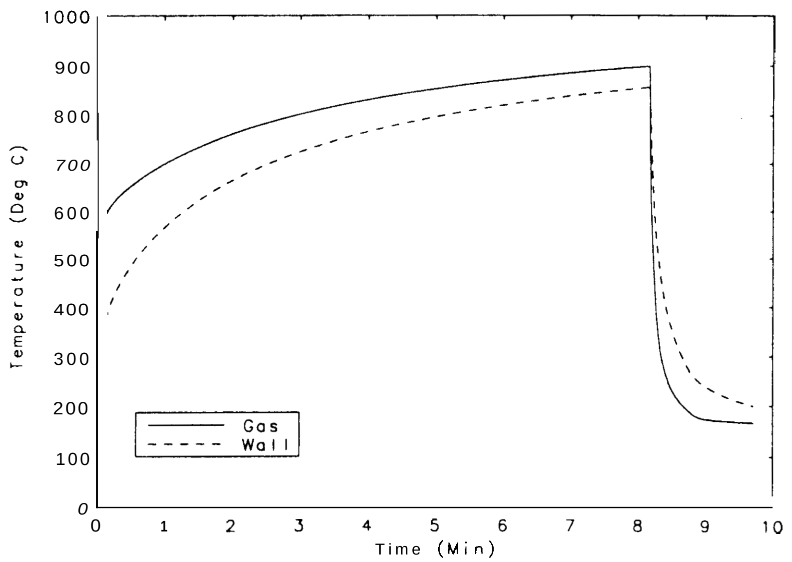
The following two water application parameters are required for a single time-temperature history run of the FDM (Figure 2.2).

WATER APPLICATION RATE (L/MIN OR GAL/MIN):
VOLUME MEDIAN DROP DIAMETER (MILLIMETERS OR INCHES):

The model assumes a Rosin-Rammler (Reference 16) distribution of drop sizes, which may be characterized by the volume-median-drop-diameter, half of the water volume occurs in drops below this size and half above. Figure 4.5 compares the drop size distributions obtained from measurements at BFRL-NIST (Reference 17) against the Rosin-Rammler distribution programmed into the FDM for three water



(a) Initial wall/ceiling temperature = 425°C, gas temperature = **625°C.**



(b) Initial wall/ceiling temperature = 250°C, gas temperature = **350°C.**

Figure 4.4. Time-temperature plots showing sensitivity to initial wall/ceiling and gas temperature with Rate = 36.5ℓ/min, D_m = 0.93mm.

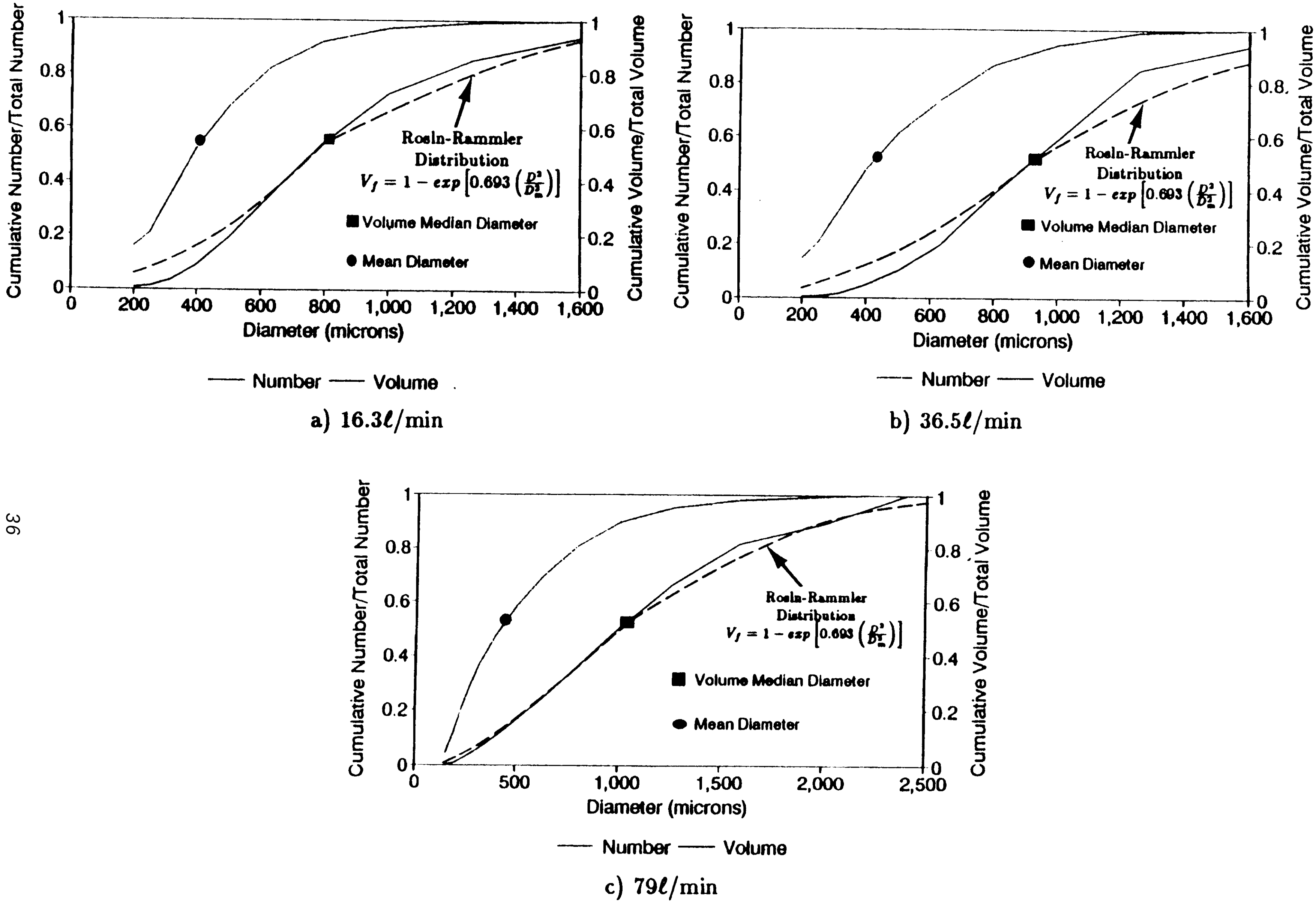


Figure 4.5. Measured verses assumed drop size distribution (Reference 17).

flow rates from a Quadra Fog DQ540 variable flow rate spray nozzle manufactured by KK Products.

When a Fire Control Failure Line Plot (Figure **2.3)** is to be produced, the following parameters are prompted for,

WATER APPLICATION RATE MINIMUM (LPM/M2 OR GPM/FT2):
WATER APPLICATION RATE MAXIMUM (LPM/M2 OR GPM/FT2):
WATER APPLICATION RATE INCREMENT (LPM/M2 OR GPM/FT2):
VOLUME MEDIAN DROP SIZE MINIMUM (MILLIMETERS OR INCHES):
VOLUME MEDIAN DROP SIZE MAXIMUM (MILLIMETERS OR INCHES):
VOLUME MEDIAN DROP SIZE INCREMENT (MILLIMETERS OR INCHES):

With the above inputs, multiple simulation runs off the FDM are automatically executed. The model loops on water rate from the highest water rate specified by the user to the smallest, or to fire control failure - whichever comes first - for a given drop size. This limits the number of steps needed for a particular drop size. Note that if fire control failure occurs at the highest water rate specified, the FDM continues on to the next higher drop size (looping on drop size is from minimum to maximum). If fire control successes have occurred, then the entire process is terminated. This is because fire control failures at lower volume median drop sizes may still have successes at the higher drop sizes of the range input, i.e., once fire control successes stop occurring at a particular water rate, they will continue to fail at higher drop sizes.

The user should also note that the above increments in the water rate and drop size must be chosen carefully. Points that are too dense will cause the model to take a long time to run.

TIME WATER APPLIED (MINUTES):

This is the simulation time after flashover when water is applied. Prior to this time, the fire is burning freely in a post-flashover condition.

NUMBER OF WALL VENT IN WHICH WATER IS APPLIED:

This is the number in the Wall Vents List (described earlier) which identifies the vent. Note that water can only be applied through a single specified wall vent. Application through multiple wall vents and/or a roof vent is currently not possible.

WATER EXPOSED FUEL AREA FRACTION (PERCENT):

This is the estimated fraction (in percent) of the initial fuel surface area input previously which is directly exposed to the water spray. **A** number between 0% and 100% should be input.

References **2** through 6 shows the significant sensitivity of FDM results to the fraction of the burning fuel accessible to direct water impact. In general, if the "Water Exposed Fuel Area Fraction" is high, direct extinguishment of the burning fuel dominates rather than gas and non-burning-surface cooling, or vent choking by steam. Presently, the ***user must estimate*** this fraction. The model does not calculate this fraction nor how it might change **as** a fire fighter is able to gain more accessibility to the burning fuel as the temperatures in the compartment decrease. Currently, this fraction remains constant throughout a given simulation, i.e., one must vary this fraction parametrically to observe its effect.

NOZZLE PRESSURE (KG/CM2 OR LB/IN2)
DISTANCE OF NOZZLE FROM VENT (M OR FT):

The nozzle pressure must be greater than 0. The nozzle distance from the vent effects both the induced air inflow into the compartment and, if the distance is large enough the amount of water entering the vent, i.e., the effective rate entering is decreased if the area of the spray at the vent is larger than the area of the vent into which it is applied (Reference **2).**

FULL CONE ANGLE OF STREAM (DEGREES):
SWEEP TIME OF COVERAGE (SECONDS):

These parameters affect the water spray coverage and cooling of the compartment surface. The cone angle can be between 0" and **360".** The sweep time is the amount of time the hose spray is moved to sweep over the entire interior area of the compartment.

WATER SPLATTERS FROM CEILING (O=NO, 1=YES):

This parameter affects the distance available for droplet vaporization. When the spray is directed to splatters on the ceiling (1), the entire room height is considered for a falling droplet to vaporize otherwise ***half*** of the room height is used.

4.3.8 Run-time Control Parameters.

SIMULATION TIME LIMIT (MINUTES):

This parameter protects against problems in the program code and/or input data which may cause the simulation to run unreasonably long. When the limit is exceeded during a run of the model a message will indicate so. The simulation time limit can not exceed the time specified for closure of the vent in which the water is applied (if any). If the simulation time limit input exceeds this time, the code will prompt the user either to change the vent closure time or to change the simulation time limit.

TIME STEP DIVISOR:

This parameter controls the size of the time step used in the simulation. The simulation internally calculates a time which represents the interval for one complete cycle of gas into and out of the compartment. The time step divisor is divided into this time to obtain the time step for which to advance the history of the fire on the next cycle. It is recommended that a divisor of **10** or higher be used if one desires accurate time temperature histories. On the other hand, the Fire Control Failure line plots can generally be achieved with sufficient accuracy and shorter execution times with a divisor as low as 1. Figure **4.6** shows the effect of divisors of **1,** 10 and 20. Note that the time step divisor has virtually no effect on the failure line curve.

4.4 Execution of PROGRAM FDM.

Once the input parameters have been defined and setup as described in Section **4.3,** the user is returned to the FDM Program Menu to RUN THE PROGRAM (Choice **B** in Figure **4.1).**

On execution, a request for a parameter input file of the case to be run is made identically to the setup mode. The request is prompted as follows,

ENTER INPUT FILE VERSION NUMBER OR NAME:

Entering carriage return only causes a return to the FDM Program Menu (Figure **4.1**), otherwise the input file must be identified by version number or name

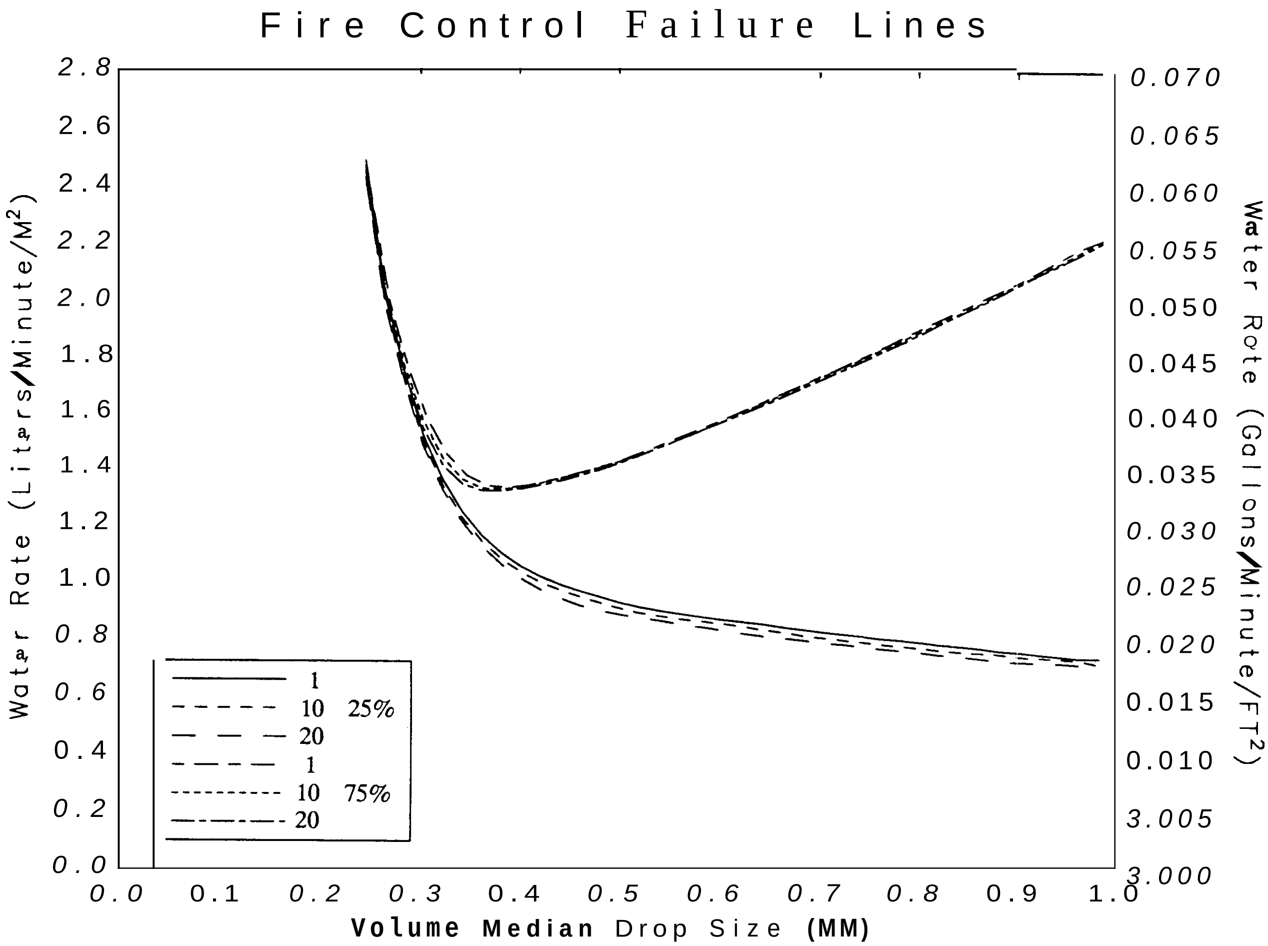


Figure 4.6. **Cross-plots of 6 failure lines for "Time Step Divisor" values 1, 10, and 20 with "Water Exposed Fuel Area Fraction" values of 25% and 75%.**

(see Section **3.2).** If the file is available, it is opened. If it is not found, a message indicates the problem and control returns to the FDM Program Menu.

If the user is running a single time/temperature history working with the tabular results option, on completion of a case, the termination reason. is displayed in the tabulated output results. For example, if fire control has been achieved, the following message occurs:

```
FIRE CONTROL AT      7.5 MINUTES, 34.862% OF FUEL LEFT
          32.6 GALLONS OF WATER APPLIED,      25.0 GALLONS VAPORIZED
   END SIMULATION
```

The complete list of possible termination messages are described in Section **4.5.**

If the user is running a single time/temperature history, then at the end of a simulation the following prompt requests the user for either another case or to stop:

```
REPEAT SIMULATION (Y/N):
```

A 1 causes another case to be run allowing the user to change the water application rate and/or volume median drop size parameters only, using the prompts described earlier (all other compartment and fuel remain the same). If the fire histories are saved in tabular form (Figure **4.3)** the following is displayed as a reminder to print the LOG file.

```
REMEMBER TO PRINT FILE OUTFDM.LOG
```

4.5 Termination Messages for PROGRAM FDM.

The following reviews various output messages associated with termination of a run.

```
*FIRE OUT BEFORE WATER APPLIED*
```

This message could mean one of the following:

- The fuel load is insufficient to sustain the fire before water is applied.

- In the cases of non-charring plastic fuels, the level of thermal radiation reaching the fuel is insufficient to sustain combustion. One should increase the initial gas and wall/ceiling at flashover.
- The choice of initialization temperatures of the compartment surfaces and gases at flashover is too low whatever the fuel type.
- The choice of integration step divisor is too low.
- The choice of the grid interval or segments used in the heat conduction calculations of the compartment surfaces is too low.
- Combinations of the above.

FIRE CONTROL AT _______________ MINUTES, ____________% OF FUEL LEFT ____________ GALLONS OF WATER APPLIED, ____________ GALLONS VAPORIZED

This occurs when fire control is achieved. It indicates the time after flashover when the user input walls/ceiling and gas temperature control criteria are achieved, the percentage of fuel remaining at that time, the cumulative amount of water applied to the fire, and the amount of water vaporized.

EXCEEDED SIMULATION TIME LIMIT = __________

This occurs when the simulation time limit input by the user is exceeded.

PYROLYSIS COMPLETE AT _________ MINUTES

This indicates that time after flashover when the fraction of ***charring*** solid fuels that pyrolyzes has burned away.

BURNOUT AT ____________ MINUTES

This indicates that time after flashover when ***all*** the fuel has burned away.

END SIMULATION

This message indicates the simulation has ended.

UNABLE TO OPEN PARAMETER INPUT FILE

This message occurs when the parameter input file named to contain the data for the case to be run is unable to be accessed. The most likely cause is that the file does not exist.

4.6 PRINTING THE FDM LOG FILE.

If the user has specified the output time-temperature histories in tabular format as illustrated in Figure **4.3** (i.e., OUTPUT FORMATTED TABULAR RESULTS FLAG = 1), after execution of PROGRAM FDM and return to the FDM Program Menu, the command "PRINT FDM LOG FILE" is selected to print these results (see Figure **4.1).** On execution of this command, the log file hard copy output is sent to the DOS printer device name "PRN".

SECTION 5

GENERAL MENU CHOICE 2 -- PLOT TIME/TEMPERATURE HISTORY

5.1 Overview.

This menu choice is used to produce graphical time/temperature histories of FDM simulations. The gas temperature and walls/ceiling temperatures are plotted in degrees Centigrade versa the simulation time in minutes. An example plot is shown in Figure **2.2.** In this example, the solid line represents the gas temperature and the dashed line represents the walls/ceiling temperature. The time/temperature history is traced from the start of the simulation, at fire flashover, to either fire control or burnout.

One time/temperature history plot is produced per each sirnulation case run. Multiple cases (varying the water characteristics only) can also be output to the plot data **file** during an interactive FDM session. When multiple cases exist in the plot data **file,** a separate plot for each case is created automatically.

5.2 Executing the Time/Temperature History Plot Program.

The program begins by displaying a list of valid plot data files from which the user may generate a plot. For example,

```
Time/Temperature History Plot Program:

List of Available Data Files:

     P1_1        P1_2        P1_5
```

The program then prompts the user to enter the name of the data file to be plotted **as** follows:

```
Enter Name of Data File to be Plotted:
```

The user then types the name of the desired plot data file from the list of available files. If the name entered is not on the list of available data files, the following message appears:

Input Name Not On Available Data File List. Please Re-enter.

After displaying this message, the program will re-prompt the user to input another data filename.

5.2.1 Time/Temperature History Plot Program Termination Messages.

The following reviews various messages associated with termination of the time/temperature history plot program.

No Plot Data Files Found

This message occurs when the program cannot locate any valid time/temperature history plot data files. These files are created only when the TIME/TEMP plot option is specified during the **SETUP** sequence for PROGRAM FDM.

SECTION 6

GENERAL MENU CHOICE 3 – – PLOT FIRE CONTROL FAILURE LINE

6.1 Overview.

This menu choice is used to produce a fire control failure line plot as shown in Figure 2.3. The fire control failure line traces the water rate for each drop size where failure to achieve fire control occurs. The axis limits of the plot are determined by the range of drop sizes and water rates chosen for the FDM run.

The reader should note that if fire control failures have occurred at the ***highest*** water rate and ***lowest*** drop sizes before any fire control successes have occurred, the fire control failure line will continue to be plotted since larger drop sizes may result in successes. On the other hand, if failures occur immediately at the highest water rate and drop size specified by the user then the failure line is stopped.

8.2 Executing the Fire Control Failure Line Plot Program.

The program begins by displaying a list of valid plot data files from which the user may generate a plot. For example,

```
Fire Control Failure Line Plot Program:

List of Available Data Files:

     P2-1         P2-2        P2_5
```

The program then prompts the user to enter the name of the data file to be plotted as follows:

```
Enter Name of Data File to be Plotted:
```

The user then types the name of the desired plot data file from the list of available files. If the input filename is not on the list of available plot data files, the following message appears:

Input Name Not On Available Data File List. Please Re-enter.

After displaying this message, the program will re-prompt the user for another data filename.

Before plotting the curve, the program displays the following prompt:

Smooth Data Before Plotting (Y/N)?

Typing "Y" or a carriage return will result in the program smoothing the data points to be plotted using a Gaussian-type filtering algorithm. If the user enters "N", the data will be plotted as is, connected by straight line segments.

6.3 Fire Control Failure Line Plot Program Termination Messages.

The following reviews various messages associated with termination of the fire control failure line plot program.

No Plot Data Files Found

This message occurs when the program cannot locate any valid fire control failure line plot data files. These files are created only when the FAILURE LINE plot option is specified during the SETUP sequence for PROGRAM FDM.

SECTION 7

GENERAL MENU CHOICE 4 -- CROSS-PLOT FIRE CONTROL FAILURE LINES

7.1 Overview.

This menu choice allows for up to *six* fire control failure lines to be cross-plotted from different files on the same plot. Each separate failure line is identical to the plot produced by the Failure Line Plot Program (see Section 6) and identifies the water rate for each drop size where failure to achieve fire control occurs. The fire control temperature criteria are during PROGRAM FDM setup.

A sample cross-plot is shown in Figure 2.4. It shows two failure line curves plotted with two different line types: solid and dashed.

7.2 Executing the Fire Control Failure Line Cross-Plot Program.

The program begins by displaying a list of valid plot data files from which the user may generate a plot. For example,

```
Fire Control Failure Line Cross-Plot Program:

List of Available Data Files:

     P2_1         P2_2        P2_5
```

The program then displays the following menu of choices to create/edit the list of data files to be plotted:

```
Type S to Show Available Plot Data Filenames
     L to List Selected Plot Data Filenames
     A to Add a Plot Data Filename
     D to Delete a Plot Data Filename
     R to Replace a Plot Data Filename
     M to Move a Plot Data Filename
```

Q to Quit Plot Data Filename Definition
Enter Choice:

Selecting the **Show (S)** option causes the program to display the list of available plot data files, as shown above.

Selecting the List **(L)** option causes the program to display the list of data filenames that will be plotted. For example,

Plot Data Filenames Currently Selected:

1. P2_2
2. P2_5

If no data filenames have yet been entered, the following message appears:

No Plot Data Filenames Selected

The **Add (A)** option allows the user to add a filename to the list of data files to be plotted using the following prompt:

Enter Data Filename to be Plotted:

The user would then type the name of the desired plot data file from the list of available files. If the name entered is not on the list of available data files, the following message appears:

Input Name Not On Available Data File List. Please Re-enter.

After displaying this message, the program will re-prompt the user to input another data filename.

The **Replace (R)** option allows the user replace a filename on the list of data files to be plotted with another file from the available data file list. Selecting this option causes the program to prompt the user for the list position number of the file to be replaced as follows:

Enter List Number of File to be Replaced:

The program then prompts for a new plot data filename as described above.

The **Delete (D)** option allows the user to delete a filename from the list of data files to be plotted by selecting the list position number of the desired file.

The **Move** (M) option allows the user to change the order of filenames in the list data files to be plotted by manipulating the list position number of the desired filename. The order of the filenames determines which line type will be used to plot each curve. The first data file on the list will be plotted with a solid line. The other curves will be plotted with dashed lines of various patterns.

The **Quit (Q)** option ends the definition of plot data filenames, optionally saving any changes made.

Before plotting the curves, the program displays the following prompt:

`Smooth Data Before Plotting (Y/N)?`

Typing "Y" or a carriage return will result in the program smoothing the data points to be plotted using a Gaussian-type filtering algorithm. If the user enters "N", the data will be plotted as is, connected by straight line segments.

7.3 Fire Control Failure Line Cross-Plot Program Termination Messages.

The following reviews various messages associated with termination of the fire control failure line cross-plot program.

`No Plot Data Files Found`

This message occurs when the program cannot locate any valid failure line plot data files. These files are created only when the FAILURE LINE plot option is specified during the SETUP sequence for PROGRAM FDM.

SECTION 8

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APPENDIX A

OVERVIEW OF THE FDM AND INTERPRETATION OF RESULTS

A.l Overview.

This Appendix gives a brief overview of the FDM. Details of the physics and software are provided in Reference **2** through 5. Experimental comparisons and recommended future improvements to the model are addressed in Reference 6.

The FDM is designed to relate the suppression effort via a simulation of the fire character to the suppression results (i.e., water requirements for fire control). This is illustrated in Figure **A-1.** Fire Character is determined by building and fuel parameters. The fire fighting equipment (including the fire hose-nozzles) and related systems factors have a strong influence upon all three of the physical inputs shown in the diagram. Consequently, the FDM serves to relate these factors to the final suppression result. Conversely, suppression goals can be translated into system specifications.

Some of the factors (fire ground tactics, training, etc.) determine primarily the time at which suppression efforts (water application) start, and only secondarily affect the other physical inputs of the current FDM. The application time of water subsumes, in a single variable, most of the controllable suppression factors (i.e., logistics of getting the water to the fire) with the exception of those related to the equipment. Reference **1** presents a broad scope system level modeling concept that includes fireground operational considerations. The current FDM is presented as a key sub-model in this system level model.

For fire service applications a fully involved (post-flashover), single compartment fire was chosen **as** the fundamental case, because **(1)** it represents a stressful fire suppression situation, and **(2)** previous investigators (References **19, 20** and **21**) successfully modeled this fire in its freely burning phase (without suppression). In the FDM, the freely burning segment of the fire history follows their methods and calculates the fire development in time in terms of lumped parameters describing the energy and mass balance of the compartment **as** a whole. The FDM adds the effect of water application suppression efforts to this work.

The level of detail of the current FD Model is determined by its practical objectives and the requirements for simplicity and computability. Figures **A-2** and

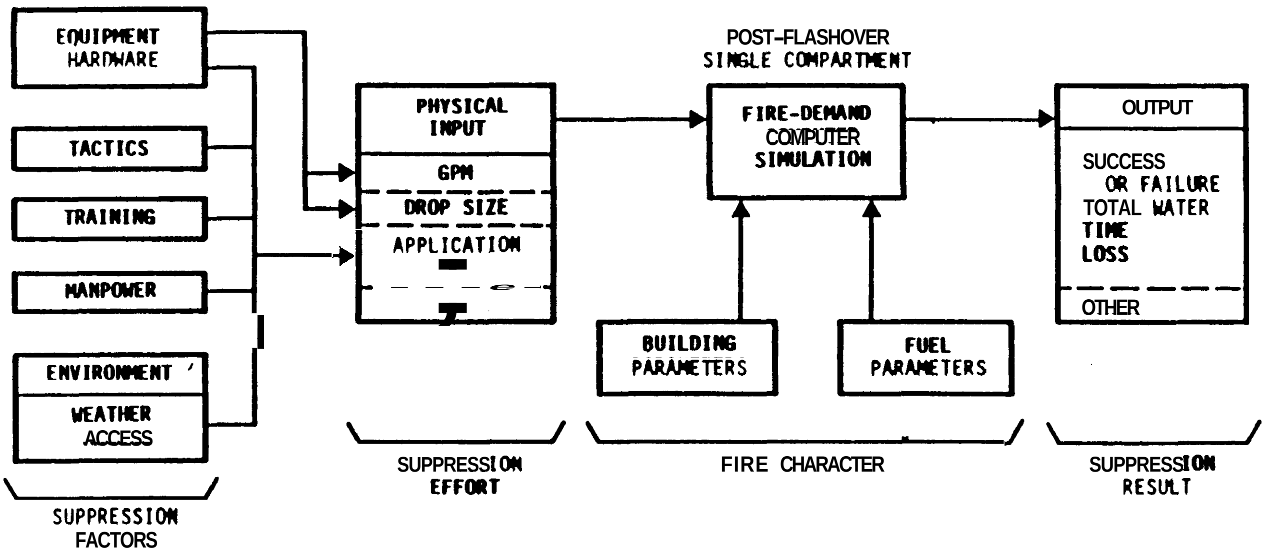

Figure A.1. Scope of the existing Fire Demand Model.

A-3 provide an overview of the physical effects and interactions incorporated in the model (with and without suppression effects, respectively) for fires involving both char forming and non-charring solid fuels. The model is capable of simulating fires in compartments with single or multiple vents of different sizes and in different locations, venting changes with time due to fire fighting activities, and water spray induced air inflow.

In the freely burning period (without suppression effects) (Figure **A-2),** the fire behavior is determined by the room itself (dimensions, size, and shape of the ventilation openings, thickness and composition of bounding walls, etc.) and by fuel features (heat of combustion, weight of fuel, total surface area of fuel, etc.). The fire behavior is described by the average temperature of the room gas, the average temperature of the walls and ceilings, floor temperature, the retained heat in the room, and the burning rate of the fuel. **As** shown in Figure **A-2,** the fundamental basis of the freely burning post-flashover fire model is a mass balance and a heat balance of the gas contained in the compartment. One key operational feature of the FDM is the causal relation (shown by the wavy line) whereby the buoyancy of the hot room gas drives combustion products out of the ventilation opening and draws fresh air in. In turn, for ventilation controlled fires the rate of fresh air entry determines (for this post-flashover case) the combustion rate, which is the major source of heat for the room gas. The model also accounts for fuel controlled and pyrolysis controlled burning and including for non-charring fuels thermal heat transfer effects to the fuel bed.

As noted earlier, the parameters required for description of post-flashover fires can (in most cases) be lumped into a level descriptive of the compartment as a whole. For example, one can assume that the hot gases in the compartment are well stirred and can be represented by a single average temperature representative of the whole compartment.

In the modeling concept shown in Figure **A-2** one starts from conditions at flashover and calculates physical quantities descriptive of the compartment fire at succession of time steps. The alteration of conditions with time is determined by preservation of a mass balance of mass entering and leaving the compartment, and by preservation of a balance of heat transfer rates to the gas of the room.

The mass balance is an accounting of gas entering and leaving the room through ventilation openings and includes sources of mass due to the combustion of fuel. In the freely burning fire without suppression effects, the flow can be assumed to be buoyancy driven through the ventilation openings by the temperature difference

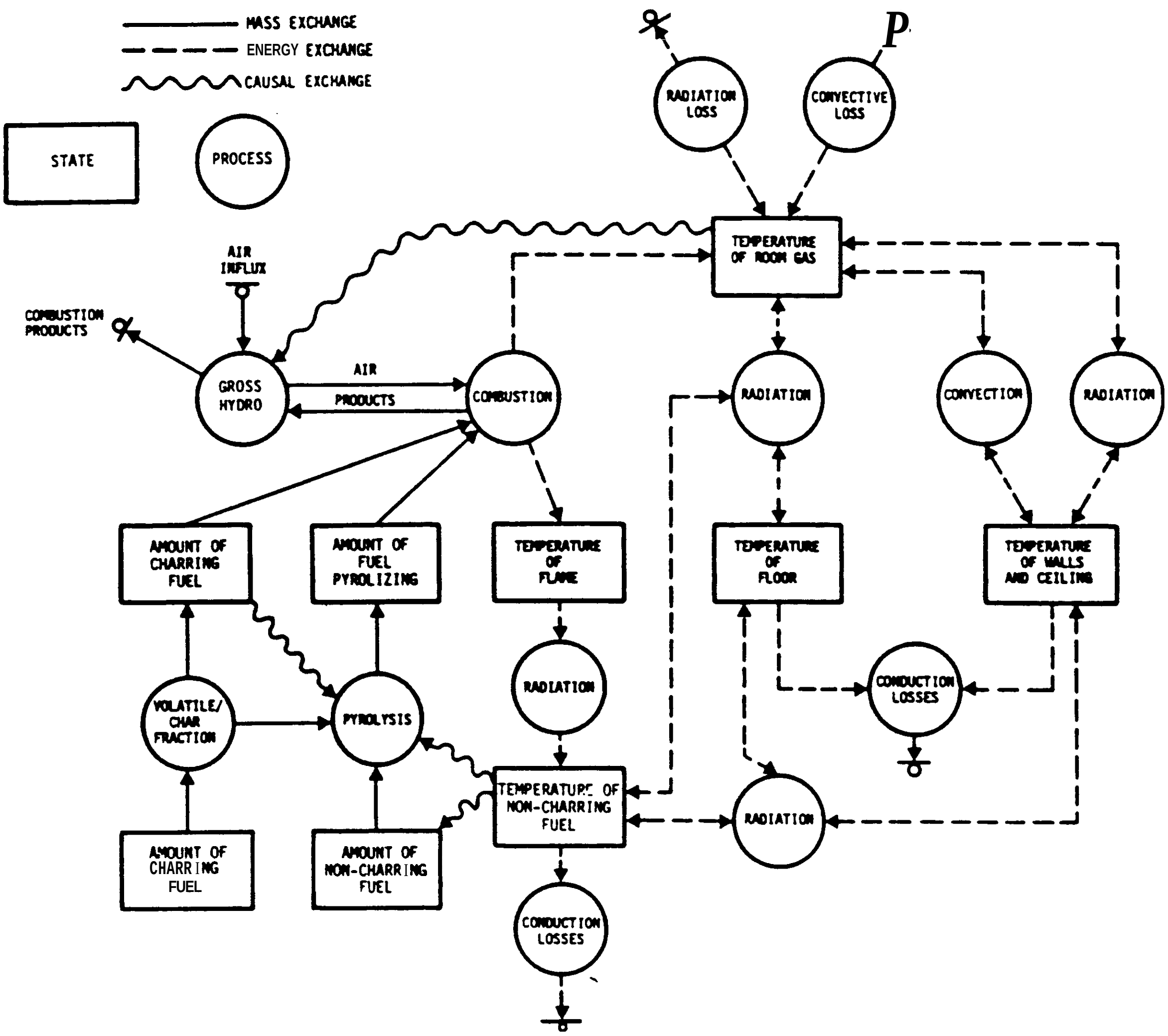

Figure A.2. Fire Demand Model post-flashover compartment fire interactions.

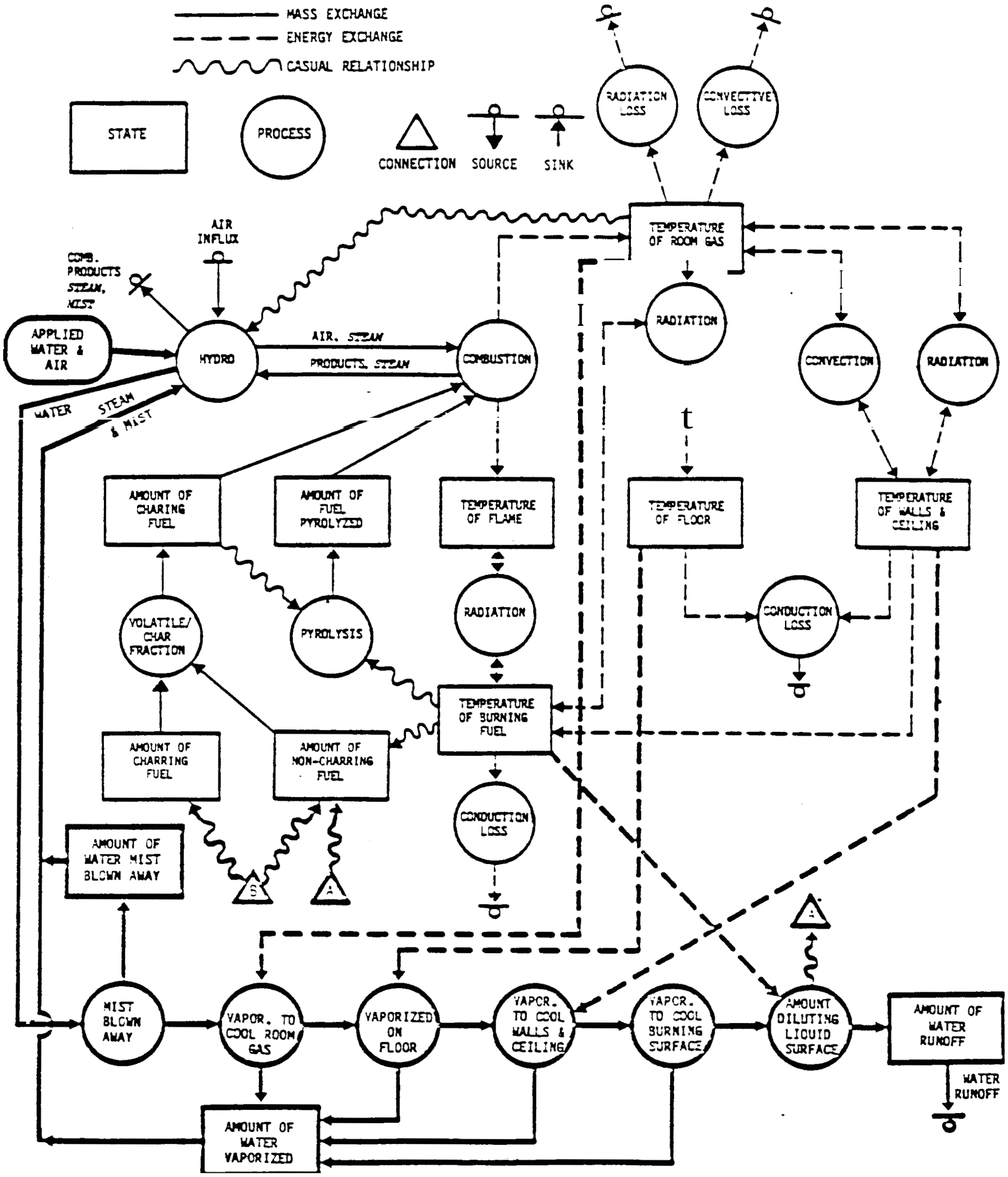

Figure A.3. Interaction of Fire Demand Model for suppression of post-flashaver fires with water spray.

between the hot room gas and the ambient atmosphere. This is the principle upon which the "Hydro" sub-model shown in Figure **A-2** operates.

The heat balance of the room gas accounts for heat sources (burning), heat losses (conduction to walls, convection out vents, etc.), and heat exchange mechanism (radiative, convective, conductive) with the other system components (ambient atmosphere, walls and ceiling, floors). Evaluation of heat transfer between room gas and interior surfaces requires calculation of temperature profiles through the cross-section of the walls and floor.

Heat generation rate by combustion in the compartment depends upon the ventilation (air influx), the fuel area, and the fuel stacking or distribution. The burning may be either fuel controlled, ventilation, or pyrolysis controlled. The current FDM is limited to combustion involving deep-seated char in combination with pyrolyzed vapor burning (e.g., for cellulosic and some thermoset plastic fuels), and non-charring solid fuels involving vapor burning only (e.g, most thermoplastics).

The factor of water application modifies the fire behavior drastically. The cooling of interior gases and interior surfaces by water vaporization, the choking of ventilation by the exit stream, and the direct extinguishment of burning surfaces reachable by water are simulated by the FDM. The FDM also accounts for any additional air from outside being forced into the fire by the induced effects of the water spray. The relative magnitude of these effect determines whether fire control is achieved (with sufficient water) or whether the fire only stabilizes at lower temperatures (with insufficient water). To estimate these effects the FDM requires the specification of the time of water application, the distance of the hose-nozzle from the vent, and water spray characteristics such as: the flow rate, pressure, the distribution and volume-median-diameter of water drops in the spray pattern, the cone angle of the stream, the sweep time required for the stream to cover the interior of the compartment, and the fraction of fuel area accessible to water impact. Apart from the fire conditions–as determined by the compartment and fuel– these are the factors which determine the FDM estimate of suppression effectiveness.

The suppression effects are accounted for using relatively simple submodels consistent with the lumped parameter nature of the overall model. These submodels are based on the overall assumption that on introduction of the water spray into a fully involved fire, the resulting steam expands and mixes rapidly with the compartment gases so that one can continue to represent the processes in terms of lumped parameters characterized by average temperatures and heat fluxes within the compartment.

Central to the estimation of water effects is the apportionment of the water volume into three parts: **(1)** a part which is blown away through failure to penetrate the updrafts in the compartment, **(2)** a part which is vaporized in the compartment gas, and **(3)** the remainder which impacts the fuel and interior surfaces in liquid form. This simplified submodel assumes a water drop of given initial diameter falls and evaporates in a compartment characterized by a uniform temperature and a uniform updraft velocity. The temperature is the gas temperature of the compartment and the updraft velocity is estimated from the room geometry and the air circulation rate in the compartment. The water drop is assumed to fall vertically at terminal velocity (relative to the gas) determine by its instantaneous diameter which changes as the drop falls. For given compartment conditions there are two critical drop diameters: the diameter of a drop whose terminal velocity equals the updraft velocity, and the diameter of a drop which will just reach the floor before its diameter has decreased by evaporation to a size small enough to be swept away by the updraft. Results for single drops are averaged over an assumed drop size distribution to produce a water partitioning as illustrated in Figure **A-4.** The model assumes a Rosin-Rammler (Reference **16)** distribution of drop sizes which may be completely characterized by the volume-median-drop-diameter, half of the water volume occurs in drops below this size and half above. No account is taken of any further breakup of the spray by impact on surfaces. The fraction of water which is vaporized cools the compartment gas. The fraction which reaches the floor is re-interpreted as the fraction which reaches interior surfaces and fuel, and is distributed to them in proportion to wall/ceiling area, floor area, and exposed fuel surface area.

Regarding the cooling of hot, non-burning interior surfaces, account is takes of the fact that only a fraction of these surfaces are instantaneously impacted at any one time by a sweeping water spray of limited cone angle. There is therefore a residence time during which cooling of the surface can occur. In the case of walls the fraction vaporized there and the fraction which runs off is estimated. In estimating surface cooling the impacting water spray is assumed to coalesce into a thin sheet over the impacted surface. The average rate of heat extraction is then calculated as the limiting value obtained by either the amount of water available or by conduction from the interior. If conduction limits, surface temperature under hose impact is assumed to equal 100°C and the vaporized and runoff water fraction is calculated based on this. If the available water is limiting all the water is assumed to vaporized and the surface temperature is calculated accounting for the cooling effect of this water and the residence time of the hose stream. For the water reaching and standing on the floor, another limiting condition accounted for is the heat transfer possible by boiling.

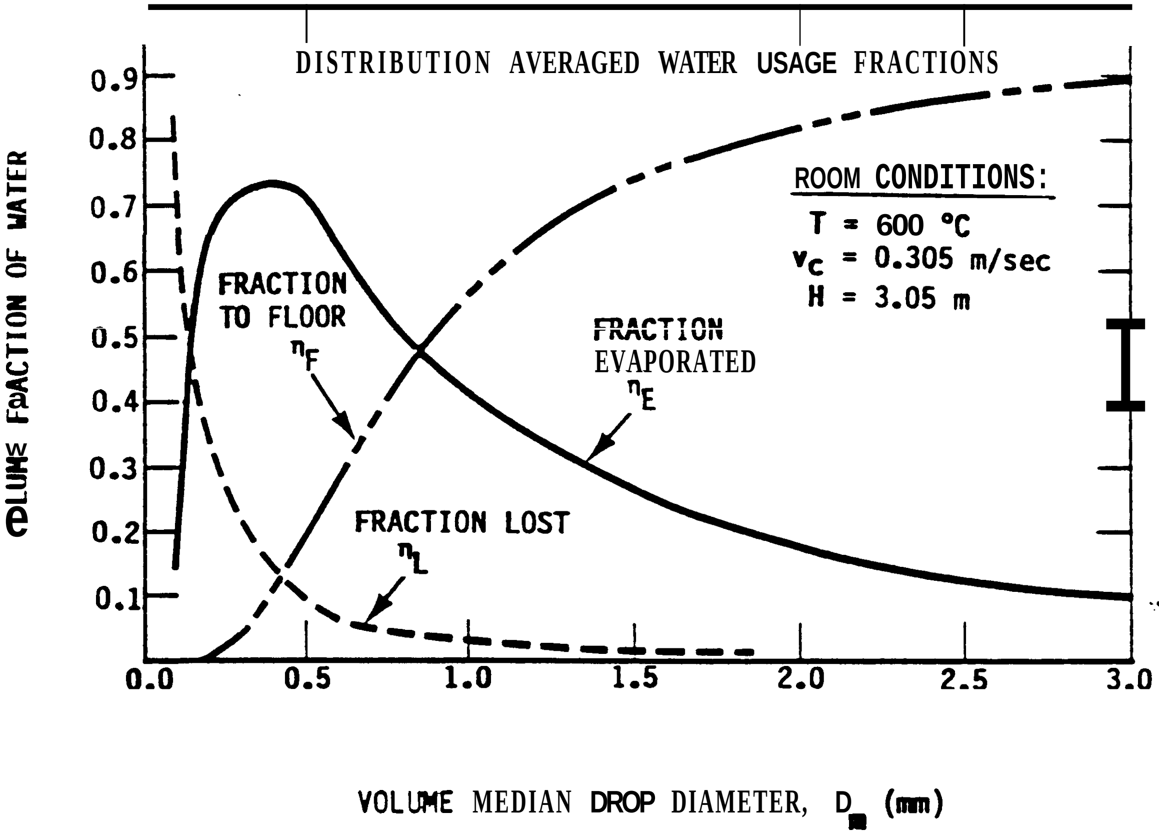

Figure A.4. Volume fraction of water versus drop diameter.

The fraction of the total burning fuel surface area accessible to water impact may also vaporize liquid water and thereby reduce the rate of heat generation. Extinguishment of this fuel area occurs by different criteria depending upon the type of fuel. For charring cellulosic or plastic fuels, extinguishment is assumed to occur when the rate of heat extraction by water vaporization exceeds the heat generation rate by charring combustion alone.

For non-charring fuels, the extinguishment submodel follows the conditions examined experimentally by Magee and Reitz (Reference 15) wherein critical water application rates were measured as a function of incident radiation. The model assumes that for post-flashover conditions, radiation from the fire plumes, hot surfaces and gases in the compartment control the rate of fuel pyrolysis or vaporization even as a portion of the fuel is directly extinguished by the water. The critical water application rate is therefore taken to be that required to counter the heat received by radiation, i.e., extinguishment is assumed to occur when the rate of heat extraction by water vaporization exceeds the net heating rate to the exposed fuel by radiation[1].

The rate of heat extraction is calculated for the following two cases: For non-charring fuel surfaces burning in a rigid or softened state, the impacting water spray is assumed to coalesce into a thin sheet and to act as a thermal radiation barrier from above and a coolant that cools the hot fuel from below. For surfaces burning in a molten or liquid state the impacting water is assumed to penetrate the surface and cool the fuel from within. Empirical data from Reference 15 is used to account for possible burning rate enhancement due to splashing of droplets on impact and/or bubbling of the vaporizing water from within.

A.2 Interpretation or FDM Output Results.

FDM results and principal sensitivities can be presented in terms of graphs that relate water application rate per unit total interior area of the room to the volume-median-drop-diameter of the water spray. For example, for the room and fuel conditions listed in Table 4.2, simulation predictions of total water requirements are given in Figure A.5.

The "control-failure" line appearing in Figure A.5 divides the graph into two regions characterized by combinations of water delivery rate and volume median drop diameter which are successful or unsuccessful in controlling the fire. The significance of these two regions is illustrated in Figure A.6, which displays the simulated temperature history of a fire suppressed by water spray having the same volume median drop diameter of 0.4mm but two different flow rates: $1.0\,l/\mathrm{minute}/\mathrm{m}^2$ and $1.6\,l/\mathrm{minute}/\mathrm{m}^2$, respectively. The gas temperature is shown by a solid line and the temperature of the wall and ceiling surface is shown by a dashed line. The fire burns freely for 8.18 minutes. Subsequent to this free burning period the water is applied at two different rates. An application rate of $1.0\,l/\mathrm{minute}/\mathrm{m}^2$ (Figure A.6a) produces a temperature drop but the average gas temperature eventually stabilizes at about 330°C and the fire continues until burnout of the available fuel[2]. By contrast, an application rate

[1]For the case of suppression of small fires consisting of a single fire plume or multiple but non-interacting plumes, convection or conduction from the local plume rather than radiation can dominate. In Reference 18, Rasbash calculates the critical rate at which a water spray abstracts heat from liquid fuels at the surface to reduce the vaporization below fire sustaining levels

[2]The sudden increase in the temperatures observed in Figure A.6a at about 14 minutes is explained by an analysis of the heat and mass balance calculation results from the FDM as a function of time (see Reference 6). The FDM shows that at lower values of the water exposed fuel fraction, the effect

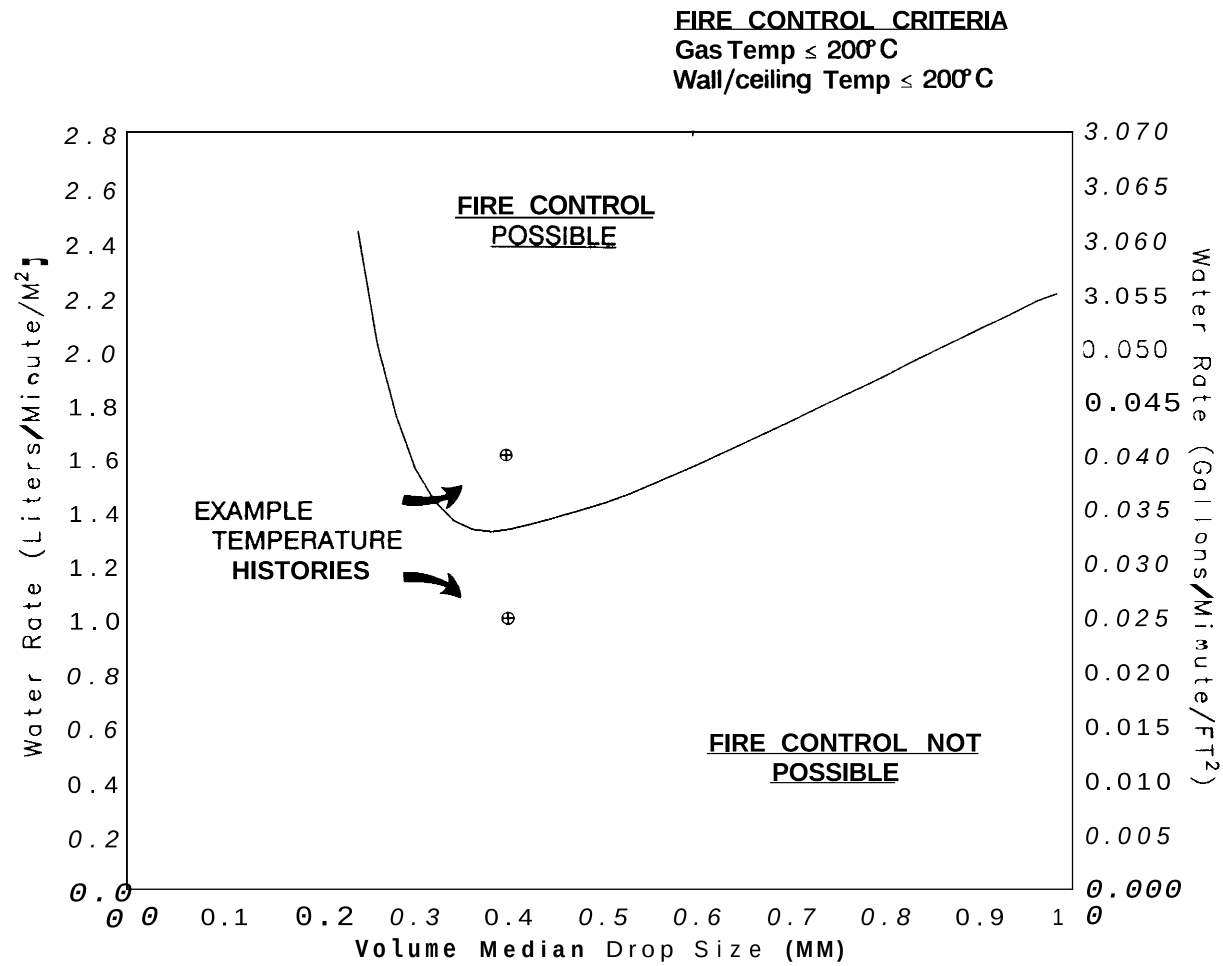

Figure A.5. **Example failure line plot for 25% water extinguishable fuel fraction.**

of 1.6 l/minute/m^2 (Figure A.6b) reduces the average gas temperature below 200°C and the wall/ceiling temperature below 200°C and fire control is achieved at about 1.6 minutes after water is applied. The gas and surface temperatures, which the FDM employs as fire control criteria, are arbitrarily selected and results are sensitive to them.

Referring again to Figure A.5, note that as the volume-median-drop-diameters increase from about 0.2mm to 1mm, the bounding control-failure line first slopes downward, achieving a minimum at about 0.35mm, to drop size of fires controlled primarily by gaseous and non-burning surface cooling as well as vent choking mechanisms. For the example shown in Figure A.5, this means a significant fraction of the drops with sized less that 0.35mm are blown away by hot gases and are not effective in achieving fire control. On the other hand, droplets greater than 0.35mm result in a significant fraction that fail to fully vaporize and, therefore, contribute to water runoff. In each case water is wasted and, because of this, the total water application rates required for fire control increases.

The shape of the line defining the control-failure region is also sensitive to the exposed fraction of the burning fuel area accessible to direct water impact. If the "exposed fuel fraction" is high, direct extinguishment rather than gaseous/non-burning-surface cooling and vent choking may dominate. For this cast the FDM indicates (see Figure 2-4) that the critical water application rate required for fire control is similar to the lower drop sizes but after a certain point decreases as the drop sizes increase. Clearly, the results are strongly sensitive to the fraction of fuel area which is reachable by water. Fire control occurs by different mechanisms in the two cases. If little or no fuel can be directly extinguished, control must occur by the cooling of compartment gases and surfaces, and vent choking. The cooling and choking mechanisms, which are very sensitive functions of drop size, produces the minimum of the curve at an optimum drop size (i.e., 0.35mm at 25% water exposed fuel fraction in Figure 2-4). By contrast, when a large fraction of the burning fuel area is accessible to direct water impact, the critical water application rate for fire control continues to decrease as drop size increases (see the 75% water exposed fuel fraction line in Figure 2.4).

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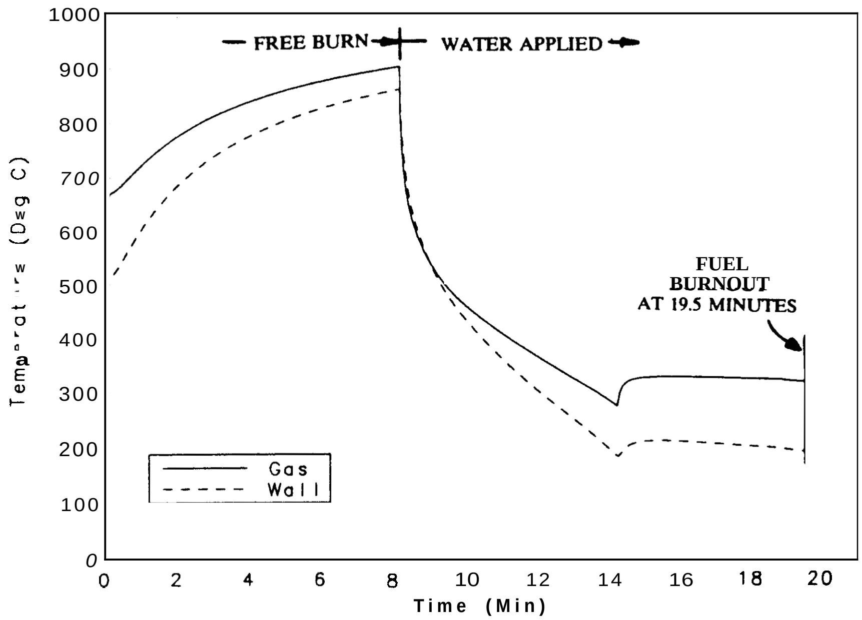
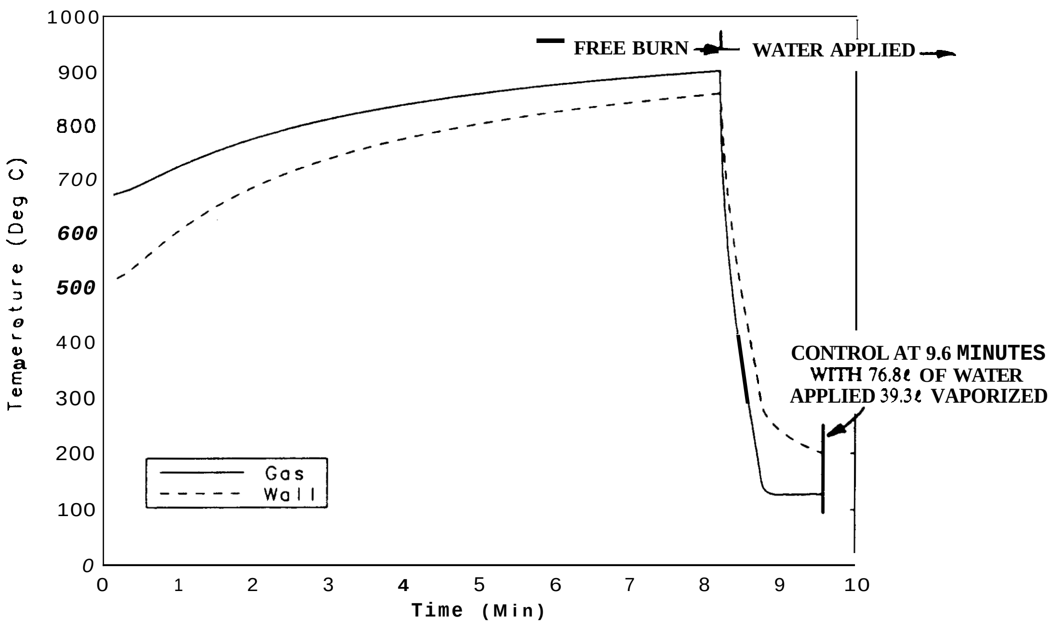
of adding water into the compartment can actually *increase* the amount of fresh air entering the compartment causing an increase in the burning rate of the remaining fuel. This is a consequence of the air entrained in the water spray as well as the decreasing rate of steam flowing out of the compartment as the gas/surface temperatures decrease or extinguishment of portions of the fuel occur. As the rate of outgoing steam decreases, a higher mass rate of inflowing air occurs. Reference 6 shows that for 50% and 75% water exposed fuel fractions, the effect of extinguishing significant portions of the fuel lessens the effect of the increase in air inflow on the burning rate. For these cases, the gas temperatures continue to decrease with time.



(a) Fire control not achieved with 1.0 l/minute/m^2.



(b) Fire control achieved with 1.6 l/minute/m^2.

Figure A.6. Temperature histories for 0.4mm volume medium drop diameter–Fire control criteria: wall/ceiling temperature = 200°C; gas temperature = 200°C.

For large exposed burning fuel fractions, fire control is effected by a decrease of heat production rate consequent to extinguishment of burning surfaces. The larger drops become more effective since they penetrate better, lose less of their volume by evaporation, and carry more water to the burning surfaces. This means that if the seat of the fore is directly accessible, in order to minimize water usage, extinguishment may be preferred to gaseous/non- burning surface cooling and vent choking. On the other hand, because of standoff requirements direct access is not always possible in post-flashover fire situations.

Finally, although Figures **A.5** and **A.6** are used to illustrate typical FDM results for the specific compartment ventilation and fuel conditions given in Table **4.2,** the model can used to examine the sensitivities of a range of fire conditions (see References **2** through 6).

NIST-114A
(REV. 3-90)

U.S. DEPARTMENT OF COMMERCE
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

BIBLIOGRAPHIC DATA SHEET

1. PUBLICATION OR REPORT NUMBER
NIST-GCR-92-612

2. PERFORMING ORGANIZATION REPORT NUMBER

3. PUBLICATION DATE
July 1992

6. PERFORMING ORGANIZATION (IF JOINT OR OTHER THAN NIST, SEE INSTRUCTIONS)

Mission Research Corporation
735 State St., P.O. Drawer 719
Santa Barbara, CA 93102

7. CONTRACT/GRANT NUMBER
NIST Grant 60NANBOD1050

8. TYPE OF REPORT AND PERIOD COVERED
Final April 1992

U.S. Department of Commerce
National Institute of Standards and Technology
Gaithersburg, MD 20899

10. SUPPLEMENTARY NOTES

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

The Swedish Fire Research Board and the U.S. Federal Emergency Management Agency, with the cooperation of the U.S. National Institute of Science and Technology, supported the development of a computerized Fire Demand Model (FDM). The FDM simulates the suppression of post-flashover charring and non-charring solid fuel fires in compartments using water sprays from portable hose-nozzle equipment used by fire departments. The output of the FDM shows the extinguishing effects of water sprays at various flow rates and droplet sizes. The calculations are based on a heat and mass balance accounting for gas and surface cooling, steam-induced smothering, direct extinguishment of the fuel and water spray induced air inflow and venting of heat and products of combustion. This document provides instruction on how to execute the FDM on a Personal Computer (PC). This includes a description of the required input parameters and instructions for producing three different types of graphical plots: (1) time-temperature histories, (2) volume-medium-drop-size verses water application rate defining combinations where fire control is and is not possible, and (3) cross plots to facilitate comparison between different cases.

12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)

13. AVAILABILITY

X	UNLIMITED
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	ORDER FROM SUPERINTENDENT OF DOCUMENTS, U.S. GOVERNMENT PRINTING OFFICE, WASHINGTON, DC 20402.
X	ORDER FROM NATIONAL TECHNICAL INFORMATION SERVICE (NTIS), SPRINGFIELD, VA 22161.

14. NUMBER OF PRINTED PAGES
79

15. PRICE
A05

NIST-114A
(REV. 3-90)

U.S. DEPARTMENT OF COMMERCE
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

BIBLIOGRAPHIC DATA SHEET

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NIST-GCR-92-612

2. PERFORMING ORGANIZATION REPORT NUMBER

3. PUBLICATION DATE
July 1992

the Suppression of Post-Flashover Compartment Fires

5. AUTHOR(S)
L.M. Pietrzak and J.J. Dale

6. PERFORMING ORGANIZATION (IF JOINT OR OTHER THAN NIST, SEE INSTRUCTIONS)
Mission Research Corporation
735 State St., P.O. Drawer 719
Santa Barbara, CA 93102

7. CONTRACT/GRANT NUMBER
NIST Grant 60NANB0D1050

8. TYPE OF REPORT AND PERIOD COVERED
Final April 1992

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (STREET, CITY, STATE, ZIP)
U.S. Department of Commerce
National Institute of Standards and Technology
Gaithersburg, MD 20899

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