A SCIENTIFIC ANALYSIS OF STORED PLASTIC FIRE TESTS

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ABSTRACT

An analysis is made of freeburn and sprinklered Plastic Storage Tests conducted at Factory Mutual Research Corporation (FMRC) from 1970 to 1979. The analysis includes: 1) the freeburn fire growth rates dependent on plastic commodity and storage arrangement; 2) the temperature histories in the freeburn fires; 3) the response time of the first sprinkler operation in the sprinklered operation in the sprinklered tests; and 4) the number of sprinklers (and, therefore, indirectly the fire severity) activated as a function of the growth rate and the maximum burning rate measured in freeburn tests. Fire growth rates depend on the overall geometry of the array, on the arrangement and the volume occupied by the plastic commodities inside the cardboard boxes. Temperature histories near the ceiling are correlated using relations applicable for unsteady fires. The sprinkler response time can be predicted by a simple expression of the heating history of a sprinkler fusing element in a growing fire. Based on the experimental results, it is suggested that the number of sprinklers activated in the sprinklered tests depends on a characteristic growth time of the freeburn fire growth and on the heat release rate at the moment of first sprinkler activation. Freeburn tests are not sufficient in general to classify the hazard which a commodity and storage arrangement will present to a specific sprinkler protection. An additional parameter required for classification is the time characteristic for fire extinction or control, which depends on the sprinklers and the geometry and contents of the stored plastic configuration.

1. INTRODUCTION

This report presents an analysis of two series of Stored Plastic Fire Tests performed in 1970-1974 and in 1978-1979 at Factory Mutual Research Corporation. For each series of tests, the analysis includes: 1) burning rates; 2) temperature rise histories; 3) first sprinkler activation times; and 4) number of sprinklers activated. Because the two series have differ-

ent geometries, the analysis of each series is presented separately within each section of the report. The two series of tests are compared at the end of each section. Since reference to the two series is frequent in the text, the following abbreviations are used: 1) for tests performed in 1970-1974: SST74 (small-Scale Tests, 1974); 2) for the tests performed in 1978-1979: IST79 (Intermediate-Scale Tests, 1979).

The following brief description is given of each test series.

1.1 Small-scale tests 1974 (SST74)

In 1979 an extensive program to evaluate the fire hazard of plastic storage stacks was initiated at Factory Mutual Research Corporation (FMRC). The necessity for this investigation arose from the increasing use of plastic materials in the construction of several commodities and industrial items. A detailed description of the fire tests including selection of plastic commodities, storage arrangement and measurements was presented in Ref 1.

The Stored Plastic Program consisted of three different series of tests ⁽¹⁾: laboratory-scale, small-scale, and full-scale tests. Only the small-scale tests (SST74) are analyzed in this report.

In the SST74 program a fixed overall storage geometry was selected and the burning characteristics of the plastic commodities (i.e., burning rate, temperature history at various positions and sprinkler responses) were measured. The test site was the Factory Mutual Test Center in Rhode Island.

Normally, the small-scale test array (see Figure 1) consisted of four stacks each containing three pallet loads of material usually packaged in corrugated paper cartons. The stacks were butted together in one direction and separated in the other by 6 in. and covered an area of approximately 8 ft x 8 1/2 ft. Stack heights among tests ranged from 13-16 ft; the majority were about 15 ft. The fuel array was placed on a weighing platform so that a continuous record of weight loss could be obtained as the fire progressed. A pair of tests was run for each commodity: one free-burn (60-ft site); and one sprinklered (30-ft

Fig. 1 Small-scale test array showing typical setup within portable caging and resting on load cells located in a water bath.

site). The purpose of the sprinklered tests was to rank the relative fire hazard of commodities subjected to identical protection (i.e., 280° F rated, 1/2-in. orifice ceiling sprinklers, located on 80 ft² spacing, and controlled to discharge at a 0.45 gpm/ft² density).

Ignition was accomplished by a single 3-in. diameter by 6-in. long cellucotton roll soaked in 8 oz of gasoline, placed in a plastic bag and located in the center of the 6-in. space at the top of the first pallet (about 6 in. up from the floor). The igniter bridged the 6-in. space between the stacks. Recorders were centralized in the control room and yielded chart records for each measuring device, except for the weighing platform recorder which was operated independently in a remote location. At the start of a test, all recorders were actuated simultaneously. Prior to each test a relative humidity measurement was taken at the test site; outside wind speed and direction were noted; and a sample of a carton was taken, which subsequently was checked for moisture content. All windows and doors of

the test building were closed. Movies, slides and photographs were taken of the fire's progress. At the conclusion of the test a damage assessment was made. For all practical purposes the only parameter that changed from test to test was the commodity.

1.2 Intermediate-scale tests 1979 (IST79)

A series of intermediate-scale stored plastic tests was conducted in 1978-1979 ⁽²⁾. The overall objective of the project ⁽²⁾ was to unify the method of assessing and classifying the fire hazards of products, commodities, and storage arrangements. A detailed description of the tests is presented in Ref 2.

In the IST79 program, the same storage geometry was selected for all tests and measurements were made of burning rates, temperatures, and sprinkler response. Figure 2

Fig. 2 Test set-up in intermediate-scale tests, 1979
(taken from ref. 2)

shows the storage arrangement. The test commodity was arranged on eight wood pallets in a 2 x 2 x 2 rack segment; 6-in. wide vertical flue spaces separated the pallet loads. Overall dimensions of the rack were 8 ft x 8 ft x 10 ft high. The entire rack was placed on a load cell system.

Three types of tests were included in the program: 1) intermediate rack freeburn tests; 2) intermediate rack sprinklered tests; and 3) intermediate rack "drip" tests.

In the freeburn tests no protection was provided; in the sprinklered tests, automatic sprinklers provided the protection; in the drip tests, protection was obtained at selected times after ignition by a special water nozzle 56 in. above the top of the array.

1.3 Remarks and objective of the present work

The storage arrangements in Figures 1 and 2 have geometric differences which significantly affect their burning behavior. In the SST74 (Figure 1), there is one more pallet load than in IST79 (Figure 2). There is only one 6-in. wide vertical flue space in the SST74 (Figure 1), whereas there are two 6-in. wide vertical flue spaces in IST79 (Figure 2). Finally, the plastic loads in SST74 (Figure 1) are palletized while the plastic loads in IST79 (Figure 2) are rack stored.

The objective of the present program is to investigate how freeburn test results can be used to predict the water demand in corresponding sprinklered tests of the same fuel and the same fuel storage arrangement. Freeburn growth rates (presented in Section II) and temperature histories (in Section III) are used to predict sprinkler response times (Section 4.1) and the number of sprinklers acti-

vated (Section 4.2). It is shown from the experimental results of both series of tests (SST74 and IST79) that the number of sprinklers activated depends essentially on: 1) the burning growth rate at the moment of sprinkler activation, 2) the time of sprinkler activation, or more exactly the heat release rate at the moment of first sprinkler activation, and 3) the time characteristic of extinction or control of the fire.

2. FIRE GROWTH RATES

2.1 Fire growth in small-scale test (SST74)

The storage arrangement used in small-scale tests is illustrated in Figure 1. The plastic items used in the tests were usually contained inside cartons, with the exception of meat trays and insulation boards. The items inside the cartons were either loosely packed or individually separated from one another by horizontal and vertical cardboard dividers. Figure 3 presents a sketch of the storage arrangements of the plastic commodities in each pallet load for different tests. Each part of the figure represents a horizontal cross section of a portion of the small-scale fuel array. Figure 3-a represents plastic items (denoted by circles) loosely packed*. Figure 3-b shows plastic items (denoted by circles) separated from one another by horizontal (not shown) and vertical dividers (compartmented cartons). Figure 3-c shows a solid insulation plastic board.

The propagation of a flame front through each of the storage arrangements shown in Figure 3 is expected to vary significantly; in

addition, growth rates are expected to depend not only on the plastic commodity but probably also on the storage arrangement inside the cardboard boxes.

2.1.1 Burning Mode

From written descriptions (Dean⁽¹⁾) of the fire tests and visual observations, by the author, two modes of fire involvement of the plastic material in the small-scale tests have been noticed.

In most of the freeburn tests the flames spread fast (after ignition) vertically up to the plastic storage array. Horizontal flame spread along the 6-in. space separating the stacks was observed to occur simultaneously with vertical spread. The flames reached the open ends of the 6-in. space first at the top pallet load and subsequently at the next lower pallet load. It is surmised from observations that only the cardboard of the boxes containing the plastic was involved in fire during the flame spread along the walls of the 6-in. space.

The flames, after reaching the open ends of the 6-in. space, spread through the top pallet load. Much of the air required for flame propagation in the pallet load was supplied from the openings of the wooden pallet separating the second from the third (upper) pallet load. A similar flame propagation pattern was observed at the second pallet load after the flames reached the open ends of the 6-in. space at the second pallet level. The first (base) pallet load was not yet involved in fire.

Collapse of the third and/or the second pallet loads during their involvement in fire was observed in several tests. This phenomenon was more pronounced for the tests (Tests

* including items packed in non-compartmented cartons, and meat trays

Fig. 3 Horizontal cross section of a portion of the storage arrangements in small-scale tests

5, 7, 22, 43, 44)* in which the plastic commodities were loosely arranged inside the corrugated paper boxes (see Figure 3a). The collapse of the pallet loads toward the center of the fire resulted generally in temporary decrease in fire intensity. The intensity of the fire, before collapse occurred, varied with the plastic material and storage arrangement of the commodities inside the cardboard boxes. Fire growth rates for all the freeburn tests are presented in Section 2.2.

In the other mode of fire development, involving commodities not stored in corrugated paper cartons (Tests 25 and 35 of Ref 1), the flames from the ignition source failed to propagate upward in the 6-in. space. Instead they lingered (for approximately 5 min in contrast to the approximate 1 min required for plastic involvement in fire for the first mode) at the level of the first pallet load. Melting of plastic material was observed during this period. The melting material was dripping (flowing slowly) on the weighing platform. It is believed that heat from the ignition source contributed to the melting of the plastic material, which was continuously removed by gravitational forces and dripped onto the weighing platform. The growth rate after ignition of the plastic was extremely fast owing to 1) the long preheating period, and 2) the formation of additional ignition sources originating from the molten plastic on the weighing platform.

* A table of all the test is included in Dean's⁽¹⁾ report.

2.1.2 Fire Growth Rates (SST74 Tests)

The weight loss was recorded on strip chart recorders. Plotting of the data in this section for SST74 tests has been done by means of a different method than the method used in analyzing the data in Section 2.2.1. (for IST79 tests) wherein the newly installed data acquisition system was used to collect the data. Figures 4 to 11 present weight loss measurements characteristic of the different growth rates observed in the small-scale freeburn test. In these figures, a log-log plot presents the cumulative weight loss versus the time from the moment of ignition. Figures 4 and 5 include the growth rates of cartons with metal liners (Test 14)* and compartmented cartons (Test 41) without any plastic commodity

From these figures and the weight loss measurements from the other freeburn tests, the following general conclusions can be drawn:

1) The weight loss history for the empty cartons and the plastic commodity stored in compartmented cartons can be represented during the fire growth period by the approximate equation (Figures 4, 5, 6):

$$\Delta m \propto t^2 \quad (1)$$

2) The weight loss history for the loosely packed plastic commodities (including the meat trays) can be represented by one or the other of the following relationships (Figure 7 and 8)

$$\Delta m \propto t^2 \quad (2)$$

or

$$\Delta m \propto t^3 \quad (3)$$

3) Two different growth rates have been observed for the flat insulation boards (Figures 9 and 10). For the polyurethane boards (Test 34, Figure 10) the burning rate becomes constant in about 1 min after ignition. For the polystyrene boards (Test 35, Figure 9), a prolonged preheating period (approximately 5 min) is observed, during which melting of the polystyrene occurs. Subsequently an extremely fast growth rate is observed.

4) Behavior similar to that in Test 35 was observed in Test 25 (Figure 11), in which melting near the ignition source occurred for a prolonged period of time (approximately 5 min).

Fig. 4 Weight loss history (Test 14)

* Test 14 involved a commodity (double triwall cardboard cartons with sheet metal liners) developed for and extensively used in the Rack Storage Program (Rack Storage Fire Protection Committee-Interim Report-4th Draft, December 17, 1969).

Fig. 5 Weight loss history (Test 14)

Fig. 6 Weight loss history (Test 19)

Fig. 7 Weight loss history (Test 23)

Fig. 8 Weight loss history (Test 30A)

Fig. 9 Weight loss history (Test 35)

Fig. 11 Weight loss history (Test 25)

Fig. 10 Weight loss history (Test 34)

Table 1 presents the weight loss histories (approximated by a power law function of time) of all the small-scale freeburn tests. The table also includes the estimated volume fraction and the percentage in weight of plastic and cardboard in each test*.

The growth rates in the small-scale freeburn tests depend on several variables. It is very difficult to assess the importance of these variables on the observed burning rates during the fire growth period. However, a simplified fire growth model in an open "porous" fuel assembly, presented in Appendix A (pertaining to all tests except Nos. 25, 34 and 35), can be of some help in understanding the most important parameters which affect the growth rates. It can be concluded from the analysis in Appendix A that

* Additional information (related to discussion in subsequent chapters) such as maximum heat release rate (HRR), time of first sprinkler operation, heat release rate at first sprinkler operation and sprinkler rings actuated, is also included in Table 1.

Table 1 Growth rates in small-scale freeburn tests

Commodity Description	Volume Fraction of Fuel (ϕ) (%)	Weight Percentage of Plastic and Cardboard	Approximate ($\pm 20\%$) Weight Loss History (1) t : in min	Maximum HRR* (Btu/min)	Time of 1st Sprinkler Operation (min)	HRR*(2) at 1st Sprinkler Operation (Btu/min)	Sprinkler Rings** Opened	No. of Sprinklers
A. Commodities in compartmented cartons								
Test 4, jars, polystyrene 16 oz in compartment cartons	15	75% plastic 25% cardboard	$\Delta m = 15 t^2$	$7.06 \cdot 10^6$	1.82	$8.75 \cdot 10^5$	1 + 3	13
Test 6 bottles PVC, 32 oz in compartmented cartons	16.4	50.3% plastic 49.7% cardboard	$\Delta m = 14 t^2$	$2.38 \cdot 10^6$	1.68	$6.07 \cdot 10^5$	1	4
Test 15, bottles 16 oz polyethylene, in compartmented cartons	20	57% plastic 43% cardboard	$\Delta m = 8 t^2$	$2.58 \cdot 10^6$	1.68	$4.03 \cdot 10^5$	1 + 3	13
Test 19, tubes, polypropylene, 16 oz in compartmented cartons	15	53% plastic 47% cardboard	$\Delta m = 8.5 t^2$	$3.26 \cdot 10^6$	2.25	$5.51 \cdot 10^5$	1 + 3	12
Test 41, cardboard boxes compartmented without any plastic commodity	13	100% cardboard	$\Delta m = 17.5 t^2$	$1.41 \cdot 10^6$	1.6	$4.48 \cdot 10^5$	1	4
B. Commodities loosely packed (including meat trays)								
Test 30A, toy parts, polystyrene	14	91% plastic	$\Delta m = 7 t^2$	$2.19 \cdot 10^6$	3.43	$7.94 \cdot 10^5$	1	4
Test 13, meat trays wrapped in plastic sheet	2.7	100% plastic	$\Delta m = 19.5 t^3$	$4.36 \cdot 10^6$	0.93	$1.10 \cdot 10^6$	1 + 3	13
Test 23, meat trays wrapped in paper	3.1	100% plastic	$\Delta m = 24 t^3$	$4.5 \cdot 10^6$	0.95	$9.13 \cdot 10^5$	1 + 3	12
Test 44, tubes 16, 24, 32 oz polystyrene	—	92% plastic 8% cardboard	$\Delta m = 9.2 t^2$	$2.78 \cdot 10^6$	—	—	—	—
Test 5, bottles, 16 oz Polyethylene	9.2	81% plastic 19% cardboard	$\Delta m = 1.1 t^{2.5}$	—	5.90	—	1	4
Test 7, bottles assorted 1/2 12 oz, polyethylene	—	—	$\Delta m \cong 5 t^2$	$1.44 \cdot 10^6$	5.28	$4.81 \cdot 10^5$	1	3
Test 22, trash barrels polyethylene	5.8	87% plastic 13% cardboard	$\Delta m = 4.35 t^3$	$2.72 \cdot 10^6$	1.9	$7.72 \cdot 10^5$	1	3
Test 43, bottles 64 oz polyethylene	6	—	$\Delta m = 3.97 t^3$	$2.46 \cdot 10^6$	—	—	1	4
C. Insulation boards								
Test 34, polyurethane foam with paper facing	—	71% plastic	$\Delta m = 64 t^4 (t < 1.5 \text{ min})$ $65 t (t > 1.5 \text{ min})$	$1.09 \cdot 10^6$	0.56	$5.04 \cdot 10^5$	1	4
Test 35, polystyrene board, no wrapping	—	100% plastic	$\Delta m \cong 4.41 \cdot 10^{-8,12}$	—	—	—	—	—

* HRR: Heat Release Rate (estimated)

(1) See eqs (1), (2), and (3)

** 1: means first ring of sprinklers

(2) See eqs (13) and (14)

3: means third ring of sprinklers

the most important variables, for the same general fuel assembly configuration, are:

- 1) The properties of the plastic material, as ignition temperature, density, heat capacity, and heat of combustion, both radiative and convective;
- 2) The volume fraction of the fuel elements in the assembly;
- 3) The form and shape of plastic commodity, especially the ratio of its surface area to its volume; and
- 4) The mode of flame propagation, namely, whether it is cylindrical or planar.

Based on the above considerations, we can make the following remarks:

1) The growth rate in terms of mass loss in the tests with commodities stored in compartmented cartons decreases noticeably with an increase in the volume concentration of fuel (in accordance with the analysis in Appendix A). This behavior is clearly indicated in Figure 12. In this figure, the coefficient c ($= \frac{\Delta m}{t^2}$) is plotted versus the volume fraction. Test 41, which involved empty compartmented cartons, is also included in the figure. Figure 12 indicates that the properties of the plastic material have a small effect on the growth rate. However, it should be emphasized that the fire hazard, besides the growth rate, depends also on the heat of combustion of the fuel elements.

Fig. 12 Growth rate in tests with compartmented cartons versus volume concentration of the fuel (plastic and cardboard cartons). The numbers at each point represent the test number (see Table 1).

2) The maximum mass burning rates* for loosely packed plastic items are usually smaller than the maximum burning rates for plastic items packed in compartmented cartons (cf. Dean⁽¹⁾). It follows that, in the small-scale freeburn tests, the fire hazard associated with loosely packed commodities may be actually less than the fire hazard of the same plastic commodity stored in compartmented cartons (see also Dean⁽¹⁾). However, the growth rates for the loosely packed commodities (prior to collapse) are just as rapid as the growth rates for the commodities packed in compartmented cartons (see Table 1).

2.2 Fire growth in intermediate-scale tests (IST79)

The storage arrangement in the intermediate-scale tests (IST79) is illustrated in Figure

* Notice that the mass burning rate is equal to the variation with time of the weight loss $\left[= \frac{d(\Delta m)}{dt} \right]$.

2. The plastic commodities in the IST79 were:

- 1) 16-oz polystyrene jars in compartmented cartons (denoted as IRF1);
- 2) 16-oz polyethylene jars in compartmented cartons (denoted as IRF2);
- 3) double triwall cartons with metal liners (denoted as IRF3);
- 4) empty compartmented cartons (denoted as IRF4).

The plastic rack storage was ignited at the center of its base. Consistent with visual observations flames spread vertically at the center flue shaft and then radially and symmetrically in all directions around the center shaft. This burning behavior is different from the burning behavior of similar commodities in the SST74 tests (see Section 2.1.1) where the flames spread normal to the single vertical flue space. It is expected that burning rate histories will be different in the IST79 tests from the values in the SST74 tests for the same plastic commodities.

2.2.1. Fire Growth Rates (IST79 Tests)

The growth rate histories in the SST74 tests (see Table 1) were represented by power functions of time of the form:

$$Q = q t^p \quad (4)$$

where Q is the heat release rate** of the fire, q and p are constants determined by the experimental results; and t is the time from ignition.

It is possible to express the growth rates of most fires using eq (4) if a modified time parameter, $t^* = t - t_0$, is used. The constant time, t_0 , determines the virtual time origin of

the fire and depends on the initial ignition mode. When the stored plastic starts burning, the initial ignition period does not affect the fire growth rate and, therefore, the fire severity.

A new method is proposed to represent the growth rates of plastic storage fires. This method is objective and eliminates the need to correlate the growth rate histories in IST79 tests.

According to the new method the burning rate histories are represented in the following manner:

$$\frac{1}{Q} \frac{dQ}{dt} = \text{fcn}(Q) \quad (5)$$

In eq (5), time enters only as time intervals (dt); observe that a time history can be obtained from eq (5) by integrating over time. The expression of burning behavior of a storage arrangement in the form of eq (5) will be independent of the details of ignition as long as the ignition source is small relative to the fire.

It is important to note that the left hand side of eq (5) can be interpreted as an inverse growth time of the fire. In addition, it is shown in Sections III and IV that eq (5) is all that is required to predict temperature histories and sprinkler response in growing fires.

The burning rate history expressed in the form of eq (5) is obtained by a simple computer program from the experimental results. The weight loss history measured in each test is fitted by a polynomial approximation. The burning rate is calculated by numerical differentiation. Then, the burning rate history is

** The heat release rate of a fire is equal to the product of mass burning rate and the heat of combustion of the burning material $\left[Q = \frac{d(\Delta m)}{dt} \cdot H \right]$.

* To determine the abscissa in Figure 13, the measured burning rate is multiplied by an effective heat of combustion of the fuel mixture⁽²⁾.

similarly differentiated, and the LHS of eq (5) is determined. The burning rate is multiplied by the heat of combustion of the commodity⁽²⁾ in order to determine the heat release rate, Q .

Experimental results of the growth rate histories of the freeburn IST79 tests are shown in Figure 13, using the variables of eq (5)*. The following observations are made:

Fig. 13 Inverse growth time versus heat release rate in the intermediate-scale tests (ref 2)

1) Since the ordinate, $\frac{1}{Q} \frac{dQ}{dt}$, is not a constant for the results plotted in Figure 13, the burning rate cannot be represented by an exponential function of time.

2) At a specific value of heat release rate, depending on the commodity, the ordinate tends abruptly toward zero. The maximum value of the heat release rate corresponds to the maximum (steady) burning rate of the stored plastic commodity.

3) For the growing period of the fires, the following growth rates are obtained from Figure 13 for all freeburn tests:

Polystyrene jars in cartons (IRF1):

$$\begin{aligned} \frac{1}{Q} \frac{dQ}{dt} &= 1.28 \times 10^2 Q^{-1/2} \\ Q_{\max} &= 4.06 \times 10^7 \text{ W} \end{aligned} \quad (6a)$$

Polyethylene jars in cartons (IRF2):

$$\begin{aligned} \frac{1}{Q} \frac{dQ}{dt} &= 1.09 \times 10^2 Q^{-1/2} \\ Q_{\max} &= 2.58 \times 10^7 \text{ W} \end{aligned} \quad (6b)$$

Double triwall cartons with metal liners (IRF3):

$$\begin{aligned} \frac{1}{Q} \frac{dQ}{dt} &= 6.08 \times 10^1 Q^{-1/2} \\ Q_{\max} &= 1.21 \times 10^7 \text{ W} \end{aligned} \quad (6c)$$

Empty compartmented cartons (IRF4):

$$\begin{aligned} \frac{1}{Q} \frac{dQ}{dt} &= 1.16 \times 10^2 Q^{-1/2} \\ Q_{\max} &= 2.07 \times 10^7 \text{ W} \end{aligned} \quad (6d)$$

In eqs (6a) to (6d) the heat release rate Q is expressed in W and the time, t in sec.

It is easily demonstrated by integration over time of eqs (6a) to (6d), that the burning rate can be expressed as the second power of a modified time in a more familiar expression:

$$Q = q(t-t_0)^2 = qt^{*2} \quad (7)$$

where q is determined from eqs (6a) to (6d); and t_0 is determined by matching the heat release rate calculated from eq (7) with the measured value of the heat release time at any actual time after ignition, t . For completeness, the growth rates of freeburn, IST79 expressed by using expressions similar to eq (7), are:

$$\text{(IRF1)} \quad Q = 4.1 \times 10^3 t^2 \quad (\text{W}) \quad (8a)$$

$$\text{(IRF2)} \quad Q = 2.82 \times 10^3 t^2 \quad (\text{W}) \quad (8b)$$

$$\text{(IRF3)} \quad Q = 9.24 \times 10^2 (t+15)^2 \quad (\text{W}) \quad (8c)$$

$$\text{(IRF4)} \quad Q = 3.36 \times 10^3 (t+5)^2 \quad (\text{W}) \quad (8d)$$

In eqs (8a) to (8d) the theoretical heat release rates are expressed in W and the times

in seconds.

It is emphasized that expressing the growth rates of fires by relations based on eq (5) (see, e.g., eqs (6)) is a superior method than by relations based on eq (4) (see, e.g., eq (8a)), for the following reasons:

1) Equation (5) is all that is required to determine the gas temperatures, when a sprinkler responds.

2) A power law growth with time of the burning rate is directly determined by plotting the experimental results using the variables of eq (5).

3) The LHS of eq (5) mean a more severe fire and present a higher challenge to sprinklers.

2.3 Comparison of freeburn growth rates in SST74 and IST 79 tests

The freeburn tests conducted in IST79 tests are compared with the freeburn tests in SST74 tests, using plastic in compartmented cartons in both test series (see Table I part A). It is observed (from eqs (8a) to (8d) and Table I) that the burning rate, expressed as heat release rate or mass loss rate, varies with the second power of time in the IST79 tests (see eqs (8a) to (8d) and with the first power of time in the SST74 tests (see Table I). This difference in growth behavior can be attributed to the different spread behavior of the fires in IST79 and SST74 tests, because of the different geometries (see Section 2.2 and Figures 1 and 2). In the IST79 tests the flames spread in all radial directions symmetrically while in the SST74 tests the flames spread normal to the single 6-in. wide vertical spacing between the pallet loads. It is important

to point out that the observed burning behavior with time is consistent with the model presented in Appendix A.

It is also possible to compare the relative hazard of plastic materials in freeburn tests of the IST79 program with similar compartmented tests in the SST74 program for the growing period of the fires. Their relative hazard is listed for comparison in Table II. The severity of the tests is characterized by the value of the proportionality constant in the growth rate equations (see eqs (6) or (8) and Table I, column 4). In both series of tests, the double triwall cartons with metal liners developed the slower growing fire and are used as the basis of relative fire growth in freeburn tests. The relative hazards shown in Table II have been derived by dividing the proportionality constants in the fire growth equations (see eqs (6) or (8) and Table I, column 4) of each commodity by the value of the double triwall carton commodity (Test IRF3 in IST79, Test 14 in SST74). Notice that the values of the proportionality constants in the SST74 tests have been appropriately modified by multiplying each value by the corresponding actual heat of combustion of the commodity⁽¹⁾.

Figure 14 presents a graphical comparison of the fire growth rates between the freeburn tests of SST74 and IST79.

It is remarkable that the relative hazard of each commodity remains approximately the same although it was deduced from geometrically different stored plastic arrangements of essentially the same commodity. This behavior is consistent with the model of fire growth in stored plastics presented in Appendix A.

Table II Comparison of the relative hazard of freeburn tests

IST79 Program		SST74 Program	
Test No.	Relative Hazard	Test No.	Relative Hazard
IRF1 – polystyrene jars	4.43	4 ^(a)	3.85
IRF2 – polyethylene jars	3.05	15 ^(a)	2.6
IRF3 – double triwall cartons	1	14 ^(b)	1
IRF4 – empty compartmented cartons	3.64	41 ^(a)	2.8

(a) See Table I

(b) See R. Dean⁽¹⁾

Fig. 14 Comparison of the relative fire hazard between palletized tests (SST74) and rack storage tests (IST 79) of various commodities.

3. TEMPERATURE HISTORIES OVER IGNITION IN THE SMALL-SCALE FREEBURN TESTS

Analysis of temperature histories for the IST79⁽²⁾ program is not included in this report. Only an analysis of maximum gas temperatures near the ceiling for the SST74⁽¹⁾ program is presented.

The maximum temperature over ignition at a height, H , in a steady turbulent buoyant plume originating from a fire is related to the heat release rate in the following manner (see, e.g., Heskestad⁽³⁾):

$$\frac{\Delta T}{Q^{2/3} H^{-5/3}} \cong 14 \cong 16 \quad (9)$$

Where ΔT is the temperature excess (over the ambient conditions) in $^{\circ}\text{F}$; Q is the total heat release rate from the fire source in Btu/min; and H is the height from the top of the fuel in feet. Notice that eq (9) is valid for both weak and strong plumes as the experiments⁽⁹⁾ verify and theoretical models imply (see, e.g., Turner⁽⁵⁾ and Morton⁽⁶⁾).

Equation (9) could also be used to obtain the excess temperature at a certain point over ignition for a slowly varying fire (quasi-steady approximation; see Heskestad⁽⁴⁾) as a function of time. Actually, eq (9) was used in the present work to correlate gas temperatures on the ceiling for the small-scale freeburn tests as a function of time. Unfortunately, it was found that eq (9) cannot describe satisfactorily temperature histories for fast growing fires occurring in the small-scale freeburn tests.

Generalized relations, based on dimensional arguments, for the plume and ceiling jet temperature histories in growing fires have been suggested for the first time by Heskestad⁽⁴⁾. Time similarity analysis of the flow in a plume originating from growing fires⁽⁷⁾ has lead to new variables for the correlation of temperatures with time in fast-growing fires. It has been shown that the time similarity solutions⁽⁷⁾ can be valid only when fires are

growing with a power law dependence on time. The temperature history at any position in the plume and the ceiling jet originating from a growing fire can be expressed by the following relations:

$$\frac{\Delta T(t, z)}{[Q(t)]^{2/3} z^{-5/3}} = \text{fcn}^* \left[p, pq^{\frac{1}{p}} \frac{z^{4/3}}{[Q(t)]^{\frac{p+3}{3p}}} \right] \quad \text{in the plume} \quad (10a)$$

where z is the vertical distance from the virtual fire origin; and

$$\frac{\Delta T(t, H, \frac{r}{H})}{[Q(t)]^{2/3} H^{-5/3}} = \text{fcn} \left[p, pq^{\frac{1}{p}} \frac{H^{4/3}}{[Q(t)]^{\frac{p+3}{3p}}}, \frac{r}{H} \right] \quad \text{in the ceiling jet} \quad (10b)$$

where r is the radial distance from the center of the fire in the ceiling jet for a ceiling height H above the fire. In eqs (10a) and (10b) the heat release rate from the fire source is assumed equal to

$$Q(t) = q t^p \quad (10c)$$

where q and p are constants.

In attempting to verify eqs (10a) and (10b) from experimental results in the small-scale freeburn tests considerable caution should be exercised. The heat release rate can be determined from the burning rate and the heat of combustion of the fuel. Although the burning rates have been reliably measured in the small-scale freeburn tests, the heat of combustion of the array cannot be easily determined, since the fuel in most of the tests consists of a mixture of plastic and cardboard. In addition,

although it is true that the burning rates (and hence the heat release rates) follow approximately a power law dependence (see Section 2.1.1), nevertheless, it should be pointed out that small variations of the exponent, p (cf. eq (10c) lead to large variations of the exponent, $\frac{p+3}{3p}$, in the denominator of the last term in eqs (10a and 10b). A useful modification of the second group in the RHS of eqs (10a) and (10b), following from eq (10c), renders comparison of the experimental results with the theory more amenable:

$$pq^{\frac{1}{p}} \frac{z^{4/3}}{[Q(t)]^{\frac{p+3}{3p}}} = \frac{1}{Q} \frac{dQ}{dt} \left(\frac{z^4}{Q} \right)^{1/3} \quad (11)$$

The temperature history at the ceiling over ignition takes the simplified form:

$$\frac{\Delta T(t, H)}{[Q(t)]^{2/3} H^{-5/3}} = \text{fcn} \left[p, \frac{1}{Q} \frac{dQ}{dt} \left(\frac{H^4}{Q} \right)^{1/3} \right] \quad (12)$$

It is worthwhile to observe that the quasi-steady temperature approximation given by eq (9) is obtained when the function at the RHS of eq (12) approaches a constant.

In Figure 15 the temperature histories over ignition for several small-scale freeburn tests are plotted in terms of the dimensionless arguments indicated in eq (12). The values of the ordinates and the abscissa in this figure have been determined in the following manner:

1) The temperature excess near the ceiling ΔT was extracted from the strip chart records at a certain time, t . Corrections in the gas temperature due to thermocouple lag were

* fcn = functional relation

estimated to have a negligible effect on the general trend of the curves, always being less than 10 percent of the instantaneous temperature excess. (The diameter of the chromel-alumel thermocouple bead used in the tests was approximately 0.1 in.)

2) The heat release rate $Q(t)$ was estimated from the relation:

$$Q(t) = \dot{m}(t) H_c \quad (13)$$

where $\dot{m}(t)$ is the measured burning rate at time, t ; and H_c is the heat of combustion. To calculate the heat of combustion, it was assumed that the fuel is a homogeneous mixture of plastic and cardboard. The estimated percentage content in weight for plastic and cardboard is presented in Table I. It follows that, for perfect (complete) combustion,

$$H_c = H_{c1} w_1 + H_{c2} w_2 \quad (14)$$

where H_{c1} is the heat of combustion of the plastic commodity (taken from Dean¹); H_{c2} is the heat of combustion of cardboard ($\cong 8,000$ Btu/lb); and w_1 , w_2 are the weight percentages of plastic and cardboard respectively.

Fig. 15 Modified temperature over ignition versus modified growth factor (cf eq (12))

3) Finally, the height, H , was taken equal to 45 ft, the distance from the top of the array to the ceiling (in consistence with present evidence)⁽³⁾. Tests consisting of plastic commodity stored in compartmented cartons are included in Figure 15 in addition to Tests 23, 43 and 35. It should be noted that, for tests involving compartmented cartons, the heat release rate is approximately proportional to time (cf. Table I). For Tests 23 and 43 the heat release rate is approximately proportional to the second power of time, while for Test 35 the heat release rate is approximately proportional to the eleventh power of time (cf. Figures 6 and 8).

It can be observed from Figure 15 that the groups introduced by eq (12) correlate remarkably well with the experimental results for fires growing with the first power of time ($Q(t) \sim t$). The value of temperature over ignition at small values of the abscissa (quasi-steady conditions) agrees with the previously established value in eq (9). Moreover, the measured temperatures over ignition for the fires growing faster than the first power of time (Tests 23, 35 and 43 in Figure 15) do not show large divergence compared with the respective temperature histories for fires growing with the first power of time (Tests 4, 15, 19 and 41). The above behavior indicates that the functional dependence on the power of time, p , in growing fires, as shown by eq (12) may not be significant but is actually lumped in the second group at the right-hand side of eq (12), (cf. eqs (10a) and (10b))* . Finally, we can infer from Figure 15 that the temperature history at the ceiling over ignition

* This observation is very significant and has been shown to agree with a theoretical model for the unsteady behavior of a plume (see Delichatsios⁽⁷⁾).

for a specific fire is expected to be well represented by the quasi-steady approximation, when the effective ceiling height changes from 45 ft (freeburn tests) to 15 ft (sprinklered tests).

4. EXTINGUISHABILITY OF A STORED PLASTIC COMMODITY

4.1 General discussion

The analysis of water protection tests conducted in the small-scale test program (SST74) and in the intermediate-scale test program (IST79) is presented in Sections 4.2 and 4.3 respectively. In the SST74 program water protection tests were conducted using automatic sprinklers⁽¹⁾ (see Section 1.1), whereas both "drip" water tests and automatic sprinklered tests were included in the IST79 program (see Section 1.2).

The response of sprinklers can be predicted by integration of the thermal response equation of the sprinkler link using quasi-steady relations for gas temperatures and velocities under the ceiling. The general method of solution, an approximate solution, and particular simple analytic solutions and included in Appendix B. The heat release rate at response of the first sprinkler ring can be determined directly using the new method of representing the fire growth rates (eq (5)). It is shown in Sections 4.2 and 4.3 by comparison with the experiments that sprinkler response is well predicted from freeburn data, sprinkler array geometry, ceiling clearance, and sprinkler link thermal lag properties.

The fire severity in a stored plastics fire is measured practically in water protection tests with automatic sprinklers by 1) the number

of sprinklers activated, and 2) the extent of the damage in the stored plastics arrangement. Before presenting the water protection data and their interpretation in Sections 4.1.2 and 4.2.2, an a priori fire hazard classification of various stored plastics tests is proposed based on a) freeburn growth rates, and b) the fact that heat release at response can be well predicted from freeburn growth rates, sprinkler geometry and ceiling clearance (see previous paragraph). Limitations of the classification and additional information required are clearly defined as well as shortcomings of the water protection tests conducted in the SST74 and IST79 programs.

It is proposed that parameters relevant for characterizing the fire severity of a stored plastics arrangement based only on freeburn tests are: 1) the heat release at the first sprinkler activation, Q_s , and 2) the characteristic inverse growth time of the fire at the moment of first sprinkler activation, $\frac{1}{Q_s} \frac{dQ_s}{dt}$. Both parameters can be determined from the freeburn data (see Appendix B), if the freeburn growth rates, expressed in the form of eq (5), are known, together with ceiling clearance, sprinkler array geometry, and sprinkler link thermal lag. Note that the inverse growth time $\frac{1}{Q} \frac{dQ}{dt}$, in stored plastics tests may be interpreted as inverse fire spread time through the fuel. The maximum burning rate of the fuel arrangement is not essential in classifying the hazard, because its value depends essentially on the total fuel load available in the freeburn tests.

It is evident that, if the sprinklers operate early (small values of Q_s), the effectiveness of the water protection will be greater. However,

the growth time of the fire, $\left[\frac{1}{Q_s} \frac{dQ_s}{dt} \right]^{-1}$, at the moment of first sprinkler activation is equally important. The smaller it is, the more severe is the fire as demonstrated in the following discussion. For simplicity, it is assumed that the same time, τ_e , can be associated with the control or extinction of the fire in all stored plastic tests*. Before the fire is extinguished it will have grown approximately to a magnitude:

$$Q_m \cong Q_s \left[1 + \frac{\tau_e}{Q_s} \frac{dQ_s}{dt} \right] \quad (15)$$

It follows that the smaller the growth period of the fire $\left[\frac{1}{Q_s} \frac{dQ_s}{dt} \right]^{-1}$ the more severe the fire is.

As a demonstration, the heat release rate at first sprinkler operation and the inverse characteristic growth time of the fire at first sprinkler operation are indicated in Figure 16 for all freeburn tests in the Intermediate-Scale Test Program (IST79), together with Small-

Fig. 16 First sprinkler response coordinates in the plastic storage tests SST74 and IST79.

* The "extinction" time will depend on the penetration of water through the plume to the base of the fire, the fire extinction characteristics of the commodity, and the dripping of water through the storage arrangement.

Scale Tests (1974) having the same commodity as the IST79 tests (see Table II). In Figure 16 the growth time of the fires is plotted in a log-log plot versus the heat release rate for both the Small-Scale Tests conducted in 1974 and the Intermediate-Scale Tests conducted in 1979. The growth periods are represented by straight lines corresponding to the measured growth behavior (see Figure 13 and Table I), and the constant burning period is represented by a vertical line. The points marked on each of these curves denote the activation of the first sprinkler.

Based on the previous discussion the following remarks may be made regarding Figure 16:

1) For the same storage arrangement (in both IST79 and SST74 programs) and the same water discharge characteristics (as indicated in Figure 16), the greater challenge to the sprinkler is expected to be made by the faster growing fires (in the order shown, for example, in Table II).

2) The fire severity will be less for sprinklers with higher sensitivity and/or smaller activation temperature; see the two sets of points corresponding to IST79 tests: IRF1, 2, 3, 4 in Figure 16.

3) For the same commodity in different storage arrangements (e.g., SST74 tests compared to IST79 tests as shown in Table II), it is obvious from Figure 16 that the rack storage arrangement in IST79 tests presents the greatest fire hazard.

4) Although it is possible to characterize the relative hazard of some stored plastics

tests (see remarks 1), 2), and 3)) based on Figure 16 (and the primitive assumption that the extinction time is the same for all tests), some test conditions in Figure 16 cannot be compared regarding their hazard, because for these test conditions one parameter, Q_s , is smaller and the other parameter, $\frac{1}{Q_s} \frac{dQ_s}{dt}$, is larger in one test, or vice versa. The previous remark demonstrates that, in general, freeburn test results are not sufficient to classify even in the simple way proposed here, the fire severity except in certain areas (see remarks 1, 2, and 3)).

It is emphasized that, if the time characteristic for extinction is measured by ingenious tests or using a model, then the fire severity can be predicted accurately using arguments which will lead to an equation similar to the simple eq (15). A discussion on extinction of stored plastics tests is included at the end of this section (Section 4.3.1).

The essential question is whether the classification of fire severity based on freeburn tests, even though obtainable for only limited types of tests, is a valid representation of the actual fire severity as measured by sprinklered tests in both test series SST74 and IST79. The relative fire severity in sprinklered tests agrees in general with the fire severity as predicted from the freeburn tests, if the sprinklered tests are otherwise comparable, namely, if the sprinkler discharge density and sprinkler spacing are the same. A single major drawback of the SST74 and IST79 programs should be pointed out: in both series of tests the fuel load is small (in contrast to actual full-scale arrangement). The maximum heat release rate (steady burning state) may be reached soon after the first sprinkler is activated (see Figure

16). Therefore, in some cases the sprinkler system is not challenged as much as if the fire continued growing (i.e., if more fuel were available).

4.2 Sprinkler response in the small-scale tests (SST74)

Sprinklered tests were conducted in the 30-ft site at the West Gloucester Test Center using the same storage arrangement and plastic commodities employed in the freeburn plastic tests (Dean⁽¹⁾). The most important measurements in the sprinklered tests were the time, from the beginning of ignition, of the first sprinkler opening, and the number of sprinklers activated during the tests. These data are tabulated in Dean's report⁽¹⁾ (see also Table I). In analyzing the above results, it should be noted that, although the sprinklered and the corresponding freeburn tests were nominally identical (with the exception of ceiling height), differences in fire growth might occur.

The sprinklers (link and lever type) used in the sprinklered tests, were of 1/2-in. orifice diameter, rated at 280°F, located on 80 ft² spacing (8 ft × 10 ft), and controlled to discharge at 0.45 gpm/ft² density.

4.2.1. Response Time Of the First Activated Sprinkler

A simplified equation for the temperature increase of a sprinkler link in a growing fire (see Appendix B) is used to correlate the experimental results. We assume that all the quantities in the fire plume can be estimated using the quasi-steady plume equations, in accord with the concluding remarks in Section III.

For a fire growing proportionally to a power function of time (see eq (10c) we obtain, using eq (B-15) and assuming quasi-steady plume development:

$$\frac{9 (q t_r^p)^{2/3} H^{-5/3}}{1 + \frac{\tau(t_r)}{t_r} \frac{2p}{3}} = \Delta T_s$$

Here, $\tau(t_r)$ is the characteristic sprinkler time constant (see, e.g., Heskestad⁽¹²⁾) at the time, t_r , the first sprinkler operates; ΔT_s is the sprinkler fusing temperature excess over the ambient temperature in the sprinklered tests, equal approximately to $(280-65) = 215^\circ\text{F}$; the height, H , is taken as the elevation of the ceiling over the top of the fuel pile, equal to 15 ft. The proportionality factor 9 in the numerator of the left hand side of eq (16), has been calculated via correlations presented in Heskestad⁽⁴⁾, for a value $\frac{r}{H} = \frac{6.40}{15} = 0.43$, where r is the distance from the fire axis of a sprinkler in the first ring. The burning rate is expressed in Btu/min and the time in minutes.

The time constant of sprinklers, which were similar to those used in the sprinklered fires, has been measured (Heskestad⁽¹²⁾) equal to 2.15 min at a gas velocity of 5 fps. The burning rate at the moment of first sprinkler operating has a value, in general, of about 5×10^5 Btu/min (see Table I). Since the time constant of a sprinkler changes as the one-sixth power of the burning rate, (see Heskestad⁽¹²⁾), it is assumed that the time constant remains constant in all the sprinklered tests. In particular, a value is assumed corresponding to the gas velocity induced by a fire with a burning rate 5×10^5 Btu/min, the average burning rate at sprinkler activation for all the tests. The time constant is inversely proportional to the square root of the gas velocity⁽¹²⁾. It can

be estimated (Heskestad⁽⁴⁾) that, for the assumed burning rate at sprinkler activation, the gas velocity at the first sprinkler ring $\frac{r}{H} = 0.43$ and ceiling height of $H = 15$ ft) is 30.4 fps. Hence,

$$\tau(t_r) \cong \text{const} = 0.87 \text{ min}$$

Following the above simplifications, eq (16) becomes:

$$\frac{t_r^{2p/3}}{1 + \frac{0.87}{t_r} \frac{2p}{3}} = \left[\frac{\Delta T_s}{q} H^{5/3} \right] \frac{1}{q^{2/3}} \quad (17)$$

In Figure 17 the LHS function of response time in eq (17) is plotted versus $q^{2/3}$ for tests which were run both freeburn and sprinklered. The value of q has been determined from Table I and the heat of combustion as calculated in Section III. The units are such that the heat release rate is expressed in Btu/min. Figure 16 includes some rather well defined fires, which follow a linear power (#19, 15, 4, 6, 41) and a second order power time dependence (#22, 13, 23) in their growth rate (see Table I). The test numbers in Figure 17 correspond to the freeburn tests. It was assumed in drawing the points in Figure 17, that the sprinklered tests, corresponding to each of the freeburn tests indicated in Figure 17, follow the same fire growth rate as the respective freeburn tests. A semiempirical approximate correlation between the sprinkler response time and the fire growth coefficient is also shown in Figure 17. The theoretical value for the coefficient in parentheses in eq (17) is less than the value indicated for the experimental data in Figure 17 by a factor 1.6 (see discussion at the end of Appendix B).

4.2.2. Number Of Sprinklers Activated As A Function Of The Freeburn Growth Rates

Extinguishment or control of a fire by water may be obtained by three different mechanisms: 1) direct impingement on the fuel surface, which inhibits pyrolysis; 2) cooling and/or smothering of hot gases, which inhibits the fire spread; and 3) prewetting of the unburned fuel, which stops the fire spread.

It is not known which is the principal mechanism of fire extinction or control in the SST74 tests. A discussion on fire extinction is presented in Section 4.4.

Evidence of drop entrainment by the hot gases exists in the observed skinpping of sprinkler rings in the opening pattern of sprinklers. A typical opening pattern is shown in Figure 18. The skipping problem is currently under investigation at FMRC. Skipping probably occurs because the sprinklers in the ring adjacent to the actuated ring are cooled by the entrained water drops in the ceiling jet of hot gases⁽¹³⁾.

To classify the fire hazard of a stored plastic arrangement in a specific sprinkler protec-

Fig. 17 Sprinkler response function versus the fire growth coefficient

tion, it has been argued in Section 4.1 that two parameters which can be derived from freeburn tests are required:

Fig. 18 Figure 18 sprinkler opening patterns (ref. (1)) indicating the three sprinkler rings around the center of the fire.

1) the heat release rate at the response of the first sprinkler, Q_s (the fire hazard increases with Q_s); and

2) a characteristic growth time of the fire $\left[\frac{1}{Q_s} \frac{dQ_s}{dt} \right]^{-1}$ at the response of the first sprinklers (the fire decreases as the growth time increases). However, a better classification could be possible if the characteristic extinction time, τ_e , (cf. eq (15)) were known. The characteristic extinguishability time depends on the sprinkler characteristics, the storage arrangement and the fuel (compare with discussion in Section 4.4, where suggestions are made for an investigation required to determine the extinguishability time, τ_e). It was also suggested in Section 4.1 that the maximum steady burning rate in the stored plastic tests is not essential in the hazard classification, because it depends on the available fuel load and it is expected to increase with the fuel load (see Figure 16 and compare IST79 with SST74 tests).

The number of sprinkler rings activated in

the SST74 sprinklered tests is included in Table I. It can be shown that the most severe fires (first and third ring open) have consistently higher values of heat release rates, Q_s , and lower values of growth time $\left[\frac{1}{Q_s} \frac{dQ_s}{dt}\right]^{-1}$ at the first sprinkler response. This behavior is consistent with the proposed classification based only on freeburn test data. In this report, only the SST74 data plotted in Figure 16 will be discussed in greater detail. Table III indicates the relative hazard classification based on the freeburn test data (cf. Figure 16) and the actual hazard as measured by the number of sprinkler rings activated. The only discrepancy is between Tests 41 and 15. This discrepancy may be due to 1) different extinction times, τ_e , between these tests (cf. eq (15)), or 2) the smallest maximum burning rate achieved in Test 41 (see Figure 16) compared to Test 15.

4.3 Sprinkler response in the intermediate-scale tests (IST79)

Two types of water protection tests were run in the Intermediate-Scale Test (IST79) program⁽²⁾: 1) sprinklered tests at the 30-ft site of the West Gloucester Test Center wherein the test array was protected by automatic sprinklers; and 2) drip tests wherein the test array was protected at selected times after ignition by a special water nozzle 56 in. above the top of the array.

Table III Relative hazard in SST74 sprinklered tests

Test No.	Hazard Classification Based on Freeburn Tests*	Number of Sprinkler Rings Activated
4	1	1 + 3
14	4	1
15	2	1 + 3
41	2	1

*1 represents the largest hazard (based on Figure 15)

4 represents the smallest hazard (based on Figure 15)

Two types of sprinklers and sprinkler arrangements were used in the sprinklered tests: 1) 1/2-in. orifice diameter sprinkler, rated at 165°, located at 10-ft × 10-ft spacing and discharging 30 gpm per head; and 2) 17/32-in. orifice diameter sprinklers rated at 280°F at 10-ft × 10-ft spacing and discharging 42 gpm per head.

Three different nozzles discharging 60 gpm, 50 gpm and 35 gpm were used in the drip tests.

The most important measurements in the sprinklered tests were the time of first sprinkler activation and the number of sprinklers activated during the tests. The drip tests were planned to measure the effectiveness of the water to extinguish the fire at the fuel array after it penetrates the fire plume. The results from the drip tests can be used as a link between freeburn and full-scale tests and can help in the classification of the hazard of different commodities.

4.3.1. Response Of The First Activated Sprinkler

The response time and heat release rate of the fire at first sprinkler activation can be predicted by the method developed in Appendix B. The results are plotted in Figure 19 for the following conditions:

- 1) parabolically growing fires with time ($Q \propto t^2$);
- 2) ceiling clearance 20 ft applicable to the IST79 program;
- 3) sprinkler spacing 10 ft × 10 ft applicable for the IST79 program;
- 4) sprinkler link rating 280°F and 180°F (characteristic response time 129 secs at 5 fps);

- 5) quasi-steady correlations are used for the prediction of ceiling gas temperatures and velocities.

It is emphasized that the time co-ordinate in Figure 19, t^* , is the time from the virtual origin of the fire (cf. eq (7)). The abscissa, q , is the growth coefficient in front of the time function, $Q = q t^{*2}$. The real response times of first sprinkler activation measured in the sprinklered tests are also indicated in Figure 19. In general, there is good agreement between the experiments and the predicted response. The major reason for disagreement in some cases may be the difference in behavior of the nominally similar fires at the initial period after ignition so that the delay time, t_0 , (cf. eq (7)) is different in the sprinklered and corresponding freeburn tests.

Fig. 19 Response time and fire intensity at first sprinkler response for parabolically growing fires ($q = qt^2$)

4.3.2. Number Of Sprinklers Activated

A summary of results of the intermediate-scale tests sprinklered series is included in Table IV (taken from Ref. 2).

In the first series of sprinklered tests denoted by SP-I in Table III sprinklers of 1/2-in. orifice diameter were used with a rating of 165°F and discharging a nominal water density of .30 gpm/ft². The test configurations with

the polystyrene, polyethylene and empty carton commodities presented almost the same fire severity as measured by the number of sprinklers activated; in contrast, the double triwall commodity developed less hazardous fire (see column 4 in Table IV). It is now possible to compare the fire hazard measured in the sprinklered tests (SP-I) with the prediction of the fire hazard based on the freeburn tests (see Section 4.1). The heat release of the fire at first sprinkler activation is indicated for the SP-I tests on their respective growth curves on Figure 16. As indicated in Section 4.1, it is expected that fire severity will decrease in the following order: polystyrene, empty cartons, polyethylene, double triwall cartons. The sprinklered tests (SP-I series, see Table IV) seem to support the classification of fire severity by means of the freeburn tests because 1) the polystyrene-empty carton-polyethylene commodities are expected to develop almost the same hazard since the heat release and the characteristic growth time at the first sprinkler activation are very close (see circles in Figure 16); 2) the double triwall commodity is expected to present the lowest hazard.

The second series of tests SP-II (see Table IV) indicates clearly that classification of the hazard based on the sprinklered tests. In the second series of with the hazard as measured by the freeburn tests. In the second series of tests SP-II, sprinklers 17/32-in. in orifice diameter were used with a rating of 280°F and discharging a nominal water density of .42 gpm/ft². The test configurations with the polystyrene and polyethylene commodities presented the same fire severity (12 sprinklers opened) while both the double triwall commodity and the empty cartons presented

Table IV Summary of results—IRS series

Sprinkler Protection	Commodity	Test I.S.	Total A.S.	Time of 1st A.S.	Max	Over Ignition Temp at $>1000^{\circ}\text{F}(>530^{\circ}\text{C})$	
SP-I (165°F 1/2-in. spklrs 0.30 gpm/sq ft)	Polystyrene	IRS-1	31	1:00	910°C (1670°F)	3:00	7:50
	Polyethylene	IRS-2	36	1:02	754°C (1390°F)	6:17	7:30
	DTW/m liner	IRS-3	4	1:28	199°C (390°F)	1:45	—
	Empty C.C.	IRS-4	29	1:02	628°C (1163°F)	2:15	0:41
SP-SP-II 17/32-in. spklrs 0.42 gpm/sq ft)	Polystyrene	IRS-1A	12	1:33			
	Polyethylene	IRS-2A	11	1:34			
	DTW/m liner	IRS-3A	4	2:28			
	Empty C.C.	IRS-4A	4	1:28			

I.S.: Intermediate-Scale

A.S.: Activated Sprinklers

the lowest fire severity (four sprinklers opened).

The heat release of the fire at first sprinkler activation is indicated for the SP-II tests in their respective fire growth curves in Figure 16. First observe that in this series of tests the sprinklers operated when the commodities reached approximately their maximum burning rates (see Figure 16); therefore, no more fire growth could occur after the first sprinkler activates in this series of tests. Based on the discussions in Section 4.1 and on Figure 16, the fire severity in decreasing order in the SP-II tests would be: polystyrene-empty cartons-polyethylene-double triwall cartons. However, the sprinkler test results indicate that, although the remaining order is correct, the empty cartons develop a fire severity similar to the double triwall cartons. Following the discussion in Section 4.1, this difference may be attributed to the difference in the characteris-

tic combustion times, τ_e , (see also eq (15)) between tests, for example, with the polyethylene and empty carton commodities*. Indeed, there are some indications from the drip series tests conducted in the IST79⁽²⁾ program, that extinction of the fires by water impinging on the top of the fuel array is achieved much faster in the empty carton commodity compared to the polyethylene commodity for the same test conditions. No detailed discussion of the drip test series is given here, because of 1) some uncertainties in the measurements, and 2) the complexity of the extinction of the fire by water directly impinging on the top of a fuel array.

It should be emphasized that the sprinklered series SP-I cannot be directly compared with the sprinklered series SP-II, since different sprinklers and water densities were used in each series (see Table IV).

* It is seen from Figure 16, that at the moment of first sprinklers activation, the heat release rates of the polyethylene and empty carton commodities are almost the same; it is expected that the same amount of water will penetrate to the surface of the fuel for both fires. Therefore, any difference in the extinction process will be due to the effectiveness of water directly impinging and dripping through the fuel array to extinguish the fire.

4.4 Remarks

It was demonstrated in Sections 4.2 and 4.3 that freeburn test results can be used as a first approximation to classify the fire hazard of different commodities using a methodology presented in Section 4.1; to improve the classification the following additional information is needed regarding:

1) the penetration of the discharged water through the fire plume and 2) the effectiveness of the water that has penetrated the fire plume to extinguish the fire inside the fuel array.

Consider a series of growing fires (e.g., the freeburn tests in the IST79 program (see Figure 16); except for some special cases the heat release at response of the first sprinkler will be almost the same for different growing fires (see, e.g., Figure 16, IST79 tests). It is expected, therefore, that at the beginning of first sprinkler activation the same amount of water will penetrate through the plume to the top of the fuel array. If the amount of water impinging on the top of the fuel and dripping through the fuel array is able to decelerate the growth of the fire, the fire plume will decrease in strength and more water will penetrate through the plume and become available for extinction of the fire in the fuel array. Otherwise, the fire will grow out of control.

The simplified feedback mechanism of the extinguishment process presented in the previous paragraph indicates that, in parallel with penetration studies of water through a fire plume, the extinction process of the fire in a fuel array by water impinging on top of the fuel array must be investigated. The extinction of fire in a fuel array by water impinging on its top consists essentially of three inter-related phenomena: 1) extinction of the fire

by water impinging directly on a burning fuel element (This phenomenon depends on the type of the material.); 2) dripping of the water from the top inside the fuel array (This phenomenon depends on the detailed geometry of a horizontal cross section of the array and its height.); and 3) the rate of fire growth at the moment of water application at the top of the fuel. (This phenomenon is related also to the effectiveness of water in stopping the flame spread by prewetting the unignited fuel.) No systematic method has been developed of investigating the phenomena affecting the extinction of fires in a fuel array by water impinging on its top (e.g., in a drip test).

5. CONCLUSIONS AND RECOMMENDATIONS

Two series of independent tests were analyzed in this program: a small-scale test series⁽¹⁾ (1974) and an intermediate-scale test series⁽²⁾ (1979). The major accomplishments of the present program are summarized in the following paragraphs:

1) It has been shown that fire growth rates depend on the stored plastics geometry, the storage arrangement of plastics inside the cardboard cartons, and the volume fraction of the fuel elements. The associated fire hazard is related to the plastic material through its heat of combustion. A new method has been developed to plot the growth rates of growing fires in West Gloucester: a characteristic growth time is plotted versus the heat release rate (see Figure 13). In this way delays in the initial ignition period (unimportant in full-scale tests) are eliminated.

2) Temperature histories in the freeburn tests in the 60-ft site at West Gloucester Test Center do not conform with the quasi-steady plume correlations but are represented fairly well by unsteady plume correlations. A time similarity solution of the plume equations has been derived which may be used in further analysis of temperature data.

3) A simple correlation has been developed to predict the response time of the first sprinkler activated in the sprinklered tests; predictions are in good agreement with the experiments.

4) A classification of the hazard is proposed, using only freeburn results. The classification is based on the heat release rate and the characteristic growth time of the fire at first sprinkler activation (see Figure 16). The maximum heat release rate obtained in a freeburn test for the same configuration of different commodities is not representative of the challenge a fire will generate for a specified sprinkler protection, except in the undersirable case when the protection system is ineffective to control the fire. It is demonstrated that the freeburn tests are not sufficient in general to classify the hazard which a commodity and storage arrangement will present to a specific sprinkler protection. An important link in the classification (in addition to penetration studies) is the extinction of a fuel array by water impinging on its top. Three phenomena associated with the extinction of a fuel array by water impinging on its top must be thoroughly investigated: a) extinction of a fire impinging directly on a burning fuel element, which depends on the type of the material of the fuel element; b) dripping of the water inside the fuel array, which depends on the details

of a cross section of the array and its height; and c) the rate of growth of the fire at the moment of water application at the top of the fuel.

REFERENCES

- [1] Dean, R.K., "Stored Plastics Test Program," FMRC Serial No. 20269, June 1975, (Copyright, 1975-Factory Mutual)
- [2] Sumitra, P., "Intermediate-Scale Tests," in preparation
- [3] Heskestad, G., "Fire Plume Simulator," FMRC Serial No. 18792, August 1973
- [4] Heskestad, G., "Similarity Relations for the Initial Convective Flow Generated by Fire," ASME Paper No. 72-WA/HT-17, 1972
- [5] Turner, J.S., "Buoyancy Effects in Fluids," Cambridge at the University Press, Cambridge, 1973
- [6] Morton, B.R., "Modeling Fire Plumes," Tenth Symposium (International) on Combustion, 1973, The Combustion Institute, 1965
- [7] Delichatsios, M.A., "Time Similarity Analysis of Unsteady Buoyant Plumes in Neutral Surroundings," *Jo. Fluid Mech.*, 93, 2, 241 (1979)
- [8] Delichatsios, M.A., "Fire Growth Rates in Wood Cribs," *Combustion and Flame*, 1976
- [9] Block, T.A., "A Theoretical and Experimental Study of Non-propagating Free-burning Fires," Thirteenth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, p 971, 1971
- [10] Heskestad, G., "Modeling of Enclosure

- Fires," Fourteenth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, p 1021, 1973
- [11] Turner, J.S., "The Starting Plume in Neutral Surroundings," *Journal of Fluid Mechanics*, 13, 356, 1962
- [12] Heskestad, G., "Effect of Thermal Sensitivity on the Performance of Automatic Sprinklers," Proposal FMRC 22485.1, December 1975
- [13] Croce, P.A., Hill, J.P., "An Investigation of the Causative Mechanism of Sprinkler Skipping," FMRC Serial No. 22416, January 1980
- [14] Yao, C., "Development of Large-Drop Sprinklers," FMRC Serial No. 22476, June 1976
- [15] Heskestad, G. and Delichatsios, M.A., "Environments of Fire Detectors—Phase II: Effect of Ceiling Configuration," FMRC Serial No. 22584, June 1978

APPENDIX A

Growth rates in a "porous" fuel assembly

The flame spread into the third (top) and second pallet loads for the storage arrangement represented by Figure 1 (a and b) resembles the horizontal flame spread in an open "porous" bed, such as a wood crib, ignited at its center "shaft". Similar to the growth rates in a wood crib (see, e.g., Delichatsios⁽⁸⁾), the instantaneous burning rate will be equal to the exposed fuel surface area involved in burning, multiplied by an average specific burning rate, (assumed quasi-steady) i.e.:

$$\dot{m} = \dot{m}'' A_s \quad (A1)$$

where $\dot{m}$ is the mass burning rate, A_s is the exposed surface area of the fuel elements involved in burning and $\dot{m}''$ is average specific

burning rate.

The specific burning rate will depend on the shape of the fuel elements and the flow induced around a fuel element by buoyancy.

The exposed surface area of the fuel elements involved in burning is determined by the extent of flame spread and the concentration of fuel elements per unit volume of the fuel assembly. A flame spread speed can be estimated by the relation (cf Delichatsios⁽⁸⁾):

$$u_s = \frac{I_o}{\Delta Q} \quad (A2)$$

Here, u_s is the instantaneous flame spread speed, I_o is the energy flux from the flame front to the unburned fuel and ΔQ is the increase of the heat content per unit volume of a fuel element from the ambient conditions to the ignition state. The quantity ΔQ is equal to (cf Delichatsios⁽⁸⁾):

$$\Delta Q = \rho_f \phi C_p (T_i - T_\infty) \quad (A3)$$

where ρ_f is the density of a fuel element, ϕ is the volume fraction of the fuel elements in the fuel assembly (the rest of the volume being air), C_p is the specific heat capacity of the fuel elements, and T_i , T_∞ are the fuel "ignition" and the ambient temperatures respectively.

The volume of the fuel assembly, V_{fa} , involved in burning is obtained by the rate of flame spread and the frontal area, A_f , of the flame front within the fuel assembly, i.e.:

$$V_{fa} = u_s A_f \cdot t \quad (A4)$$

assuming constant rate of flame spread.

It is now straightforward to write an equation for the exposed area of the fuel involved in fire at a certain instant of time

$$A_s = (u_s A_f \cdot t \phi) \frac{S_{fe}}{V_{fe}} \quad (A5)$$

Here, $\frac{S_{fe}}{V_{fe}}$ is a shape factor for the fuel elements specifying the exposed free surface area of a fuel element per unit of its volume. The quasi-steady burning rate (eq (a1)) can now be expressed as

$$\dot{m} = \dot{m}'' \left(\frac{I_o}{\rho_f C_p (T_i - T_\infty)} \right) \left(\frac{S_{fe}}{V_{fe}} \right) \cdot A_f \cdot t \quad (A6)$$

wherein eqs (2), (3) and (5) have been used.

We can now derive an estimate of the specific burning rate using the following model and assumptions:

1) The fuel assembly is modelled as a "porous" bed of volume V_t (equal to the volume of the fuel assembly) consisting of n_p vertical air passages of cross-section area s^2 and height h .

2) The burning rate is determined from the flow rate of air through the "porous" bed (cf closely packed wood cribs Block⁽⁹⁾ or Heskestad⁽¹⁰⁾).

3) The flow through each air passage of the assembly is turbulent.

In accord with the above model and assumptions, we obtain the relations:

$$\frac{n_p s^2 h}{V_t} = 1 - \phi \quad (A7)$$

$$(\Delta \rho g h) \propto (1/2 \rho_a v^2) \frac{h}{s} \quad (A8)$$

$$\dot{m}'' \propto \frac{\rho_a v s^2}{s h} \propto \frac{\rho_a v s}{h} \propto \frac{\rho_a \sqrt{\frac{\Delta \rho}{\rho_a} g}}{h} s^{3/2} = \rho_a$$

$$\sqrt{\frac{\Delta \rho}{\rho_a} g h} \left(\frac{V_t}{n_p \cdot h^3} \right)^{3/4} \cdot (1 - \phi)^{3/4} \quad (A9)$$

Equation (A7) relates the volume fraction of the fuel elements in the model and in the actual fuel assembly. In eq (A8), the buoyant driving forces are equated to the turbulent friction losses in each air passage. Finally, eq (A9) gives an estimate of the specific burning rate. The underlined symbols in eqs (A7), (A8) and (A9) have the following meaning:

$\Delta \rho$: density difference between the hot burning gases and the ambient air.

ρ_a : density of the ambient air

v : velocity through an air passage

We conclude that the fire growth rate can be estimated by the following relation:

$$\dot{m} \propto \rho_a \sqrt{\frac{\Delta \rho}{\rho_a} g h} \left(\frac{V_t}{n_p h^3} \right)^{3/4} (1 - \phi)^{3/4} \left(\frac{I_o}{\rho_f C_p (T_i - T_\infty)} \right) \left(\frac{S_{fe}}{V_{fe}} \right) A_f \cdot t \quad (A10)$$

Notwithstanding the qualitative nature of the assumptions made in deriving eq (A10), the following important conclusions may be made with regard to the growth rates in the small-scale freeburn tests:

1) The growth rate depends strongly on the properties of the fuel material, increasing with an increase in energy flux from the flame front and decreasing with an increase in the fuel density and fuel ignition temperature.

2) The growth rate increases proportionally with the shape factor of the fuel elements (S_{fe}/V_{fe}).

3) The growth rate is proportional to the area of the flame front. For one-dimensional quasi-steady flame spread, the flame front area, A_f , is constant and the growth rate is proportional to time. For two-dimensional quasi-

steady flame spread, the flame front area is proportional to the flame spread speed and time ($A_f \propto u_s t$), and the growth rate varies proportionally to the second power of time (cf eq (A10)).

4) The growth rate decreases with increasing volume fraction of the fuel elements.

APPENDIX B

Sprinkler response time to a growing fire

An approximate expression for the sprinkler response time, desirable for the present work, is developed in the following analysis.

The temperature increase of a sprinkler with time in a growing fire is given by the equation:

$$\frac{d(\Delta T_s)}{dt} = \frac{1}{\tau} (\Delta T_G - \Delta T_s) \quad (B1)$$

where ΔT_s , ΔT_G are the sprinkler and gas excess temperature over the ambient air temperature; t is the time; and τ the time constant of the sprinkler*. The time constant τ is inversely proportional to the square root of the velocity and can be expressed as (e.g., Heskestad⁽¹²⁾):

$$\tau = \tau_0 \left(\frac{u}{u_0} \right)^{-1/2} \quad (B2)$$

where u is the gas velocity, and τ_0 , u_0 are reference values of the time constant and the respective gas velocity. We obtain the following relations for a growing fire, according to a power law time dependence, using the quasi-steady approximations:

$$\text{for } Q = q t^p \quad (B3)$$

$$\Delta T_G(t) \propto t^{2p/3} \quad (B4)$$

$$u(t) \propto t^{p/3} \quad (B5)$$

$$\tau(t) \propto t^{-p/6} \quad (B6)$$

and considering a sprinkler at a fixed position at a fixed position relative to fire.

Equation (B1) is solved in a closed form

$$\Delta T_s = \Delta T_G(t) \frac{e^{-\int_0^t \frac{dy}{\tau(y)}}}{t^{2p/3}} \int_0^t e^{\int_0^x \frac{dy}{\tau(y)}} \frac{x^{2p/3}}{\tau(x)} dx \quad (B7)$$

wherein eq (B4) has been used.

We can further observe, using eq (B6), that

$$\int_0^x \frac{dy}{\tau(y)} = \frac{x}{\tau(x) (p/6+1)} \quad (B8)$$

Moreover, with the following variables

$$\omega_0 = \frac{t}{\tau(t) (p/6+1)} \quad (B9)$$

$$\phi = \left(\frac{x}{t} \right)^{p/6+1} \quad (B10)$$

Equation (B7) can be written as:

$$\Delta Y \quad \Delta T_s = \Delta T_G(t) e^{-\omega_0} \cdot \omega_0 \int_0^1 e^{\omega_0 \phi} \phi^{\frac{4p}{p+6}} d\phi \quad (B11)$$

* The time constant is given by the relation $\tau = \frac{mc}{hA}$ where m is the mass of the sensing element, c its specific heat, h the convective heat transfer coefficient, and A the surface area of the sensing element.

or, in the more compact form:

$$\Delta T_s = \Delta T_G(t) e^{-\omega_o} \cdot \omega_o \int_0^1 e^{\omega_o(\phi + \frac{4p}{\omega_o(p+6)} \ln \phi)} d\phi \quad (B12)$$

The major contribution to the integral at the RHS of eq (B12) arises from values of ϕ of about 1. Using a Taylor expansion of the exponent, about $\phi=1$ and retaining only the first two terms of the expansion, we obtain:

$$\Delta T_s \cong \Delta T_G(t) \frac{1}{1 + \frac{1}{\omega_o} \cdot \frac{4p}{p+6}} \left[1 - e^{-(\omega_o + \frac{4p}{p+6})} \right] \quad (B13)$$

$$\Delta T_s \cong \Delta T_G(t) \frac{1}{1 + \frac{\tau(t) \cdot 2p}{t \cdot 3}} \left[1 - e^{-[\frac{2p}{3} + \frac{t}{\tau(t)}] \frac{6}{p+6}} \right] \quad (B14)$$

In general, the exponent in the term within the parenthesis at the RHS of eq (B14) is large, and the equation can be further simplified to

$$\Delta T_s \cong \Delta T_G(t) \frac{1}{1 + \frac{\tau(t) \cdot 2p}{t \cdot 3}} \quad (B15)$$

Equation (B13) can be shown to approximate the exact integral at the RHS of eq (B11) uniformly for all values of ω_o and p with an accuracy +20 percent at maximum. First, observe that the exponent of the dummy

variable $\frac{4p}{p+6}$ of the integrand at the RHS of eq (B11) varies from 0 to 4 for any positive value of p from 0 to ∞ . The integral at the RHS of eq (B11) can be calculated analytically as a function of ω_o for the integer values of $(4p/p+6)$ from 0 to 4. The exact functional form of the integral, multiplied by the exponential factor $\Delta T_G(t) \omega_o e^{-\omega_o}$, has been compared graphically (for $\frac{4p}{p+6} = 0, 1, 2, 3, 4$) with the RHS of eq (B13) and the maximum error was found to be +20 percent. The additional error introduced by dropping the term in parentheses at the RHS of eq (B13) has been estimated to be less than +15 percent for all the tests included in Figure 16. Finally, we have estimated, using the methods of asymptotic expansion and the previous observations, that the maximum deviation from the exact value of the approximate eq (B15) for all the tests included in Figure 16 is less than +20 percent with the exception of Test 34 for which the error is less than +30 percent.

The discrepancy between the theoretical (eq (17) of the text) and experimental (Figure 16) proportionality parameters can be attributed to the following factors:

1) an overestimation ($\sim +20$ percent) of the LHS of eq (16) associated with the asymptotic approximation of the exact solution (cf. previous discussion);

2) an ambiguity in the determination of the proportionality factor 9 at the LHS of eq (16) of the text. The selected value 9 corresponds to a best fit line with an associated experimental uncertainty ± 25 percent.

An exact solution of eq (B1) can be obtained for parabolic fires ($p=2$). The solution derived from eq (B12) is:

$$\Delta T_s = \Delta T_G \left[1 - \frac{1}{\omega_0} + \frac{e^{-\omega_0}}{\omega_0} \right] \quad (B16)$$

where ΔT_s is the sprinkler link activation temperature; ΔT_G is the gas temperature at the sprinkler location and

$$\omega_0 = \frac{3}{4} \frac{tu^{1/2}}{\tau_0 u_0^{1/2}} \quad (B17)$$

The gas temperature (ΔT_G) and velocity (u) can be represented by the following equations:

$$\Delta T_G(t) = g_1 (r/H) Q^{2/3} H^{-5/3} \quad (B18)$$

$$u(t) = f_1 (r/H) Q^{1/3} H^{-1/3} \quad (B19)$$

where g_1 and f_1 are functions of the normalized radial distance (r/H) from the fire axis. The forms of these functions have been determined from Ref 15

$$g_1 (r/H) = 4.54 \cdot 10^{-2} (r/H)^{-.9} \quad (B20)$$

($^{\circ}\text{C W}^{-2/3} \text{m}^{5/3}$)

$$f_1 (r/H) = 2.62 \times 10^{-2} (r/H)^{-.9} \quad (B21)$$

($\text{m/s w}^{-1/3} \text{m}^{1/3}$)

Equation (B16) can be used with the help of eqs (B17) to (B21) to predict the response time of detectors for a given fire configuration and sprinkler spacing.