Analysis of a Run-Away High Rack Storage Fire

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ABSTRACT

An intentionally set fire in a warehouse containing high rack storage resulted in total destruction of the structure and contents. The warehouse was protected by a sprinkler system designed for commodities stacked to heights substantially less than was resident at the site at the time of the fire. Consequently, enhanced fire growth and heat transfer, coupled with inadequate water spray distribution caused by the excessive storage heights, resulted in uncontrollable fire spread, and subsequent total destruction of the site. To evaluate and demonstrate the capability of the in-place sprinkler system to protect the structure and contents for the mandate storage height, a study was conducted to compare heat transfer conditions in the area above the racks for the design storage height, and for the actual storage height reported prior to the fire. The study involved experimental determination of fire growth and mass loss rate dynamics for parallel panels of heavy grade cardboard, simulating stacked boxes. The data was correlated in terms of formulas derived from theoretical analyses of upward flame spread and vertical mass burning, and the results used to predict upward flame spread rate, flame height and plume temperature rise in the rack fire. The thermal environment in the ceiling area above the racks, and the effect of sprinkler spray on the temperature reached by the ceiling/floor assembly, was then estimated for the two storage heights. The calculations were finally used to determine the ceiling structure endurance. To visualize the results of the study, a computer generated animation of the progress of the fire was also developed. For the design storage height, the results of the study show that the existing sprinkler system would have prevented structurally destructive thermal conditions in the ceiling, and would probably contained the fire in racks to near the area of origin.

KEYWORDS: Fire Spread, High Rack, Sprinkler Actuation

NOMENCLATURE

a	Parameter in flame length correlation
b	Parameter in mass loss rate correlation
c	Specific heat
d	Spacing between cardboard panels (mm)
h	Heat transfer coefficient
k	Thermal conductivity
l_f	Flame length from ignition source (m)
l_p	Pyrolysis length from ignition source (m)
$\dot{m}$	Mass loss rate (kg/m)
Q	Heat of combustion (KJ/Kg)
$\dot{Q}_s$	Energy transferred from the plume to the sprinkler water spray (KJ/m)
$\dot{q}''_f$	Heat transfer from the plume KJ/m
T	Temperature (^oC)
T_{fc}	Temperature of the flame/plume at the ceiling
T_L	Sprinkler temperature
T_{La}	Temperature for sprinkler link actuation
T_0	Initial temperature
T_p	Pyrolysis temperature
T_{pl}	Plume temperature
T_s	Temperature of structural member
T_{sc}	Critical temperature of structural member
t	Time (sec)
t_{ac}	Sprinkler link actuation time
t_{db}	Time for drop to reach the box top
t_{fc}	Time for flame tip to reach the ceiling
t_{fs}	Time for flame tip to reach sprinkler
t_0	Initial time
t_{sd}	Time to structural damage
u	Gas velocity (m/sec)
V_f	Flame tip velocity (m/sec)
V_p	Pyrolysis front velocity (m/sec)
V/A	Volume to area ratio
$\dot{V}''_s$	Sprinkler volumetric flow rate per unit area (m/sec)
ρ	Density
ε	Emissivity

<u>Subscripts</u>

ac	Sprinkler link actuation
c	Cardboard
d	Drop
f	Flame
L	Sprinkler link
0	Initial conditions
p	Pyrolysis
p*l*	Plume
s	Structural

INTRODUCTION

Because of current National Fire Protection Association Codes (NFPA), large fire losses in warehouses occur infrequently. However, if storage criteria mandated by the codes are ignored, then destructive fires can grow to intensities that overwhelm the fire protection capabilities built into the facility. When such fires do occur, they generally result in a contest between interested parties as to who is responsible and who should pay for the damages. Inevitably, the resolution of the contest is by litigation.

The subject event of this paper involves fire in a warehouse equipped with sprinkler protection designed for a limited height of storage of nominally flammable products. The owner of the warehouse leased the property to a distributor who was aware of the limited fire protection. However, in preparation for the Christmas holiday, the distributor filled the warehouse with products to the extent that the stack height and commodity type were far in excess of the fire protection capability of the sprinkler system. The fire in this case was ignited by the action of a bored guard for reasons unbeknownst to the authors.

In the year that it occurred, this fire was listed as one of the largest losses. It was initiated in a 18,580 m^2 warehouse were the ceiling height varied from 9.15 m to 7.6 m across the building width. The fire was discovered in a rear isle toward the high side of the building. Because of the approaching holiday season, the racks were loaded up to 7.9 m in this area, but the sprinkler array was designed for storage no higher than 6.1 m. When the fire was discovered, the flame height was about 1.8 m. Within five minutes the water flow alarm was received at the local fire dispatcher (the fire department had been alerted about 3 minutes earlier by the site supervisor). In 7 minutes the smoke layer was half-way to the floor, and 1 minute later the roof was penetrated. There were standard acrylic skylights distributed across the roof. By 25 minutes a major sprinkler riser failed and 75% of the building was burning. Factors that contributed to the destructive character of this fire were: 1) it was deliberately set, 2) the fuel load consisted of Class IV, Group A plastics, stacked in racks higher than NFPA 231-C recommendations for the resident sprinkler system design, 3) high cross winds resulting from open loading doors on either side of the building, and 4) failure of an 0.2 m sprinkler riser supported by the roof structure directly over the area of fire origin.

NFPA 231-C [1] provides recommendations for sprinkler protection of rack storage in terms of commodity type, rack configuration and commodity height. These recommendations were the result of extensive full scale tests where designed fires in rack storage were used to activate sprinkler systems with various head spacing and water flow characteristics [1,2]. The test evaluation criteria included: the number and location of fused heads, percentage area of fire damage in test array, and sprinkler operation area. The test results did not included data on the burning dynamics of the fuel array; i.e., vertical flame spread rate, mass loss or heat release rate. Consequently the test results were not helpful in defining conditions that could occur in rack storage fires that are not protected by or that overwhelm resident sprinkler systems. The present work aims to define those burning dynamics data so that the thermal conditions above the rack storage and their potential damage of the roof/ceiling assembly could be determined.

APPROACH

Although several studies have been conducted concerning different aspects of rack storage fires [3-5], there is a lack of data on burning parameters between parallel panels of container grade cardboard as those involved in the subject fire. This led us to conduct a series of tests for this purpose. A schematic of the rack arrangement to be studied is shown in Fig. 1. Measurements of the upward flame spread rate and mass loss rates on parallel cardboard panels were correlated in terms of a simplified model of the respective processes to produce predictive expressions for the spread of the flame and the evolution of the plume. This information was subsequently used to calculate the heating by the plume's hot gases of the ceiling/roof assembly, and of the sprinkler links actuation time. Revised calculation of the plume temperature after sprinkler actuation was then used to determine the time for structural damage of the roof members and the potential failure of the roof/ceiling assembly.

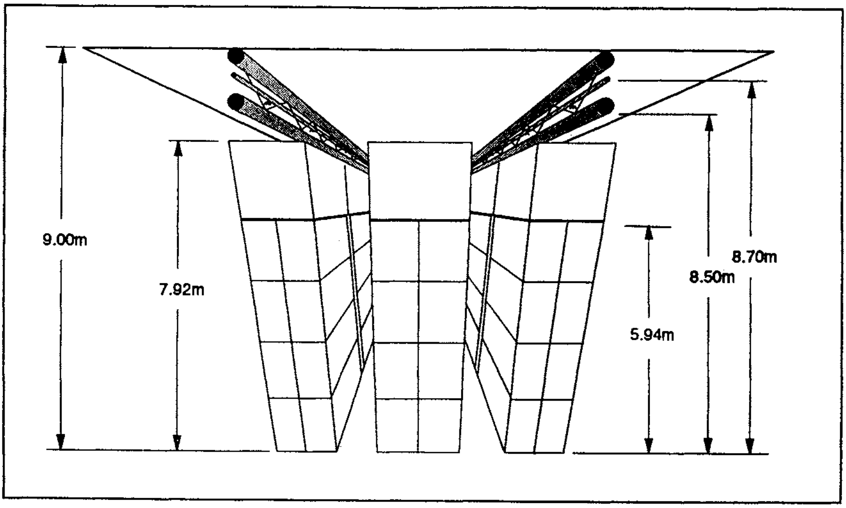

FIGURE 1. Schematic diagram of rack storage arrangement

Flame Spread and Mass Loss Tests

The test series, conducted at the Weyerhaeuser Fire Technology Laboratory, Longview, WA, consisted of measurements of the flame spread and mass loss rates for flames spreading upward between two cardboard panels at varied separation distances. A schematic of the experimental apparatus is presented in Fig. 2. The panels were 1.2 m wide by 1.8 m high made of heavy grade corrugate cardboard, and were spaced at distances that varied from 50 mm to 0.33 m, in 50 mm increments. The panels were mounted on a load cell. The ignition source was 3 ml of alcohol soaked in a wick and centered 0.33 mm above the bottom of each panel. The variation with time of the flame height was determined from video images of the progress of the flame, by averaging the visually observed location of the flame tip over determined periods of time. The mass loss rate was calculated from the load cell data.

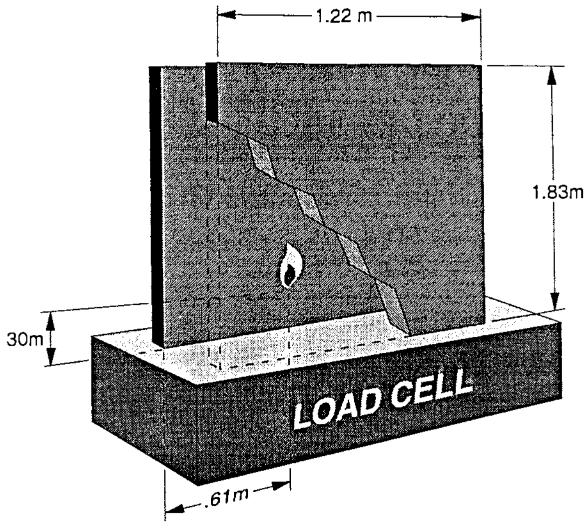

FIGURE 2.
Schematic diagram of flame spread experimental apparatus

Experimental Data Data from a series of measurements of the flame height as a function of time is presented in Fig. 3, for the different cardboard spacing tested. Two to three tests were conducted in each case to verify repeatability, and the maximum deviation observed between measurements was 15%. Flame spread rates are obtained from these data through the ratio of the corresponding height and time increments. In all cases, the spread rate accelerates as the flame propagates upward through the sample, in a manner similar to that observed in upward flame spread experiments over single vertical surfaces [6-8]. This accelerative trend is due to a larger increase in the flame length relative to the pyrolysis length, which is a strong determining factor of the flame spread rate. It is also seen from Fig. 3 that the flame spread decreases as the distance between panels is increased, in qualitative agreement with the results

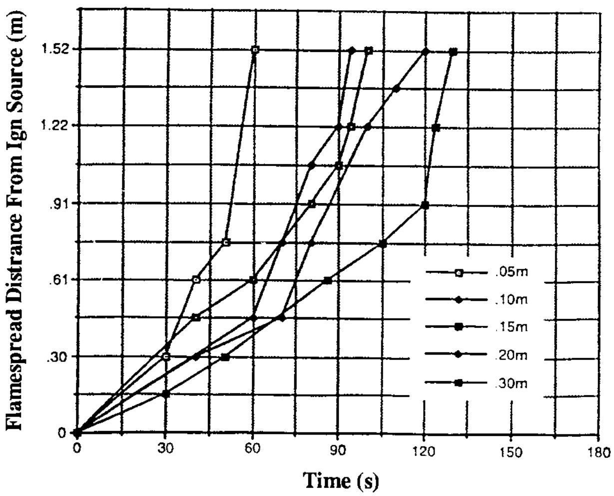

FIGURE 3.
Variation of the flame height with time for different panel spacing

from similar tests conducted with PMMA [9]. This is due to the combined effect of the reduced radiation heating between the surfaces and the reduced air flow induced by natural draft through the panels gap.

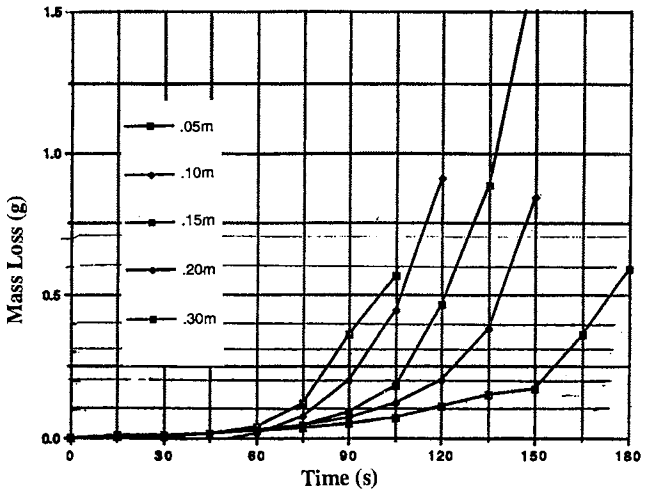

FIGURE 4. Variation of the mass loss with time for different panel spacing

Data of the mass loss measured during the flame spread tests of Fig. 3 are presented in Fig. 4. The mass loss follows a similar trend as the flame spread rate, increasing as the flame spreads upward through the cardboard panel, and decreasing as the distance between cardboard is increased. The former is due to the increase in the pyrolysis region as the flame spreads upward along the cardboard surface, and the latter to the reduced interaction between surfaces. These results agree qualitatively with those of Ref. [10] for the burning of vertical solid combustible panels exposed to the heat flux from a radiant panel mounted parallel to the combustible surface.

<u>Data Correlation</u> The similarity between the data in Fig. 3 and that from upward flame spread over single surfaces suggest the use of upward flame spread theories already developed for single surfaces to correlate the present measurements. In upward flame spread, the naturally induced air flow moves upward in the direction of spread pushing the flame ahead of the pyrolysis front and, consequently aiding its propagation. The flames spread by heating the virgin material ahead of the pyrolysis front to its pyrolysis temperature, by radiation and convection, at which point the material starts to vaporize, thus maintaining the spread of the flame in a creeping fashion. The rate of flame spread is then given by the ratio of the flame length above the pyrolysis front, and the time required to heat up the material from its initial temperature to its pyrolysis temperature. Assuming that the heat flux from the flame to the solid combustible is constant, that the flame spread rate remains approximately constant during the heating time, and that the solid behaves as thermally thick, the following expression is obtained for the spread rate [11] (the notation is given in the nomenclature).

$$V_f = 4\,\dot{q}_f''^{\,2}\, l_f \,/\, (\pi\, k_c\, \rho_c\, c_c\, (T_p - T_0)^2) \quad (1)$$

Studies of single surface burning show that the flame height is approximately related to the pyrolysis length by a relation of the form [6,12]

$$l_f = c_f \, l_p^n \tag{2}$$

Where c_f is a constant and n is close to unity. It is assumed here that this relation will hold for flame spread between parallel panels, although the values of c and n will probably depend on the spacing between panels.

Considering that $V_p = dl_p/dt$, or similarly that $V_f = dl_f/dt$, substitution of Eq. (2) in Eq. (1) and integration in time gives the following relation for the progress in time of the flame height

$$l_f = l_{f0} \, e^{a(t - t_0)} \tag{3}$$

with $a = 4 \dot{q}_f^{"2} c_f / (\pi \, k_c \, \rho_c \, c_c \, (T_p - T_0)^2)$. The effect of the separation distance between panels on the flame spread rate should appear through the flame length to pyrolysis length ratio, i.e, through c in Eq. (2), which should decrease as the distance is increased due to the increased surface heat flux and resulting pyrolysis rate, and through the heat flux in Eq. (3), that also should decrease with the increased spacing between panels. To the best knowledge of the authors no theoretical analysis of this effect has been published to date.

The similarity between the spread rates predicted by Eq. (3) and the experiments suggests the use of the equation to correlate the experimental data. It is found that Eq. (3) correlates quite well the experimental data of Fig. 2, with the following values of the coefficients,

$l_{f0} = 0.24$ and $a = 1.5 / d + 0.01$

with d given in mm. Equation (3) with the above values for l_{f0} and a will be used to predict the flame spread over the cardboard boxes in the storage rack under study here.

The mass loss of combustible material is given by the product of the mass burning (pyrolysis) rate and the area of the solid pyrolysing surface. The variation with time of this area is determined primarily by the rate of upward flame spread, because the lateral flame spread is small compared to the upward flame spread. Then, if the mass burning rate is approximately constant, the mass loss should have a similar time dependence as the spread rate. Thus, it is appropriate to attempt the correlation of the mass loss data with a time function similar to that of Eq. (3). Following that approach it is found that the mass loss data of Fig. 3 is correlated well with the following expression

$$\dot{m} = m_0 \, b \, e^{b(t - 2t_0)} \tag{4}$$

with $b = 4.1 / d + 0.013$. Once the mass loss rate is known, assuming that all the vaporized fuel is burned in the gas phase, the rate of heat released is obtained by simply multiplying the mass loss rate by the heat of combustion of the combustible material. Experimental measurements of the heat released for a given mass loss gives a value for the heat of combustion of cardboard of Q=20 MJ/kg.

Heat Transfer Modeling to Ceiling Assembly

As the flames propagate upward along the surface of the stack of cardboard boxes, the plume of hot, burning or post-combustion, gases eventually reaches the ceiling structure and starts heating its components. This aspect of the problem is analyzed in this section. There are several aspects of this modeling effort to be considered; 1) predicting the sprinkler link heating and activation; 2) determining the effect of the sprinkler water spray on the plume temperature; 3) predicting the temperature within the roof system; 4) determining when the structural steel columns and girders would weakened to the point of collapse; 5) comparing the results for the two cases of rack heights under study.

Sprinkler Link Heating and Actuation The temperature increase of the fusible link of the sprinkler, due to the heating from the ceiling spreading plume and flame, can be approximately calculated using a lumped formulation energy analysis, and assuming an average plume temperature and emissivity. This approach gives the following expression for the link temperature

$$T_L = \dot{q}''_f (t - t_{fc}) / (\rho_L \; c_L \; (V/A)_L) + T_{L0} \tag{5}$$

with the heat flux at the link surface given by

$$\dot{q}''_f \approx h_L (T_{fc} - T_L) + \sigma \varepsilon (T_{fc}^4 - T_L^4) \tag{6}$$

The sprinkler will actuate when its temperature reaches the link actuation temperature T_{La}. Thus, from Eq. (5), the sprinkler actuation time is obtained from Eq.(5) as

$$t_{ac} = ((T_{La} - T_{L0}) \; \rho_L \; c_L \; (V/A)_L) / \dot{q}''_f + t_{fc} \tag{7}$$

with an average flame/plume temperature at the ceiling of $T_{fc} = 815^oC$, with a sprinkler actuation temperature $T_{La} = 141^oC$, and assuming a lead link with $(V/A)_L = 0.01$, $h_L = 17.034 \; W/(m^2K)$, Eq. (7) gives for the actuation time

$$t_{ac} = 23 + t_{pc} \tag{8}$$

It should be noted that using the approach of Ref. [14] and assuming a RTI = 173 $(m \; s)^{1/2}$ and $u_{jc} = 1.3$ m/s a practically identical expression is obtained for the actuation time.

Plume cooling by the Sprinkler Water Spray Once the sprinkler actuates, the spray of falling water droplets will cool, by water heating and evaporation, the hot rising gases in the plume. To simplify the analysis, we will assume the conservative case that the drops will only reach the top of the boxes where they will be absorbed by the cardboard, and that they will not penetrate through the boxes spacing. Furthermore, assuming a drop diameter of 0.5 mm, it can be shown that the time for the drop to reach the top of the boxes is much smaller than the droplet life-time. Thus, for the purpose of this analysis it can be assumed that the drop diameter does not change during its fall period, and that all the heat reaching the droplet is absorbed at its surface. With this assumptions, the total energy transferred to the water spray by the plume is given by

$$\dot{Q}_s = 3\,\dot{V}_s''\,\dot{q}_f''\,t_{db}\,/\,r_0 \tag{9}$$

Using Eq. (9) in an energy balance of the column of hot gases in the plume flowing upward from the top of the boxes to the ceiling gives the following expression for the temperature drop in the plume due to the spray cooling

$$\Delta T_{pl} = \dot{Q}_s\,/\,(\rho_{pl}\,u_{pl}\,c_{pl}) \tag{10}$$

The numerical application of the above equations gives the following values for the cooling time (drop falling time), energy transferred, temperature drop, and plume average temperature at the ceiling, for the two rack heights considered

Low rack:	$t_d = 0.76$ s,	$\Delta T_p = 140^oC$,	$T_{pc} = 657^oC$
High rack:	$t_d = 0.42$ s,	$\Delta T_p = 66^oC$,	$T_{pc} = 732^oC$

Structural and Roof Response to Heating The exposure of the structural columns and girders, and of the roof/ceiling assembly to the plume hot gases, results in an increase in their temperature that depends on the plume temperature and exposure time. The objective of this section is to calculate the temperature increase of the roof structural members, and to determine if, and when, they would be weakened to the point of collapse.

The steel columns and girders had a cross-sectional area to perimeter ratio of approximately 0.01. The roof/ceiling assembly was a typical hot-mopped system consisting of a 1.5 gage metal roof deck forming the exposed ceiling. The sheet metal was covered with 19 mm thick insulation board upon which were laid three plys of fiberglass each being hot mopped with asphalt. The asphalt was then covered with a layer of gravel.

Using the analysis of Ref. [15], the above information concerning the plume temperature at the ceiling is used first to calculate the temperature increase and the structural damage to one of the girders supporting the joists and ceiling. The resultant temperature increase of a structural member due to convective and radiative heating from the hot gases in the plume is approximated by

$$T_s = \dot{q}_f''(t - t_{fs})\,/\,\rho_s\,c_s\,(V/A)_s + T_{sc} \tag{11}$$

Then if T_{sc} is the critical material temperature at which the structural material will weaken, the time to structural damage will be

$$t_{sd} = \rho_s\,c_s\,(V/A)_s\,(T_{sc} - T_{s0})\,/\,\dot{q}_f'' + t_{fs} \tag{12}$$

The girders in this case are made of steel angle (76x76x6 mm) with V/A = 0.01 and T_{sc} = 538°C. The following results are obtained for the time to structural damage: a) Without sprinkler actuation $t_{sd} = 142 + t_{fs}$ (sec) b) With sprinkler actuation and high rack $t_{sd} = 193 + t_{fs}$ (sec) c) With sprinkler actuation and low rack $t_{sd} = 258 + t_{fs}$ (sec) It is seen that the time to initial structural damage is almost a minute longer for the low racks and it nearly doubles that without sprinklers.

To determine the temperature increase of the roof ceiling assembly, a modified version of the TS Subroutine of the Ohio State University (OSU) Fire Model was used. The algorithm calculates the surface and interior temperatures of the boundary elements of the components of fire origin by employing a finite difference method to solve the transient heat equation. Since the heat transfer algorithms in the OSU code permit only a single, homogeneous material as a compartment boundary element, for the present analysis, the algorithm was removed from the OSU code to stand alone as a heat transfer analysis, and expanded to model a heterogeneous assembly. The modified program was then used to calculate the ceiling/roof heating by the plume and the time for roof failure.

COMPUTER ANIMATION

The fire dynamics predictions from the above analysis together with relevant information from previously published work [16-20] were used to generate a computer animation to visualize the sequence of events that occurred during the warehouse fire. Based on building blueprints, photographs, inventory lists, and other relevant information, a computer model of the warehouse was created. An introductory computer animated sequence was developed to aid in orienting the viewer to the pre-fire layout of the building, including pertinent characteristics of building construction, and the storage configuration. This base line sequence clearly displayed the skylights and sprinkler grid. In addition, the interior ceiling assembly was shown in detail. The results of the fire analysis were formatted and inputted into the computer to provide a real time visualization of the progress of the flame/plume as it spread upward along the cardboard box surfaces, the actuation of the sprinklers, the heating of the ceiling structure and the onset of structure damage. Two primary animations compared the flame spread rate, sprinkler effectiveness, and ceiling assembly structural response as a function of the two rack storage heights.

RESULTS AND CONCLUSIONS

Results from the theoretical modeling of the problem under consideration are summarized in Table 1. They show that vertical flame spread on the cardboard box surfaces was very rapid and that high heat release rate was produced. The increased stacking height from 6.1m to 7.9m resulted in flame extensions which were more destructive to the ceiling structure. Specifically, boxes stacked to 6.1m would produce a flame that just reached the ceiling, whereas boxes stacked to 7.9m would generate a flame that not only extended to the ceiling but bent over to form a substantial ceiling jet which would bathe a significant area of the ceiling in flames. Furthermore, heat transfer analysis showed that girders and roof joists supporting the roof deck would reach their critical failure temperature in less than half the time of the vertical column. This assessment is conservative since heat transfer to the vertical columns is substantially lower than the horizontal joists, girders, and roof deck that would be continually exposed to the horizontal ceiling flame jet.

TABLE 1. Results of Analysis

- Time to reach sprinkler / structure = 260 sec.
- Time to sprinkler activation = 282 sec. (Heat transfer / RTI)
- Plume cooling (Re: droplet residence time)

•7.92m stacks 833° C	750° C
•6.10m stacks 833° C	675° C

- Time to critical structure temperature

•7.92m stacks	7.5 min
•6.10m stacks	8.6 min

- Time to roof failure (critical temperature for composite roof)

•7.92m stacks	11 min
•6.10m stacks	no failure

The horizontal reach of the plume resulting from the extension of the vertical fire plume was far more intense for storage where commodities were stacked close to the roof structure because heat transfer to the ceiling is much more effective. Not only are the structural members directly bathed by the hot gases, but their total engulfment in heat prevents them from dissipating any heat. Moreover, the decreased distance to sprinkler heads reduces the energy absorbing potential of the sprinkler spray. The calculations comparing water spray cooling of the plume where distances between sprinkler deflectors and the top of storage varied between 2.74 m and 0.9 m indicates nearly a factor of decrease in cooling effectiveness of the latter. In addition, the close proximity of the sprinkler to the top of the box surfaces significantly reduces the spray pattern which further reduces its fire suppression capability.

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