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Suppression of Wood Crib Fires With Sprinkler Sprays: Test Results

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ABSTRACT

A series of fire tests was conducted to examine the effect of sprinkler sprays on the burning rate of materials. Tests were conducted on an array of empty cardboard boxes and two sizes of wooden cribs representing light hazard fuel packages. Free burn tests and tests with selected sprinkler sprays applied during the steady burning period were conducted. Free burn heat release rates are compared to heat release rates with sprinkler sprays operating.

Key Words: burning rate; compartment fires; crib fires; fire growth; fire tests; heat release rate; oxygen consumption; sprinklers.

1. INTRODUCTION

The General Services Administration has expressed a need for developing sprinkler design criteria for use in government office spaces which ensure adequate, cost effective fire protection. The Center for Fire Research at the National Bureau of Standards under the sponsorship of the General Services Administration, has completed the first phases of a multi-phase research project addressing the use of quick response sprinkler technology in office occupancies. The major areas of the first phases of this project were to 1) examine the potential applicability of quick response technology to office occupancies, 2) characterize office fuel packages, and 3) measure the effect of sprinkler spray density on suppression. The work to date has demonstrated some of the potential benefits of using quick response sprinkler technology and provided part of the basis for developing design criteria based on the fuel packages and the amount of water required to extinguish these packages.

The extension of quick response sprinkler technology to office occupancies has been addressed in a series of full scale demonstration tests[1][1]. These tests showed that quick response sprinklers operating within their design limits controlled a specific set of office fires as long as the water was flowing. These tests indicated that the conditions in the compartment remained sub-

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[1] Numbers in brackets indicate literature references at the end of the paper.

lethal. In addition, the tests provided heat release rate data for some typical office fuel packages.

The above tests did not address the minimum application rate of water to achieve control or extinguishment. Instead all sprinklers were operated in accordance with their Underwriters Laboratories listing. In order to examine design criteria for sprinklers in office space, it is desirable to have an understanding of effect of water application rate on fire control and extinguishment.

Therefore, a series of tests have been conducted which examine the effect of varying water application rates on the burning rate of fires of a size expected in office occupancies at the time of sprinkler actuation.

2. SELECTION OF FUEL PACKAGES

From previous tests, it was found that quick response sprinklers in office environments operated when fire sizes were the order of 400 kilowatts [1]. Therefore, it was decided to focus on fires with a heat release rate of approximately 400 kilowatts. Previous work on residential quick response sprinklers has concentrated on upholstered furniture. An informal survey of offices indicated that a significant portion of the fuel loading was cellulosic material being principally paper and some wood. As a result, it was decided to concentrate on cellulosic materials for these tests.

So the criteria for selecting a fuel package were that it be cellulosic material representative of office fuel packages with a heat release rate of at least 400 kilowatts in a free burn environment. In addition, the fuel package had to be reproducible and relatively inexpensive. A final criterion was that water could be applied at a time of known heat release rate. The tests were designed to focus on the effect of water spray on burning rate and not on sprinkler activation time. From a practical standpoint this required a low or zero natural fire growth rate at the time of water application.

A pilot test series was conducted to examine several candidate fuel packages. The first were simulated desks constructed of both particle board or plywood. These tests indicted that these combustible simulated desks with no paper material on them would not burn consistently and with sufficient heat release rate in the free burn environment to be used in this study.

The second fuel package examined was empty cardboard boxes. Tests were conducted using stacks of boxes with ignition on either the vertical or horizontal faces. These tests indicated that the growth rate of the fire was too rapid to apply water repeatedly at the time a predetermined heat release rate occurred. In addition, there was substantial variation in the sprinkler spray density over the area of the boxes, which would make the results difficult to characterize.

The final fuel package examined was wood cribs. Cribs have long been used to evaluate sprinkler performance and are the principle fuel in the Underwriters Laboratory test for listing standard sprinklers[2]. Cribs are also part of the fuel package used for listing residential sprinklers[3]. The Underwriters Laboratories tests are designed as pass-fail tests and do not directly provide information on burning and water application rates. Cribs can be constructed to provide a wide variety of burning rates and once fully ignited burn at an almost constant rate for a period of time. For the purposes of this study water could be applied during this steady burning period of known heat release rate.

The burning fuels in many real fires will be partially shielded from direct sprinkler spray impingement. The lower layers of a crib are partially shielded from direct impingement from overhead sprays. Cribs therefore can be considered to be representative of shielding found in office fuel packages. Because of the many advantages indicated, wood cribs were the primary fuel package used in this test series.

3. HEAT RELEASE RATE MEASUREMENT

The heat release rate of the burning fuel packages was determined using oxygen consumption calorimetry. A discussion of the principles of oxygen consumption calorimetry can be found in reference [4] and its use in determining the heat release rate of large furniture items in reference [5]. To summarize the method of oxygen consumption calorimetry, all of the gaseous combustion products from the burning item are designed to flow through a duct where the mass flow rate and the oxygen concentration are measured as a function of time. From these measurements the rate at which oxygen is consumed by the fire can be determined. For most common fuels the rate of heat release is proportional to the rate of oxygen consumption regardless of the fuel burned. In these tests, the collection and processing has been computerized with measurements taken and reported every 10 seconds.

4. METHOD OF WATER APPLICATION

The water spray used in the suppression tests was applied from commercially available sprinkler heads. The spray from the heads was therefore representative of sprinkler sprays found in practice. The heat sensing elements were removed from the heads and water application was remotely controlled by the test operator. The sprinkler head deflector was located 95.75 inches (2.43 m) above the floor and the sprinkler was offset radially from the fuel package. The offset distance varied according to the test conditions. No ceiling was installed for these tests.

The amount of sprinkler water spray which reaches the floor is commonly known as the sprinkler density with units of gallons per minute per square foot (millimeters per minute). Sprinkler density is usually measured by collecting the spray in pans over a period of time and measuring the water accumulated in each pan with no fire present. For the tests reported on here, 14 inch (0.36 m) square pans placed adjacent to one another were used with a collection time of 10 minutes. It has been shown density varies widely as a function sprinkler type, height above the floor, operating pressure and obstruction to the spray[6]. In addition, for a given set of conditions, the density varies significantly over the wetted floor area. Figure 1 shows an example of sprinkler density over half of a sprinkler spray pattern. Beyler measured a number of these spray patterns which can be found in reference [7].

In order to generate a number of different densities for the suppression tests a combination of techniques were used. These included varying the pressure and thus the flow, using different sprinklers, varying the orifice size and using two sprinklers simultaneously. In all cases spray patterns within the normal use range were maintained.

Early testing indicated that the local density over the area of the 14 inch (0.36 m) square pans was vary sensitive to minor variations in the flow conditions. As a result, densities were measured before and after each of the suppression tests. Uniform densities were impossible to achieve over large areas such as those used in the cardboard box tests. It was possible however to achieve relatively uniform densities over the area of the test cribs.

5. CARDBOARD BOX TESTS

Two free burn tests were conducted on cardboard boxes. Although not directly used in the subsequent analysis of minimum water flow rates for fire control performed with cribs, the cardboard box tests provide data of interest. The first test was on a vertical array of boxes and the second on a horizontal array of boxes. In addition, two sprinkler spray tests were conducted on horizontal arrays of boxes. The boxes used in each test were 18 inches (0.46 m) on each side with a weight of approximately 0.55 lb (1 kg). The boxes were empty and sealed with filament tape. A total of 32 boxes were used in each test and the configurations for the vertical and horizontal arrays are shown in Figure 2. The ignition source for the vertical box array was 100 ml of heptane in 3.75 inch (95 mm) diameter by 1.25 inch (32 mm) high pan. The ignition source for the horizontal box array was a 6 inch (152 mm) by 1/2 inch (13 mm) diameter braided cotton wick soaked in heptane.

The heat release rates for the cardboard box free burn tests are shown in Figure 3. This figure shows the growth rate for the vertical array is more rapid than for horizontal array. In addition, the peak heat release rate for the vertical array was nearly 3.6 MW while the peak for the horizontal array was approximately 1.6 MW. These tests indicated that it would be very difficult to apply water repeatedly to the vertical box fires at the same point during the growth stage of the fire. This is due in part to the fact that the data collection for heat release rate lags the actual fire development by approximately 30 seconds.

Two sprinkler spray tests were conducted with the horizontal box array. Average sprinkler densities of 0.043 and 0.065 gpm/ft^2 (1.75 and 2.65 mm/min) were used. The sprinkler densities over the area of the array are shown in Figure 4 and the heat release rates are shown in Figure 5. While these tests were able to measure the effect of sprinkler sprays on the heat release rate, as with the vertical boxes, it was difficult to apply water repeatedly at the same point during the growth stage of the fire.

When a fuel package as large as the horizontal box array is used there is typically a variation in sprinkler density over the fuel area. As shown in Figure 4, for an average density of 0.043 gpm/ft^2 (1.75 mm/min) over the fuel package the local density ranged from 0.025 to 0.056 gpm/ft^2 (1.02 to 2.28 mm/min) while for an average of 0.065 gpm/ft^2 (2.65 mm/min) the range was 0.040 to 0.090 gpm/ft^2 (1.63 to 3.67 mm/min). These local densities are measured over a 14 inch (0.36 m) square area and the actual local variation in density is likely greater. Although it was thought that the effect of density variations may average out over the area of the fuel, test observations showed that areas with very low density continued to burn while areas with higher density were extinguished. The water from the areas with higher density could not effectively reach the burning areas, indicating the density variations are not averaged out in these tests.

6. WOOD CRIB TESTS

Wooden cribs of two sizes were used in the test series. Both sizes were constructed of fir sticks 1.5 inches (38 mm) high by 1.5 inches (38 mm) wide and 2 ft (0.61 m) long. The sticks were fastened together with 8d common nails at both ends. The overall crib sizes were 2 ft (0.61 m) wide by 2 ft (0.61 m) deep with 6 sticks per layer. Two different heights were used, 1 ft (0.30 m) high with 8 layers of sticks and 2 ft (0.61 m) high with 16 layers. The 2 ft (0.61 m) high crib was effectively two of the 1 ft (0.30 m) cribs stacked one on top of the other. The 1 ft (0.30 m) high crib will be referred to as a single height crib and the 2 ft (0.61 m) high crib as a double height crib. The configuration of the cribs is shown in Figure 6. The cribs were placed on 4 in. (102 mm) high concrete blocks, one center on each side such that only the outermost sticks rested on the blocks. A 18 by 24 in. (0.46 by 0.61 m) metal pan with 600 ml of heptane was centered under the crib as an ignition source. The burning time of the heptane was approximately 120 seconds.

Table 1 gives a summary of crib test information. It shows the average sprinkler spray densities used in the crib tests. The averages were developed from water collection in four pans forming a square 28 inches (0.71 m) on a side. This area is slightly larger than the cribs which are 24 inches (0.61 m) on a side. Also shown in Table 1 are the highest and lowest densities from the 4 pans.

Table 1 gives the time during which water was applied in each test. Although it difficult to establish exactly when extinguishment occurred, this time is representative of the time at which all flaming and most of the smoldering had ceased. This time, when multiplied by the average density, gives the total water used per unit area which is an approximation of the water required for extinguishment. Table 1 also shows the crib weight and the distance from the sprinkler centerline to the leading edge of the crib. The crib weights include the weight of the nails used in constructing the crib. There appears to be a slight trend in the relationship between density and water used, indicating that higher densities require less water. This may be due in part to the difficulty in establishing an exact time for extinguishment and the variability in crib weights. More likely this results from less deep burning or charring in the cribs which were quickly extinguished.

To simplify the presentation of the results, the heat release rates have been adjusted so that the period of steady crib burning appears to begin at time zero. The time from ignition to spray application was normally 330 seconds, although this was extended in a few tests to allow for complete crib involvement. In those cases the heat release curves have been adjusted to show a uniform time of spray application.

Figure 7 shows the free burn heat release rate for the single and double cribs along with a single and double crib sprinkler test each with a density of 0.119 gpm/ft^2 (4.85 mm/min). This figure shows the heat release rate at the time of spray application ranged from 0.42 to 0.50 MW for the double cribs and from 0.20 to 0.27 MW for the single cribs. The heat release rates for both sprinkler tests show the rapid drop in heat release rate as the crib surfaces directly exposed to the spray are extinguished. The initial reduction in heat release rate is followed by a period of more gradual reduction as water drips down through the crib. Test observations show that water does not reach the floor under the crib until approximately the time of extinguishment. The initial reduction in heat release rate is almost the same for the single and double cribs but it takes a much longer time for water to reach the lower layers of the double crib.

Figure 8 shows the heat release rates for the complete series of single crib tests and Figure 9 the heat release rates for the double crib tests. Figure 8 shows a spray density of 0.02 gpm/ft^2 (0.82 mm/min) has almost no affect on the overall burning of the crib and there is a gradual reduction in extinguishment time as the density is increased from 0.039 gpm/ft^2 (1.59 mm/min) to approximately 0.1 gpm/ft^2 (4.07 mm/min). The test with a density of 0.061 gpm/ft^2 (2.49 mm/min) appears to fall out of place with respect to the other tests. This and the crossovers of the tests with densities over the range of 0.039 to 0.084 gpm/ft^2 (1.59 to 3.42 mm/min) are probably a result of the limits of test precision and small differences in the cribs and sprays. Densities from 0.1 to 0.2 gpm/ft^2 (4.07 to 8.15 mm/min) extinguished the single cribs so rapidly that differences are difficult to measure. Figure 10 shows only the tests with densities above 0.1 gpm/ft^2 (4.07 mm/min) on an expanded scale. From these tests it appears that a two-fold increase in density at the higher rates has almost no affect on the extinguishment of the fire.

The heat release rates shown in Figure 9 for the double cribs follow the same general trends as those for the single cribs. Although the number of tests is limited, it appears that a density of 0.2 gpm/ft^2 (8.15 mm/min) or greater would be required for rapid crib extinguishment.

7. COMPARISON WITH OTHER EXPERIMENTS

The data produced in these tests may be compared to results produced by other researchers in the fire suppression field. Each of the cribs used in these tests are open in the sense of the correlations for burning rate developed by Block[8]. That is, the burning rate of the crib is controlled by the internal surface area and not restricted by the porosity of the crib structure. The area of the exposed surfaces of a crib with a square cross section is given by [9].

$$A_E = 2nb^2[(2\ell/b+1)N-n(N-1)] \qquad (1)$$

where: b is the stick thickness (m)

n is the number of sticks per layer (-)

N is the number of layers (-)

ℓ is length of a stick (m)

From Block's study, the heat release rate of a burning open structure crib is

$$\dot{Q} = A_E E C b^{-0.5} \qquad (2)$$

where: E is the heat released from combustion of a unit mass of pyrolysis products ($kJ \cdot kg^{-1}$)

C is an empirical constant for the mass of pyrolysis product produced per unit surface area and unit time ($kg \cdot m^{-1.5} \cdot s^{-1}$)

Values of C for various materials are available from work by Block [8] and Quintiere and McCaffrey [10], and range from 0.88×10^{-3} $kg\cdot m^{-1.5}\cdot s^{-1}$ to 1.33×10^{-3} $kg\cdot m^{-1.5}\cdot s^{-1}$.

The value of C for the Fir wood used in this study can be calculated from equations 1 and 2 using the measured heat release rate and known crib geometry. For the two cribs used in these tests.

	Single Crib	Double Crib
b	= 0.0381 m	0.0381 m
n	= 6	6
N	= 8	16
ℓ	= 0.61 m	0.61 m
A_E	= 3.87 m^2	7.63 m^2
$\dot{Q}$	= 240 kW	460 kW

Using a value of E = 18600 $kJ\cdot kg^{-1}$ [8,10] the values of C calculated from equation 2 are found to be 0.65×10^{-3} and 0.64×10^{-3} $kg\cdot m^{-1.5}\cdot s^{-1}$ for the single and double cribs respectively.

In experiments by Tamanini [9], crib fires were extinguished by water sprayed predominately from the four sides of the crib. Based on his work, a critical water application rate to prevent complete loss of open crib structure during the burning was 0.0015 $kg\cdot m^{-2}\cdot s^{-1}$. To limit the mass loss during extinction to the order of 10 percent, he found that the water application rate must be increased to the range of 0.005 to 0.010 $kg\cdot m^{-2}\cdot s^{-1}$.

For the crib fires in this study, rapid extinction of the single and double cribs were achieved with water spray densities from the sprinkler of 0.1 gpm/ft^2 and 0.2 gpm/ft^2 (6.78×10^{-5} and 1.36×10^{-4} m/s). As an approximation, the rate of water application to the burning cribs may be calculated by multiplying the floor area occupied by each crib (0.372 m^2) by the product of spray density and water density, yielding water mass flow rates to the cribs of 0.025 kg/s and 0.050 kg/s corresponding to the 0.1 and 0.2 gpm/ft^2 spray densities. Dividing the rate of water application by the corresponding crib exposed surface area yields nearly equal values for both cribs tested for the area specific water application rate for rapid extinction of 0.0065 $kg\cdot m^{-2}\cdot s^{-1}$. This value is within the range of values found in previous testing by Tamanini.

As with Tamanini's work, the natural scatter of experimental results in spray extinguishment research at best allows estimates of fire control and extinction only within a factor of two. Although the spray geometry and crib scale were different in this study than pervious work by Tamanini, the results support continued use of crib surface area specific water application rates from 0.005 to 0.01 $kg\cdot m^{-2}\cdot s^{-1}$ for rapid extinction of wood crib fires.

8. SUMMARY AND CONCLUSIONS

These tests have provided some preliminary information concerning water application rates for controlling or extinguishing a selected group of light hazard fuel packages. In addition they have pointed out a number of difficulties in measuring the rate of water application required to control or extinguish fires.

The limited number of cardboard box tests did not provide sufficient information to generalize extinguishment of these fires. They did point out the difficulties in conducting suppression experiments on large fuel packages and also provided information on the heat release rate of these fuels.

The wood crib tests provided information on the rate of reduction in burning as a function of water applied and a limit above which the application of additional water made little difference. This critical limit was approximately 0.1 gpm/ft^2 (4.07 mm/min) for the single crib with an average heat release rate of 0.24 MW and 0.2 gpm/ft^2 (8.15 mm/min) for the double crib with an average heat release rate of 0.46 MW. For the wood cribs tested, a doubling of the crib size and the corresponding heat release rate resulted in a doubling of the water application rate to achieve rapid extinguishment. While this result may not necessarily apply to all fuel packages, it does indicate the importance of rapid sprinkler response in reducing the water requirement for rapid fire control. Calculations indicated that for wood cribs, the critical spray application rate could be predicted within a factor of two.

The variability of the measured sprinkler sprays points out the difficulty in establishing criteria using critical water application rates.. Local sprinkler densities have been shown to vary widely over the spray pattern and typically differ by a factor of two or more from the average values used for design purposes. The crib tests have shown that this variation could have a major impact on the time to extinguish or control the fire. As a result, the ability of water wetting of adjacent fuel to control fire spread should be examined when developing sprinkler density criteria. Fire development in wetted fuels has not been examined in this study.

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Table 1. Crib Test Summary

	Density							
	Low (gpm/ft^2)	High (gpm/ft^2)	Average (gpm/ft^2)	Average (mm/min)	Time* (s)	Total Water (gal/ft^2)	Crib Weight (lbs)	Distance from sprinkler to Crib (in.)
Single	free burn						45.9	
Cribs	0.020	0.021	0.020	0.82	1270	0.423	45.1	66
	0.033	0.045	0.039	1.59	1200	0.780	54.2	94
	0.054	0.060	0.058	2.36	700	0.676	46.4	66
	0.055	0.066	0.061	2.49	480	0.488	44.1	69
	0.046	0.106	0.078	3.18	730	0.949	46.7	69
	0.075	0.091	0.084	3.42	510	0.714	44.1	69
	0.091	0.107	0.099	4.03	270	0.446	55.0	66
	0.112	0.126	0.119	4.85	230	0.456	54.9	66
	0.112	0.141	0.126	5.13	240	0.504	54.6	66
	0.105	0.154	0.130	5.30	140	0.303	47.0	94
	0.169	0.205	0.196	7.99	100	0.326	50.4	66
Double	free burn						96.6	
Cribs	0.020	0.023	0.021	0.86	1151	0.403	95.7	66
	0.054	0.060	0.058	2.36	1240	1.199	89.4	66
	0.091	0.103	0.097	3.95	1140	1.843	104.5	66
	0.113	0.126	0.119	4.85	830	1.646	105.6	66
	0.112	0.133	0.124	5.05	750	1.550	107.0	66
	0.156	0.208	0.186	7.58	500	1.550	97.5	66

*Time over which water was applied during the test.

Sprinkler

10' - 6"

0.00	0.01	0.02	0.13	0.13	0.10	0.08	0.05	0.06	0.10	0.14	0.07	0.08	0.10	0.06	0.03	0.02	0.00	0.00
0.01	0.03	0.04	0.06	0.05	0.07	0.08	0.09	0.15	0.27	0.23	0.11	0.09	0.14	0.19	0.05	0.01	0.00	0.00
0.02	0.02	0.03	0.04	0.07	0.08	0.09	0.12	0.18	0.19	0.18	0.13	0.12	0.13	0.08	0.06	0.04	0.00	0.00
0.00	0.01	0.03	0.06	0.05	0.06	0.08	0.10	0.13	0.14	0.16	0.15	0.13	0.11	0.06	0.04	0.02	0.01	0.00
0.00	0.00	0.02	0.03	0.04	0.06	0.06	0.10	0.10	0.14	0.15	0.12	0.10	0.05	0.05	0.03	0.02	0.01	0.01
0.00	0.00	0.01	0.02	0.03	0.04	0.06	0.09	0.07	0.12	0.09	0.09	0.06	0.05	0.02	0.03	0.02	0.01	0.01
0.00	0.00	0.00	0.01	0.01	0.02	0.03	0.05	0.05	0.07	0.05	0.08	0.03	0.05	0.02	0.02	0.01	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.01	0.02	0.02	0.02	0.01	0.02	0.01	0.01	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

22' - 2"

Note: Density in gpm/ft^2
Areas in bold are densities greater than or equal to 0.1 gpm/ft^2

Figure 1. Sprinkler Density (20 gpm total flow)

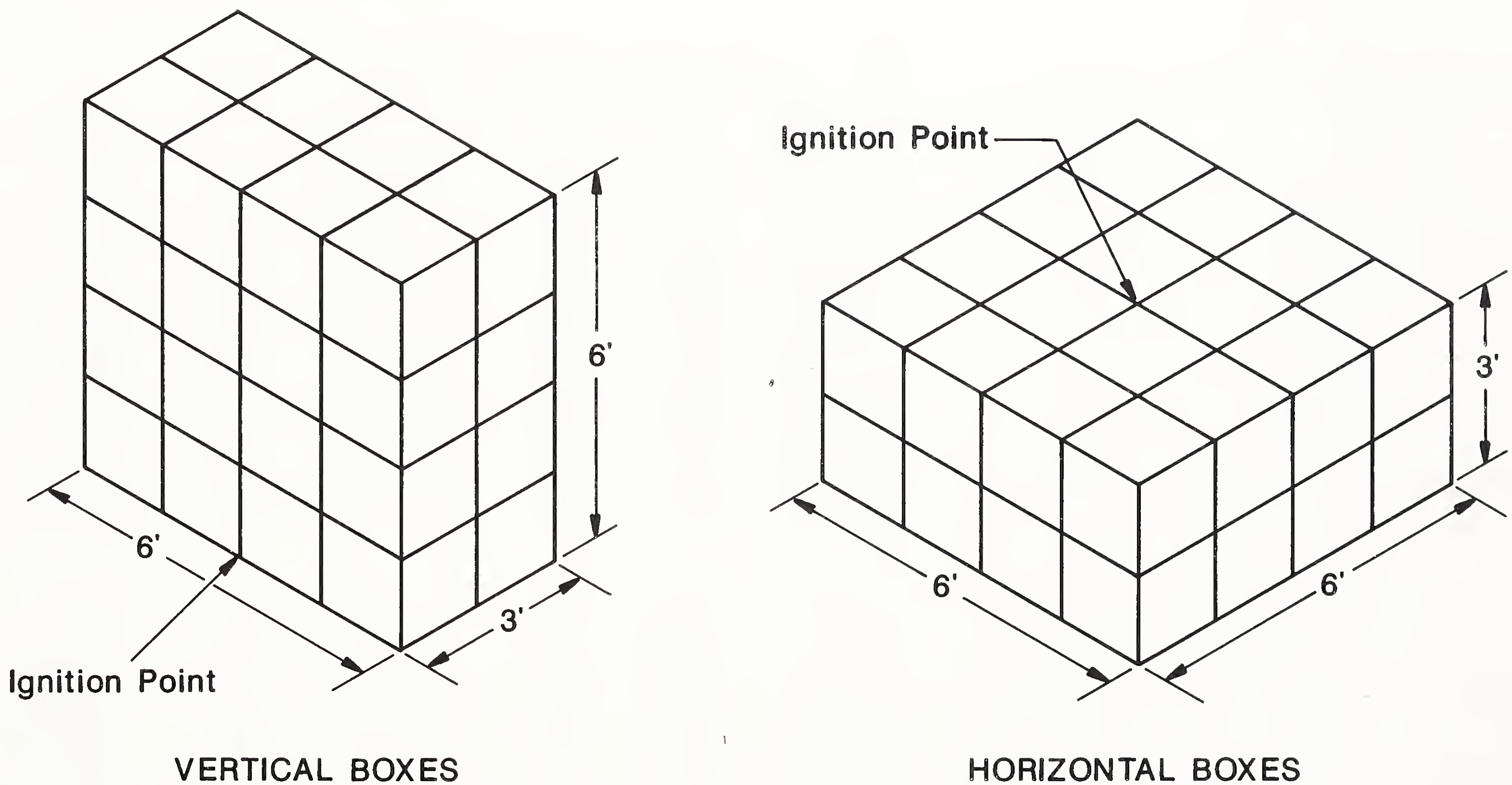

Figure 2. Cardboard Box Configurations

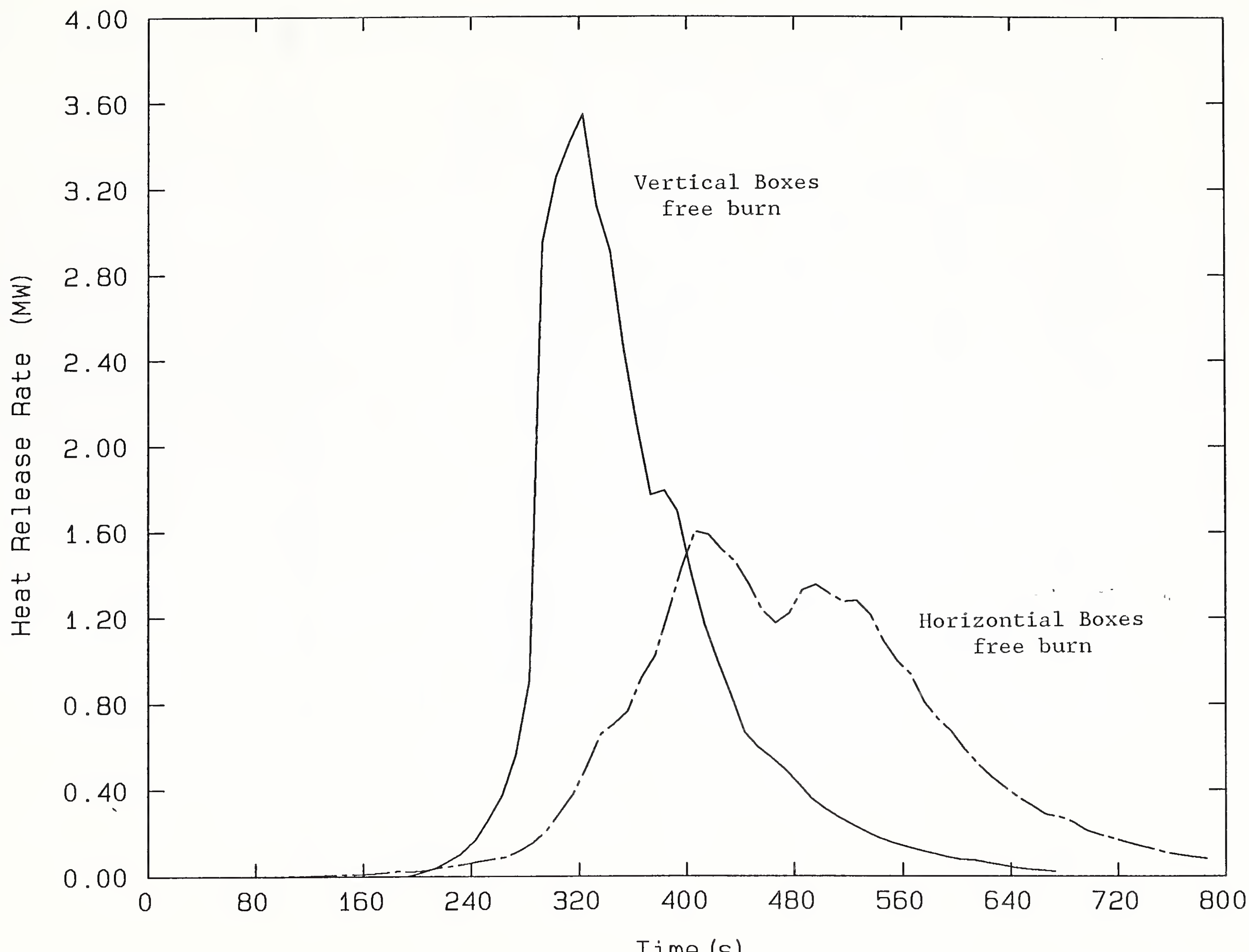

Figure 3. Cardboard Box Heat Release Rate, Free Burn

0.042	0.041	0.037	0.041
0.047	0.042	0.049	0.046
0.052	0.053	0.052	0.045
0.052	0.047	0.056	0.037
0.042	0.027	0.025	0.026

4′- 8"

Average = 0.043 gpm/ft^2

0.040	0.046	0.044	0.049
0.070	0.082	0.081	0.077
0.070	0.087	0.090	0.079
0.059	0.076	0.080	0.065
0.050	0.046	0.057	0.050

4′- 8"

5′- 10"

Average = 0.065 gpm/ft^2

Note: Density in gpm/ft^2

Figure 4. Sprinkler Densities for Horizontal Cardboard Box Tests

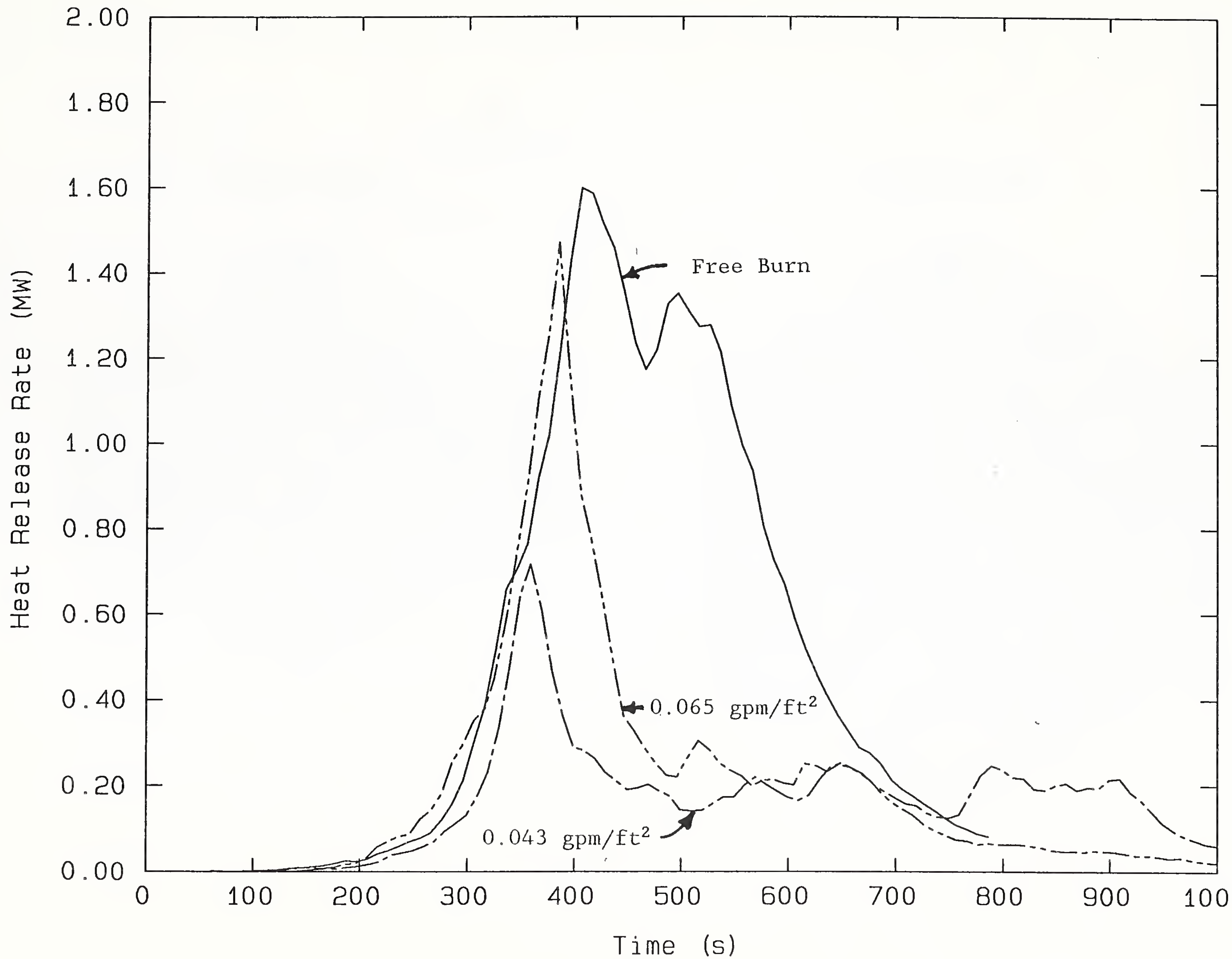

Figure 5. Horizontal Cardboard Box Heat Release Rate

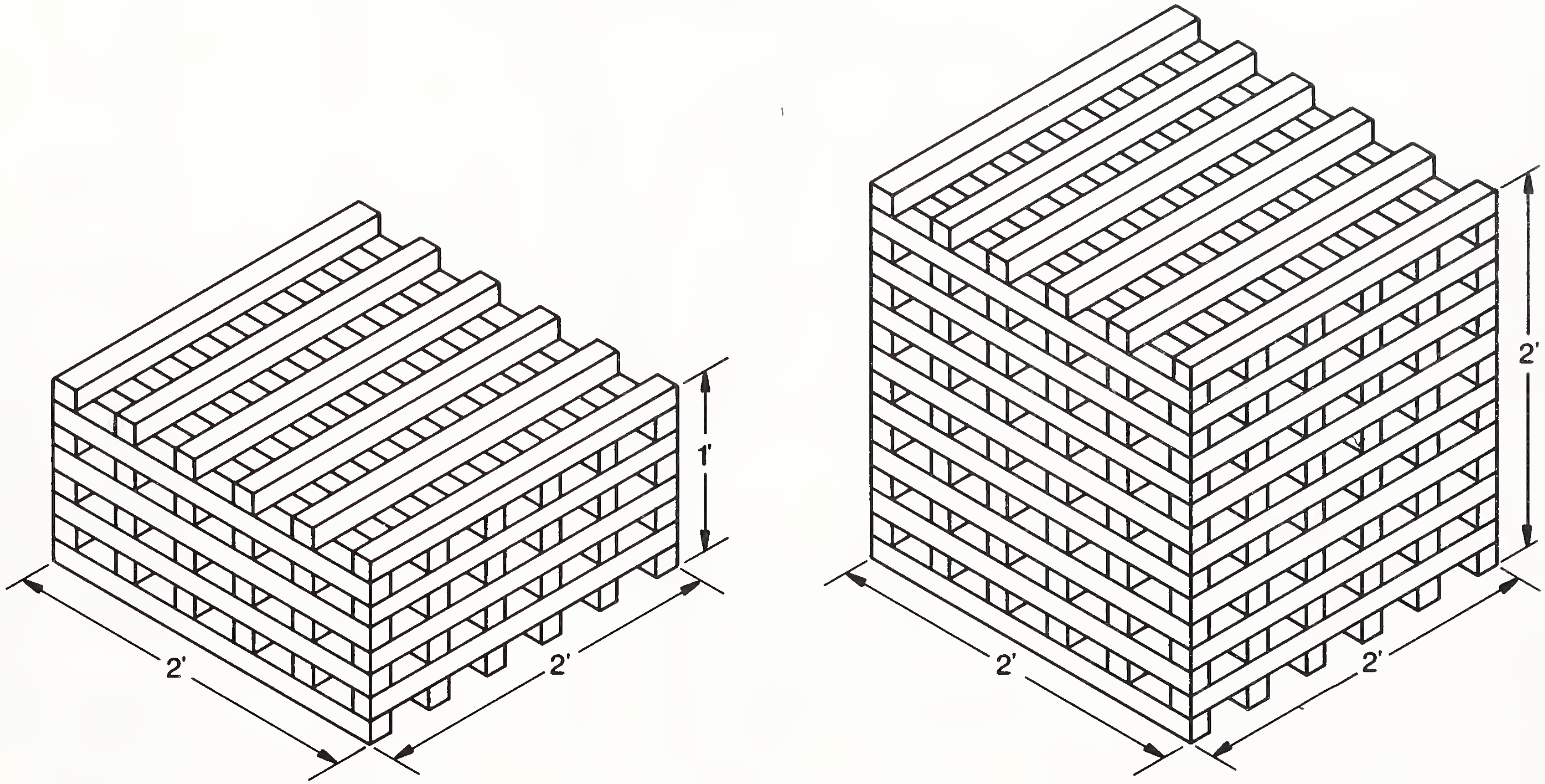

Figure 6. Crib Configurations

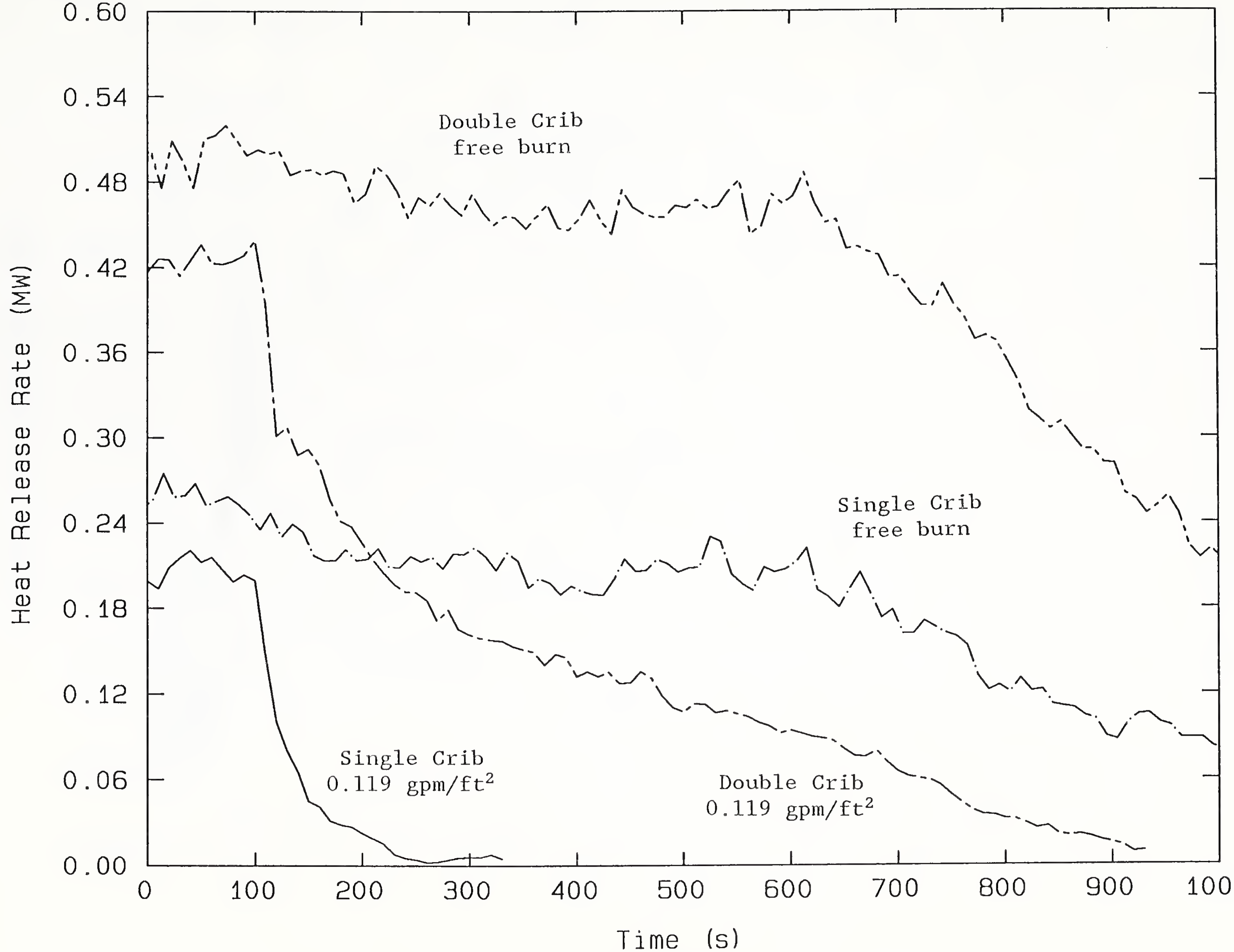

Figure 7. Single and Double Crib Heat Release Rate

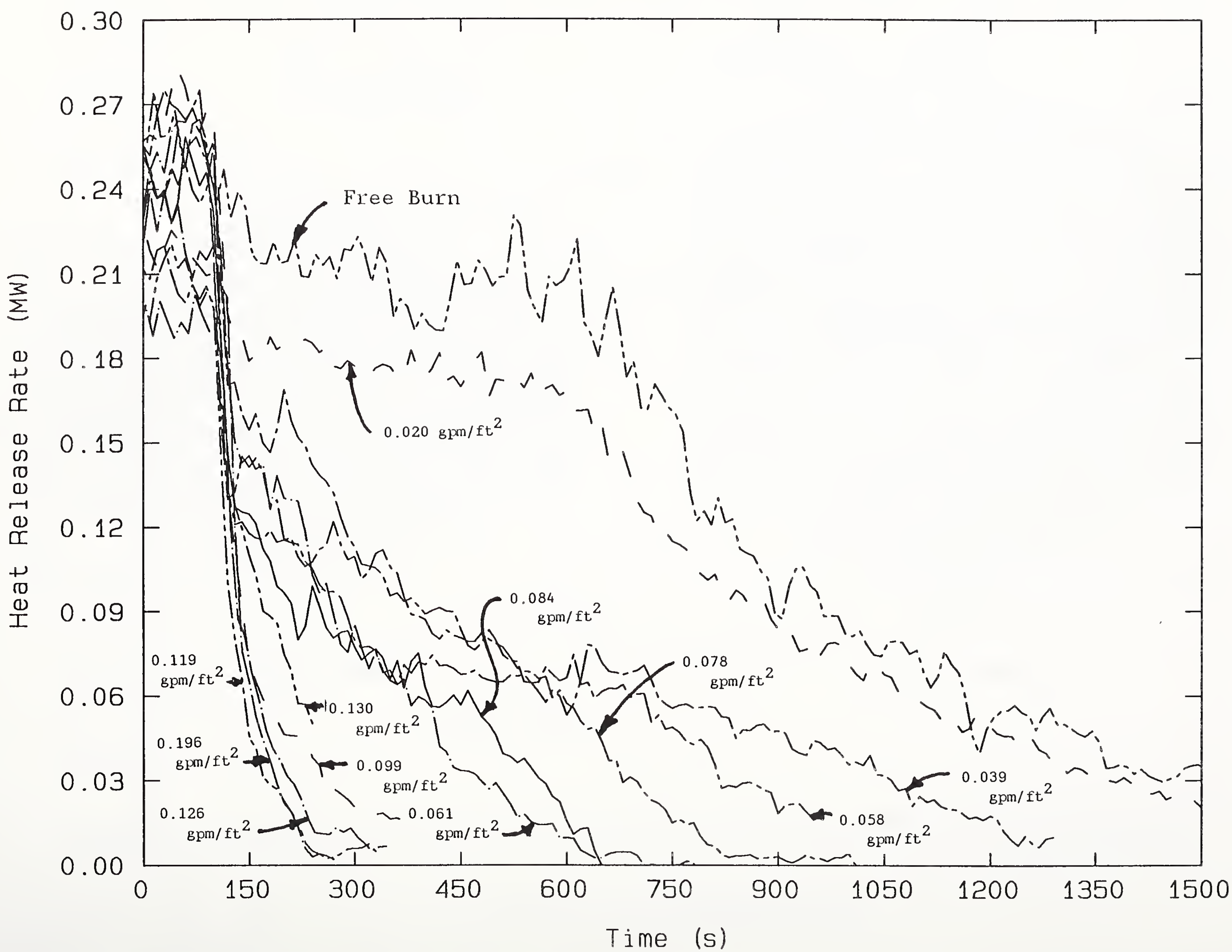

Figure 8. Single Crib Heat Release Rate

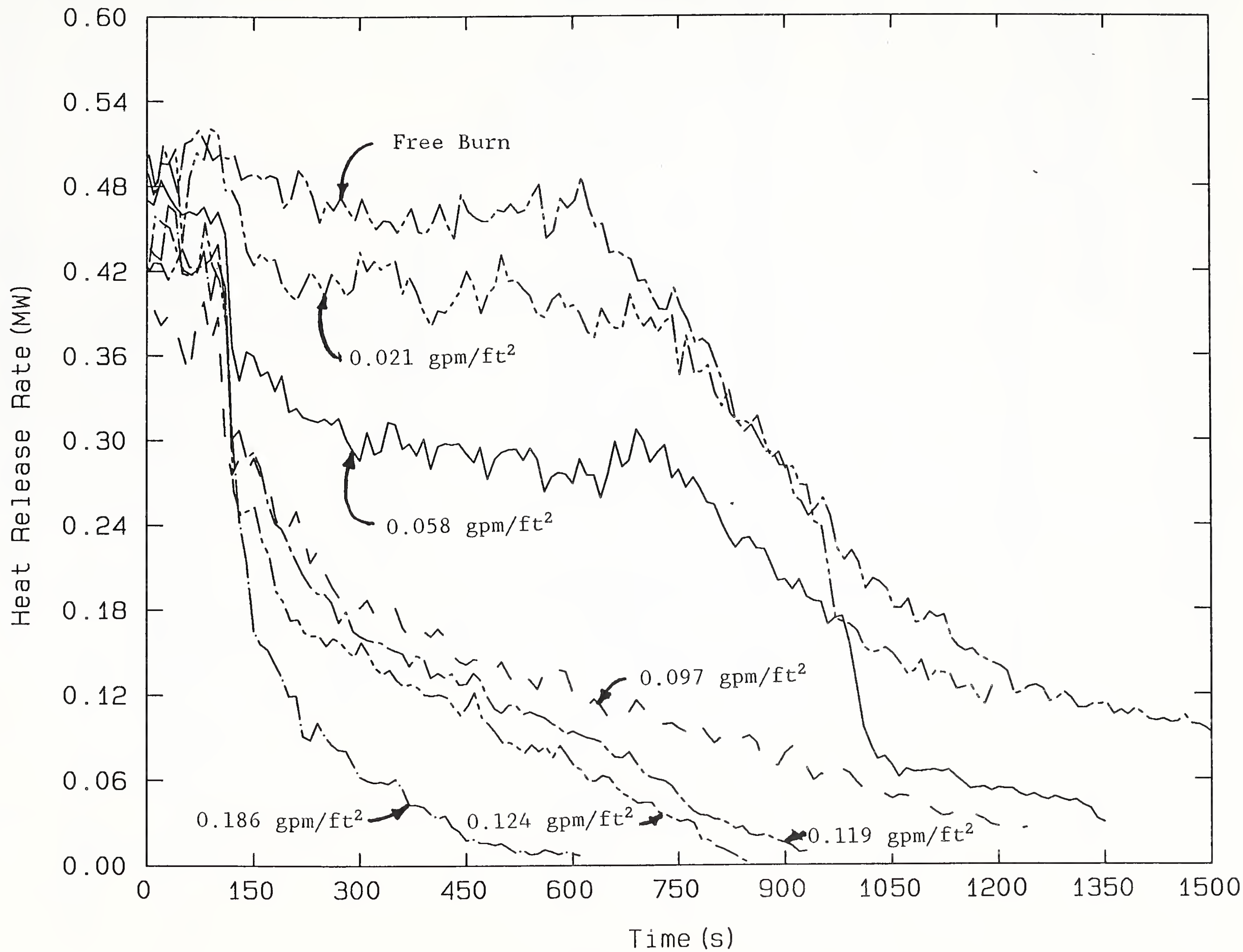

Figure 9. Double Crib Heat Release Rate

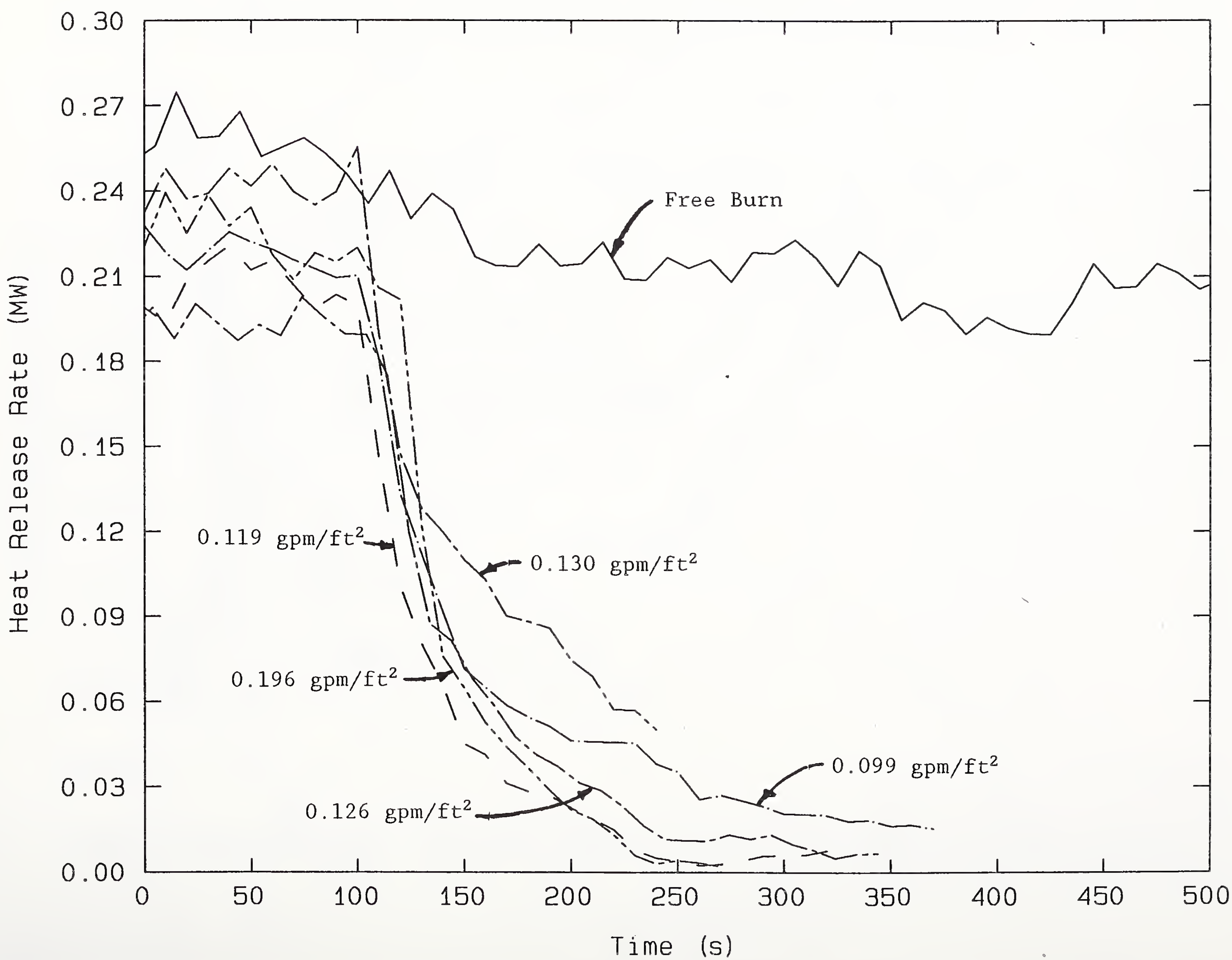

Figure 10. Single Crib Heat Release Rate, Spray Density Above 0.1 gpm/ft^2

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

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)*

A series of fire tests was conducted to examine the effect of sprinkler sprays on the burning rate of materials. Tests were conducted on an array of empty cardboard boxes and two sizes of wooden cribs representing light hazard fuel packages. Free burn tests and tests with selected sprinkler sprays applied during the steady burning period were conducted. Free burn heat release rates are compared to heat release rates with sprinkler sprays operating.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

burning rate; compartment fires; crib fires; fire growth; fire tests; heat release rate; oxygen consumption; sprinklers

13. AVAILABILITY

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