

Heat Absorption by Water in Rack-stored Corrugated Cardboard Carton Fires

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ABSTRACT

Heat absorption rates by water were determined for rack-stored, corrugated carton fires in which fire suppression was achieved. The carton was made of corrugated double triwall cardboard with metal liner. In these tests, water was applied uniformly on top of the fuel array when fire grew to selected fire sizes, and the water fluxes per unit exposed fuel surface area were much greater than the critical flux required for fire suppression. The test results indicate that, for identical fuel arrays after comparable periods of fire exposure, the heat absorption rate by water at a fire size tends to remain constant for different water fluxes. However, by applying the same water flux on identical fuel arrays, the heat absorption rate at a fire size becomes higher for a fuel array having a much longer period of fire exposure. For each storage height, the fraction of fire's total heat release rate absorbed by water can be correlated with the ratio of total heat release rate versus the total heat release rate at the time when water application is initiated.

KEYWORDS: Water-based fire suppression, water cooling

INTRODUCTION

A popular approach in warehouse storage currently is to store goods on metal racks. Rack storage provides an efficient loading and unloading operation and allows for increased storage height to maximize the storage capacity of a warehouse. Horizontal and vertical flues are formed in this storage arrangement, which promote flame spreading vertically and horizontally among stored goods. To design effective automated sprinkler protection of rack-storage fires, studies^(1,2,3) were performed for selected commodities to determine water fluxes required on top of rack storages to achieve fire suppression. In these studies, the history of total heat release rate of fire was used as an indicator of fire development under water application. Even though the macroscopic approach fulfilled its purpose to correlate the degree of fire suppression with water flux, little insight was gained on the interaction between water and fuel surfaces in the fire suppression process. The heat transfer in the flues from the flames to the stored goods is the dominant factor in fire development.

Test results have shown that faster fire suppression can be achieved with greater water flux applied on top of the rack storage. However, a study on water-film cooling of an object under thermal radiation shows that the heat absorption by water at a radiant heat flux would level off when the water application rate exceeds a threshold value⁽⁴⁾. If this finding of film cooling is applicable to the cooling of corrugated cardboard cartons in rack storage fires, and if water application is initiated at the same fire size for identical rack storages, the fire decaying rate (reduction of total heat release rate per second) should reach an asymptotic rate when water flux is greater than a threshold value. This expected asymptotic fire decaying rate is not consistent with the aforementioned observation in suppression of rack storage fires. To explore the mechanisms of fire suppression by water in rack storages, this paper focuses on the heat absorption by water during the fire suppression process in rack-stored, corrugated cardboard carton fires.

FIRE TESTS

The FMRC Standard Class II commodity was used. A pallet load of the commodity consists of metal-lined double (inner and outer) triwall cartons on a wood pallet, as illustrated in Figure 1. The outer carton measures 107 cm x 107 cm x 104 cm high and weighs 19.5 kg; the inner carton measures 104 cm x 104 cm x 96 cm high and weighs 18.6 kg. The flutes in the vertical corrugated cardboard of each carton are in vertical orientation. The steel metal liner, which has an open bottom, measures 96.5 cm x 96.5 cm x 94.0 cm high and weighs 22.2 kg. The slatted wood pallet has dimensions of 107 cm x 107 cm x 13.6 cm high and has a nominal weight of 23.4 kg. As a result, each pallet load has a nominal gross weight of 83.7 kg, of which about 74% is combustible.

A double-row steel rack was used to hold the commodity. The tested fuel arrays were two pallet loads wide and two pallet loads deep, and ranged from two tiers to four tiers high. Figure 2 illustrates the arrangement of a four-tier high array. Within each fuel array, 0.15 m wide flue spaces were kept between the vertical surfaces of the pallet loads, and 0.35 m horizontal spaces were kept between every two vertically aligned pallet loads. The overall heights for the two-, three-, and four-tier high arrays were 2.93 m, 4.45 m and 5.97 m, respectively.

A water applicator⁽²⁾ was placed 30.5 cm above the fuel array to deliver total water application rates ranging from 392 g/s to 1881 g/s directly on top of the fuel array. The water applicator consisted of eight parallel, double-jacketed, stainless steel pipes with eight spray nozzles along each pipe to form an 8 x 8 matrix of nozzles 30.5 cm apart. The applicator was cooled by passing water through the annulus between the inner and outer pipes while the water for fire suppression was supplied via the inner pipes. These spray nozzles produced 60-degree full cone sprays with median volumetric drop sizes ranging from 1.1 mm to 2.3 mm. The water pressures at the upstream and downstream manifolds of the inner pipes were monitored using two pressure transducers and the total water flow rate supplied to these inner pipes was monitored with a rotameter.

The ignition source consisted of four cellucotton rolls 7.5 cm long and 7.5 cm in diameter, each soaked with 120 ml of gasoline and wrapped in a polyethylene bag. The cellucotton rolls were placed near the central flue space of the fuel array at the bottom four corners of the lowest tier. A propane torch was used to ignite these cellucotton rolls.

A Fire Products Collector (FPC) was used to collect the exhaust gases released from the fire. The FPC is a large-scale calorimeter with an exhaust capacity of 30 kg/s of air at room temperature.

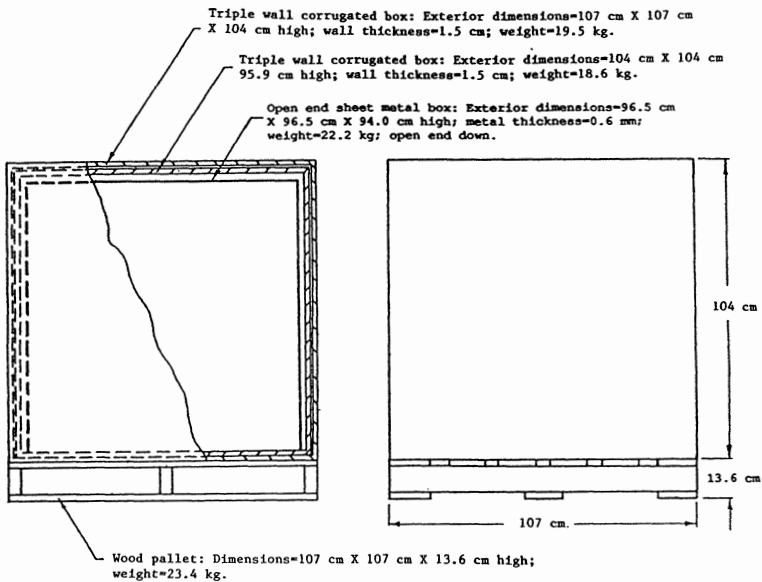


Figure 1. The Class II Commodity.

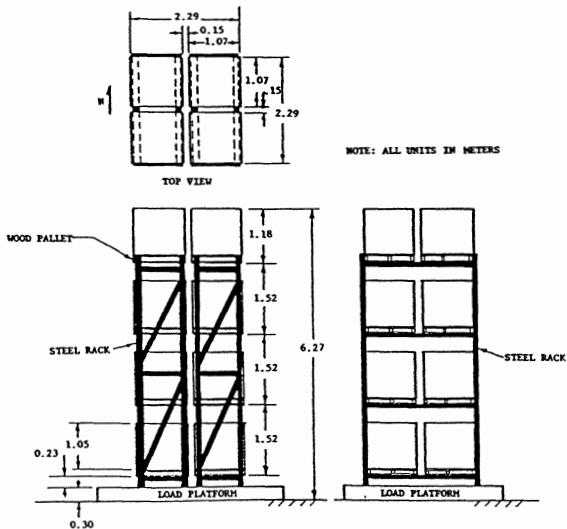


Figure 2. The 4-Tier High Fuel Array.

The FPC was instrumented to measure the gas temperature, gas flow rate and the concentrations of major combustion products (CO₂, CO, O₂ and total hydrocarbons) inside the FPC⁽⁵⁾. Based on the gas flow rate, gas temperature and gas concentrations in the FPC, as well as the ambient condition, the total (chemical) heat release rate and convective heat release rate could be derived⁽⁶⁾.

A radiometer of Type C-1 sensor (Sensor Inc.) with an Irtran II window was used to measure the radiant heat flux emitting out of the fuel array. The radiometer had a view angle of 40 degrees and was placed at a radial distance ranging from 10.0 m to 17.7 m from the vertical centerline of the fuel array to capture the entire projected area of the flame.

In each test, the water applicator was activated to deliver a pre-selected flow rate to the top of the fuel array when the heat release rate of the fire exceeded a pre-determined value. The test was terminated when the rate of convective heat flow in the FPC dropped below 50 kW or the test duration reached 30 min., whichever came first. Data signals were scanned seven times per second, and their average was recorded.

DATA ANALYSIS

The test conditions of the fifteen tests analyzed in this paper are tabulated in Table I. The water flux per unit exposed surface area is calculated by dividing the total water application rate to the fuel array by the total fuel surface area exposed to water application.

TABLE 1. Test Conditions

Test I.D.	Fuel Array (pallets)	Total Heat Release Rate at Water Application (kW)	Water Flux Per Unit Exposed Surface Area (g/m ² /s)
Rdd31	2x2x2	1860	8.9
Rdd81	2x2x2	2250	13.6
Rdd82	2x2x2	5540	18.6
Rdd83	2x2x2	2320	18.6
Rdd69	2x2x3	5210	12.9
Rdd70	2x2x3	2540	12.9
Rdd71	2x2x3	2900	9.5
Rdd72	2x2x3	2730	16.2
Rdd74	2x2x3	5470	19.1
Rdd36	2x2x4	4020	16.2
Rdd47	2x2x4	4740	17.9
Rdd51	2x2x4	3080	15.3
Rdd53	2x2x4	2580	16.2
Rdd57	2x2x4	3320	13.8
Rdd67	2x2x4	2810	9.8

The instantaneous total heat release rate of fire calculated based on the methodology outlined in Ref. 6 is the net heat release rate after the heat required to pyrolyze the fuel has been taken into account. As a result, the energy balance for the fire suppression tests can be expressed in the following:

$$\begin{aligned}
 & [\text{Net total heat release rate measured by FPC}] \\
 = & [\text{Rate of sensible heat carried by combustion gases and entrained air in FPC}] + \\
 & [\text{Rate of heat radiating to the ambient}] + [\text{Rate of heat penetrating into the cartons}] + \quad (1) \\
 & [\text{Sensible heat carried by water vapor}] + [\text{Rate of heat required for water evaporation}] + \\
 & [\text{Rate of heat carried by run-off water or stored in water trapped in the cardboard}].
 \end{aligned}$$

The total heat absorption rate by water is the sum of the last three terms of Eq. (1). For the fire tests analyzed in this paper, the vapor concentration in the FPC would range from 1.3% to 6.3% by mass if all the water applied to the fuel array were evaporated and all the vapor were preserved in the gas collection process. In reality, the mass fraction of water vapor in the FPC should be much less than the above figures because: 1) in most tests flames did not spread to the outside surfaces of the fuel array, and the major fraction of the water distributed on these surfaces was not involved in the fire; and 2) some fraction of water vapor was condensed on the walls of the FPC's gas collection cone and duct. Therefore, it is reasonable to assume that the convective heat flow rate measured based on the gas flow rate in the FPC approximates the sensible heat carried only by the combustion gases and entrained air.

Radiant heat flux measurements in previous rack-storage fire tests⁽⁷⁾ indicate that heat radiation was isotropic at the radial locations where radiant heat fluxes were measured in the tests analyzed in this paper. As a result, the rate of heat emitting to the ambient is the product of the measured radiant heat flux and the surface area of the sphere defined by the radial distance of the radiometer from the fuel array's vertical centerline.

In Ref. 3, a fire suppression parameter k for rack-stored Class II commodity is defined as:

$$k = \frac{\alpha (m_w'' Q_w - \beta m_f'' \Delta H_c + m_f'' Q_p)}{\rho_f C (T_p - T_\infty)} \quad (2)$$

where k has a unit of s^{-1} , and

α = the ratio of total burning surface area vs. total volume of fuel under pyrolysis;

Q_w = heat of evaporation of water per unit mass;

m_w'' = water flux per unit fuel surface area exposed to water application;

β = fraction of heat produced by flame transferred to the fuel surface;

m_f'' = fuel pyrolysis rate per unit burning surface area;

ΔH_c = heat of combustion of pyrolysate;

Q_p = heat of pyrolysis per unit mass;

ρ_f = fuel density;

C = specific heat of fuel;

T_p = pyrolysis temperature;

T_∞ = initial fuel temperature.

If a fire is suppressed, the k value of the fire is positive. The greater the k value is, the more easily the fire can be suppressed. The definition of k by Eq. (2) is applicable to different physical appearances of water on the fuel surface, i.e., film, rivulet, or droplet.

From data regression of fire suppression results for the Class II commodity, Ref. 3 gives:

$$k = 0.536 m_w'' - 0.004 \tag{3}$$

where m_w'' is in $\text{kg/m}^2/\text{s}$. From Eqs. (2) and (3), we obtain

$$\lambda = \frac{m_w'' Q_w}{\beta m_f'' \Delta H_c - m_f'' Q_p} = \frac{0.536 m_w''}{0.004} = 134 m_w'' \tag{4}$$

λ is the ratio of the heat required to completely evaporate the applied water flux versus the difference between the heat transferred from the flame to the fuel surface and the heat required for pyrolysis. If $\lambda \geq 1$, it is expected that insignificant fraction of $(\beta m_f'' \Delta H_c - m_f'' Q_p)$ would penetrate into the cartons. For the tests analyzed in this paper, m_w'' is in the range of $8.9 \text{ g/m}^2/\text{s}$ to $19.1 \text{ g/m}^2/\text{s}$. Based on Eq.(4), λ is in the range of 1.19 to 2.56. Therefore, it is reasonable to assume that the amount of heat penetrating into the cartons is negligible compared to the amount of heat for water evaporation.

From the above analyses, the rate of heat absorption by water can be reasonably approximated by subtracting the convective heat flow rate measured in the FPC and the rate of heat radiating to ambient from the net total heat release rate measured by the FPC.

Figure 3 shows the histories of heat absorption rate by water in two fire suppression tests using two-tier fuel arrays. A water flux of $18.6 \text{ g/m}^2/\text{s}$ was applied in both tests; however, the water application was initiated at a total heat release rate ($Q_{a,o}$) of 2320 kW in one test and 5540 kW in the other. Since the water applied from the top of the fuel array mainly cascaded down the array in films or rivulets on the carton's vertical surfaces, it is expected that, right after the instant of water application, the heat absorption rate by water (Q_{cool}) would increase with time as the films and rivulets progressively moved down to the bottom of the fuel array. As char formed on the burning surfaces, the crevices and fissures in the char effectively increased the contact surface area between water and hot combustion gases, which further increased Q_{cool} . As the fire gradually diminished, Q_{cool} would reach a maximum and then decrease as total heat release rate decreased. The above expectation appears to be supported by the way heat absorption rate varies with Q_a shown in Fig. 3. The figure also shows that the Q_{cool} value at the same total heat release rate is higher for the test with $Q_{a,o} = 5540 \text{ kW}$. The reasoning is provided in the following. The fire with $Q_{a,o} = 5540 \text{ kW}$ took longer than the fire with $Q_{a,o} = 2320 \text{ kW}$ to reduce to an identical fire size. As time elapsed, the char layer on a burning surface became thicker, which further increased the water contact surface area. Also, with longer fire exposure duration, more flames burrowed into the corrugated cardboard and forced combustion gases out through the wetted char and flutes in the cardboard, which enhanced heat transfer rate to water for the same fire size.

Figure 4 compares the heat absorption rates between two tests with nearly the same $Q_{a,o}$ but with different water fluxes. Since the critical water flux required for fire suppression is $6 \text{ g/m}^2/\text{s}^{(3)}$ for

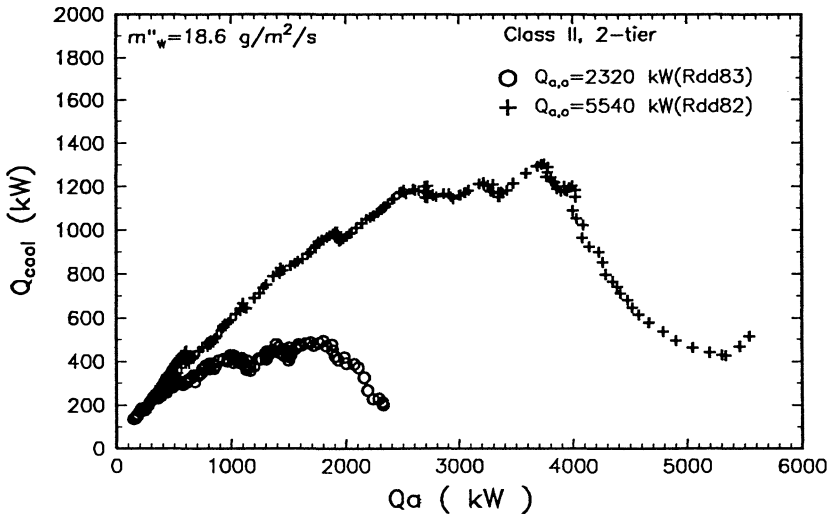


Figure 3. The Heat Absorption Rates of Tests Rdd82 and Rdd83.

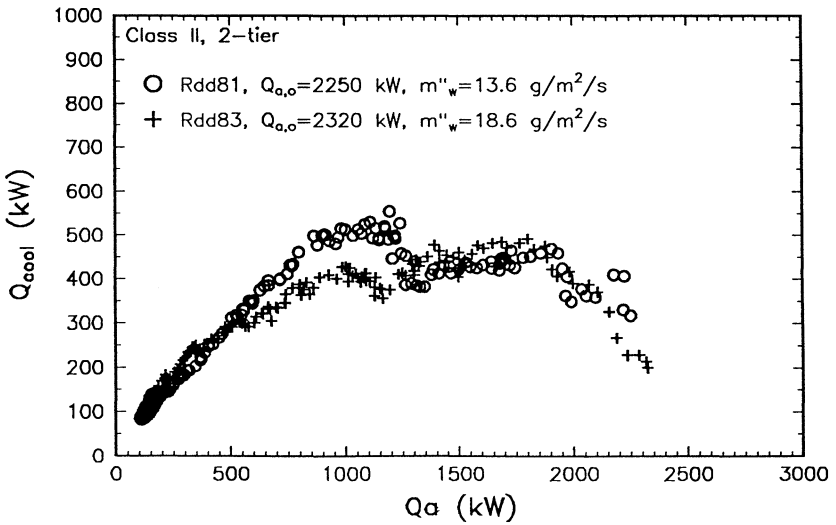


Figure 4. The Heat Absorption Rates of Tests Rdd81 and Rdd83.

Class II commodity, fast fire suppression was achieved for water fluxes of 13.6 and 18.6 g/m²/s used in these two tests. The results show that the Q_{cool} values at total heat release rates greater than 1300 kW are comparable between these two tests, a phenomenon similar to the heat transfer from a heat source to an object covered with water film reaching its asymptotic state when the application water flux exceeds a threshold value⁽⁴⁾. As a result, the amount of heat left for pyrolyzing fuel should also be comparable between these two tests at total heat release rates greater than 1300 kW. This reasoning would lead to the conclusion that these two tests should exhibit comparable fire decaying rates. However, tests show that the fire decaying rate after water application with 13.6 g/m²/s is smaller than the rate for 18.6 g/m²/s⁽³⁾, i.e., the test with 13.6 g/m²/s required a longer time to reduce the heat release rate from Q_{a,0} to a lower heat release rate. It is hypothesized that, as water flux increases, the tendency for pyrolysate to be dissolved and carried in the water films and rivulets becomes greater. Therefore, under the condition of asymptotic heat transfer described above, the fire still decayed faster under higher water fluxes because a greater fraction of pyrolysate was not burned. For total heat release rates less than 1300 kW, Figure 5 shows that the values of Q_{cool} for 13.6 g/m²/s is greater than that for 18.6 g/m²/s. This is consistent with the observation made with Fig. 3 since extra time was needed for the test with 13.6 g/m²/s to reduce fire size from Q_{a,0} to 1300 kW. Within this extra time period, the extent of increase of water contact surface area with 13.6 g/m²/s became relatively more pronounced so that higher Q_{cool} was realized. As the fire size diminished to around 500 kW, the heat absorption rates became comparable again for these two water fluxes. It appears that, for the fuel surface conditions at the later stage of fire suppression in these two tests, the higher water flux began to provide water contact surface area comparable to that provided by the lower water flux.

The results presented in Figs. 3 and 4 indicate that, with some degree of variation, there is some commonality on the relationship between Q_{cool} and Q_a among tests conducted with different Q_{a,0} and m_w". Figure 5 shows the fraction of the total heat release rate absorbed by water (Q_{cool}/Q_a) in the process of fire suppression for the two-, three- and four-tier fuel arrays. In the abscissa, the total heat release rate is normalized by the total heat release rate at which water application is initiated. For two- and three-tier fuel arrays, Q_a exhibits little overshoot beyond Q_{a,0} for the water fluxes listed in the figures. However, the overshoot is noticeable for the four-tier fuel array, i.e., the fire still grows momentarily after water application before the fire begins to recede at Q_a/Q_{a,0}~1.1. At the time when the fire begins to diminish, the nominal Q_{cool}/Q_a ratios for the two-, three- and four-tier fuel arrays are 0.13, 0.17 and 0.32, respectively, which are approximately proportional to the storage height. For each storage height, it is remarkable that, with expected variations, the Q_{cool}/Q_a ratio can be reasonably correlated with Q_a/Q_{a,0} for tests with different m_w" and Q_{a,0}. As time elapses, water is gradually absorbed into the cardboard of the cartons, which effectively increases the amount of water per surface area under constant water application rate. In the later stage of fire development, flames burrow into inner layers of corrugated cardboard. The hot gases are forced out through wetted cracks or flutes of the outer layers. As a result, the Q_{cool}/Q_a ratio increases as the fire diminishes. The Q_{cool}/Q_a ratios presented in Fig. 5 for the Class II commodity can be represented by the following equations.

For two-tier fuel arrays,

$$Q_{cool}/Q_a = -0.595(Q_w/Q_{a,0}) + 0.709 \quad \text{for } 0.1 \leq Q_w/Q_{a,0} \leq 1.0.$$

For three-tier fuel arrays,

$$Q_{cool}/Q_a = -0.715(Q_w/Q_{a,0}) + 0.925 \quad \text{for } 0.6 \leq Q_w/Q_{a,0} \leq 1.0;$$

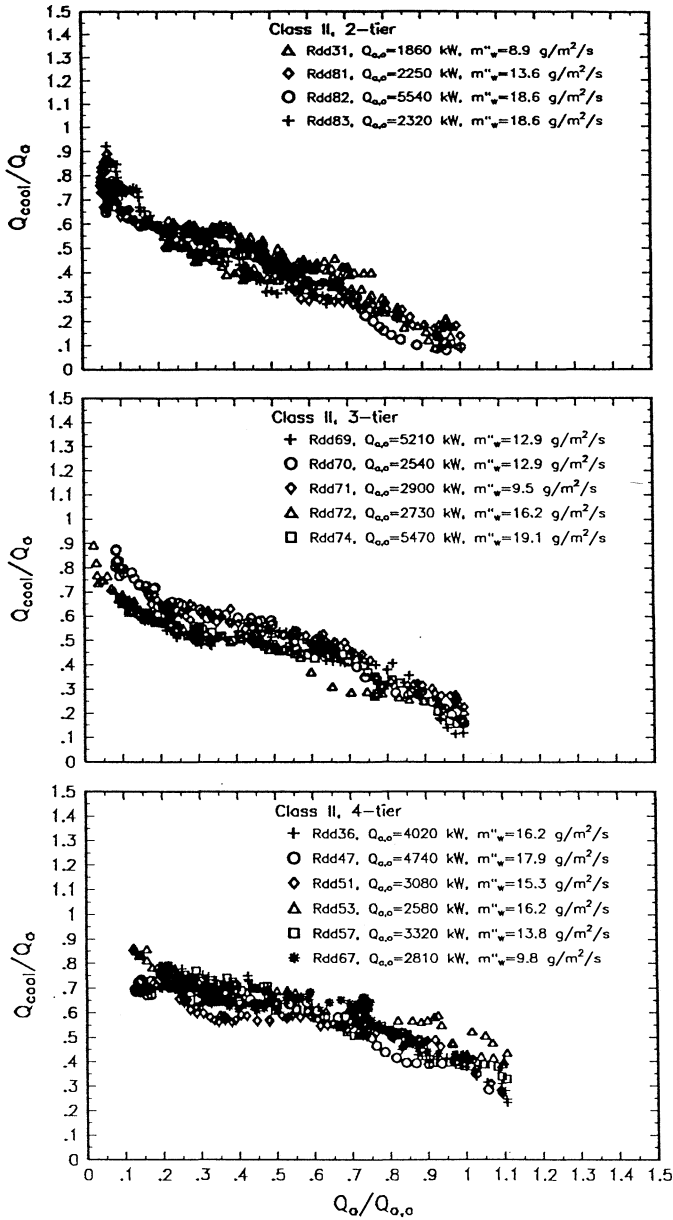


Figure 5. The Correlations between Q_{cool}/Q_a and $Q_a/Q_{a,o}$ for 2-, 3-, and 4-Tier High Fuel Arrays.

and

$$Q_{\text{cool}}/Q_a = -0.261(Q_w/Q_{a,o}) + 0.653 \quad \text{for } 0.1 \leq Q_w/Q_{a,o} < 0.6.$$

For four-tier fuel arrays,

$$Q_{\text{cool}}/Q_a = -0.498(Q_w/Q_{a,o}) + 0.897 \quad \text{for } 0.6 \leq Q_w/Q_{a,o} \leq 1.1;$$

and

$$Q_{\text{cool}}/Q_a = -0.341(Q_w/Q_{a,o}) + 0.803 \quad \text{for } 0.1 \leq Q_w/Q_{a,o} < 0.6.$$

It is expected that Q_{cool}/Q_a is close to unity when the fire is completely extinguished.

CONCLUSIONS

The heat absorption rates by water were determined for fire suppression tests using metal-lined, corrugated double triwall cartons in rack storage arrangements. The analysis indicates that, if the fuel surfaces of identical storage arrays have comparable morphological characteristics under similar fire conditions, the extent of cooling by water tends to level off for water fluxes much greater than the critical water flux to achieve fire suppression. Test results indicate that some fraction of fuel pyrolysate may have been dissolved in water and never burned in the fire suppression process. The unburned fraction becomes greater as water application rate increases. The analysis also shows that the fraction of total heat release rate absorbed by water increases as the fire diminishes. For each storage height, this fraction can be correlated with the ratio of total heat release rate versus the heat release rate at the time when water application is initiated.

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