WATER MIST EXTINGUISHMENT OF POOL FIRES: A PARAMETRIC APPROACH

by

Robert F. Chaiken and Alex C. Smith

U.S. Department of Health and Human Services
National Institute for Occupational Safety and Health
Pittsburgh Research Laboratory
P.O. Box 18070,
Pittsburgh, PA 15236

INTRODUCTION

The National Institute for Occupational Safety and Health (NIOSH) at its Pittsburgh Research Laboratory (PRL) is interested in the application of water mist sprays to extinguish diesel fuel fires in underground mine diesel refueling areas. To this end experimental studies have been carried out on the extinguishment of diesel fuel fires at PRL's large enclosed fire suppression facility (FSP) at its Lake Lynn Laboratory (LLL). Two sizes of shallow fuel pans (3x3 ft and 5x7 ft) contained the fires, and a number of commercial mist spray nozzles (at roof locations) and spray/fire locations were tested (52 fires in all). Visual observations of the pool fire extinguishment process by the overhead sprays with an infra-red sensitive videocom suggests that there are two distinct actions involved in extinguishment due to two different transport mechanisms by which the water droplets can enter the fire plume.

First, is a direct injection of water droplets into the plume from overhead. This is believed to involve larger water drops and leads to an extinguishment time of several minutes. Second, is an indirect injection process involving small water drops which are entrained in the sideways air flow that feeds oxygen to the fire. This second process apparently leads to relatively fast quenching of the fire in less than 1 minute - a highly useful attribute for a fire protection system.

This paper describes a relatively simple parametric model for the indirect water injection process, and defines the critical spray conditions for achieving rapid quenching of the pool fire. While the model is consistent with the pool fire data obtained to date, the PRL studies are continuing with more complex pool fire scenarios. It remains to be seen if this simple parametric approach applies to these future fire tests.

THEORETICAL

Critical Drop Size

In the two-dimensional representation of figure 1, an oil pool fire is considered to be a cone whose base is the vaporizing liquid oil surface having an area πr^2, above which exists a fire plume (diffusion flame) of height, L. The rising plume induces a horizontal air flow into the side of the plume supplying the oxygen necessary for propagating gas phase combustion reactions. Water droplets suspended in the air around the plume will tend to follow the horizontal air flows into the plume. The rate of air entrainment by the plume will be determined by the overall combustion reaction which is assumed to be

$$C_7H_{16} + 44\,N_2 + 11\,O_2 \text{ ---> gas products + heat}$$

$$\text{100g fuel + 1584g air ---> } CO_2,\ H_2O,\ N_2 + 10^4 \text{ cal/mole fuel}$$

It takes 16g of air to burn 1g of fuel oil.

If sufficient water is entrained into the plume to lower the temperature of the plume below some ignition temperature, T_{ig}, the plume flame will be extinguished, leaving the liquid fuel at a temperature $T_l \leq T_{bp}$, the boiling point of the liquid fuel. The mass flow rate of water required will be given by

$$\dot{m}_w [c_w (T_{ig} - T_o) + H_w] \geq H_r \dot{m}_f \tag{1}$$

where, $\dot{m}_w$ = mass flow rate of water, g/sec
$\dot{m}_f$ = mass flow rate of fuel, g/sec
T_o = initial water temperature, ~300 K
T_{ig} = extinction flame temperature, ~1300 K
c_w = heat capacity of liquid water/steam, ~0.5 cal/g-K
H_w = heat of vaporization of water, ~500 cal/g
H_r = heat of combustion of fuel, ~10^4 cal/g

For the combustion reaction, this leads to

$$\dot{m}_w \approx 10 m_f = (5/8)\, m_a \tag{2}$$

where $\dot{m}_a$ = mass flow rate of air into the plume

For a given volume of air, V_a, the concentration of water in the air required for extinguishment becomes

$$m_w/V_a = (5/8)m_a/V_a \approx (5/8)\rho_a \approx 7.5 \times 10^{-4} \text{ g/cm}^3 \tag{3}$$

where, ρ_a = ambient air density, g/cm^3

However, if there is a hot object in contact with the liquid that acts as a flame holder, permanent extinguishment of the fire might not be achieved. The flame holder could rekindle the pool fire until it too is cooled, perhaps by direct impingement of water onto the flame holder. This direct process will not be considered in the current treatment of extinguishment. Only the indirect entrainment of water is considered, which as will be shown later, leads to the rapid quenching of the fire.

The indirect rapid quenching process just described will involve a coupling between the size of the fire and the size of the water droplets that will be entrained in the horizontal air flow (figure 1). This coupling will in turn involve the horizontal air flow rate which promotes water to enter the plume, and the rate of settling of droplets from the air which promotes water not to enter the plume.

With all the air supplied by sideways entrainment, the horizontal air mass velocity requirement is given by

$$\dot{m}_a = 16 m_f = 2\pi r L \rho_a v_a \tag{4}$$

where va = linear velocity of the air,
L = height of plume.

The fuel burning rate can be written in terms of the linear rate of fuel vaporization, B, and the fuel density, ρ_f, as

$$\dot{m}_f = \pi r^2 \rho_f B \tag{5}$$

or

$$v_a = 8\left(\frac{r}{L}\right)\left(\frac{\rho_f}{\rho_a}\right) B \tag{6}$$

The time, τ_h, it takes for air to travel an average horizontal distance, r/2, into the plume can then be expressed as

$$\tau_h = \frac{\rho_a L}{16 \rho_f B} \tag{7}$$

τ_h will vary with pool size, plume height and fuel evaporation rate which in turn will vary with pool size.

The competing action to water entrainment is the fall-out of droplets from the air at the Stokes terminal velocity, v_d,

$$v_d = \frac{2 \rho_w g r_d^2}{9 \eta} \tag{8}$$

where, r_d = droplet radius, cm
ρ_w = density of water, 1 g/cm^3
g = gravitational constant, 980 cm/sec^2
η = ambient air viscosity, 3×10^{-4} poise (in cgs units)

The time, τ_v, to fall the vertical distance, L, (plume height) is considered the characteristic time for loss of water droplets from the air, i.e.,

$$\tau_v = L/v_d = \frac{9\eta L}{2\rho_w g r_d^2}$$

The extinguishment requirement is now taken as $\tau_v \geq \tau_h$, which in essence infers that water entrained in the air will be transported into the plume before it can fall vertically onto the floor. This leads to

$$\frac{\tau_v}{\tau_h} \geq 72\left(\frac{\eta}{\rho_a g}\right)\left(\frac{\rho_f}{\rho_w}\right)\left(\frac{B}{r_d^2}\right) = K\frac{B}{r_d^2} \qquad (10)$$

where the cgs value of the constant, K, for diesel oil is about 0.016 sec-cm.

It is seen that the ratio (τ_v/τ_h) will increase as B increases and as r_d decreases. Also, linear burning rates of pool fires generally increase with increasing pool size (references 1-3). Thus, larger droplets of water might be utilized for 'large' pool fires, but smaller droplets of water would be required for 'small' pool fires. This suggests that water mist sprays might be more applicable to the rapid quenching of 'large' pool fires than to 'small' pool fires.

The extinguishment requirement that $\tau_v \geq \tau_h$ leads to a droplet size criteria that

$$r_d^2 \leq 0.016B. \qquad (11)$$

Data from the literature suggests values of B would range from 0.001 to 0.01 cm/sec, which indicates a need for water spray nozzles to produce particles of radii less than 0.0040 to 0.0125 cm (80 to 250 microns diameter). These calculated droplet sizes do fall within the range of sizes available with Class I commercial water mist spray nozzles (reference 4).

Water Flow Rate Criteria

In addition to a water droplet size requirement, it will be necessary to have sufficient quantities of water entrained into the fire plume. Equation 3 indicates the required concentration of water in the air being entrained by the plume. Assuming that the fire can occur somewhere in a room having a total volume V_r and cross-sectional area, A_x, the total mass of water to be suspended in the air will be

$$M_w = (5/8)\rho_a A_x L \qquad (12)$$

Here, for convenience, it is assumed that the room height and the fire plume height are the same.

Dividing M_w by the Stokes' droplet settling time, τ_v (equation 9), yields the required total mass flow rate of water into the room, i.e.,

$$M_w = \dot{M}_w/\tau_v = (5/8)\,\rho_a A_x L\left(\frac{2\rho_w g r_d^2}{9\eta L}\right) \qquad (13)$$

or when expressed in cgs units

$$\dot{M}_w = 540\ A_x r_d^2\ \text{(g/sec)} \qquad (14)$$

For a room of cross sectional area 18x24-ft ($4\text{x}10^5$ cm^2), which is about the effective area of the fire test chamber at the LLL fire suppression facility, the critical total mass flow rate becomes

$$\dot{M}_w = 2.2\text{x}10^8\ r_d^2\ \text{(g/sec)} \qquad (15)$$

It should be noted that the r_d that appears in the above expressions for required total water flow rate refers to the critical droplet size, i.e., mist spray nozzles must produce the critical flow rate as droplets with radii $\leq r_d$, the critical droplet size. As described in the next section, this apparently was not always the case for the PRL pool fire tests.

EXPERIMENTAL

All experiments were conducted in the Fire Suppression Facility (FSF) located at the LLL facilities near Fairchance, PA. The FSF was constructed to simulate an underground diesel fuel storage area. The main entry is 78 ft (23.8m) long , with double steel self-closing doors at each end. A crosscut extends 40 ft (12.2m) from the center of the main entry, and is closed-off with a permanent concrete block stopping. All entries are 18 ft (5.5m) wide and 7 ft (2.2m) in height, and are coated with a 1 to 1.5 in (2.5 to 3.8 cm) thick fireproof material. The pool fire tests were carried out in a section of the crosscut about 24 ft (7.3m) in length.

The water mist nozzles used in the experiments were commercially available spiral or impingement types that were ceiling mounted and operated according to specifications. The spiral nozzles produce a conical shaped water distribution pattern, with the larger droplets forming the outer edge of the cone, while the impingement nozzles produce a more even droplet size distribution pattern. Nozzle droplet sizes are referred to by the nozzle's $Dv_{0.9}$, which is defined as having 90 pct of the water spray volume as droplets less than the $Dv_{0.9}$. Depending on the type of nozzle and the operating pressure, the spray discharge from a single nozzle could be from 6 ft (1.8m) to 18 ft (5.5m) with a water flow rate from 4.9 to 50.5 gallons per minute (gpm). The number of nozzles used for an individual fire test generally depended on the number (2 to 12) needed to cover the area of the 24 ft (7.3m) long fire test section.

The fuel oil was contained in two sizes of trays (3x3-ft and 5x7-ft) which normally contained 3 to 5 gallons of diesel fuel oil. The fire trays were located in one of four locations: (1) centered under a spray nozzle; (2) off-center between neighboring nozzles; (3) against a single wall; (4) against two walls (i.e., a corner). Numerous thermocouple positions and several gas sampling points enabled the course of the fire to be followed as well as the spread of fumes and heat within the test chamber. Several windows in the walls of the chamber allow for visual observation of the fire test; however, due to smoke generation, it generally requires the use of an infra-red sensitive videocom.

In carrying out a pool fire test, the oil in the pan is ignited and allowed to burn for one minute prior to activating the water spray nozzles. Tray thermocouples (3 to 5 of them), which were located directly over the surface of the fuel, generally registered temperatures of 700 to 800° C during this free burning stage. The temperature-time behavior of the tray thermocouples defined the extinguishment behavior of the fire. In the case of rapid quenching, the tray thermocouple temperatures quickly decrease to less than 100° C within one minute (Figure 2). Figure 3 depicts a pool fire that took about 4 minutes to be extinguished. Although this fire was eventually extinguished by the nozzle sprays, it is considered a 'no' extinguishment in terms of the rapid quench process being considered in this report. Figure 4 is another example of a 'no' extinguishment - this time the fuel apparently burned to extinction.

RESULTS AND DISCUSSIONS

Figure 5 depicts the results of all the pool fire tests on a single plot of total water flow rate, gpm, versus droplet size, $Dv_{0.9}$ [1]. The data points are indexed with the number of 'yes' and number of 'no' rapid quenching observed (represented by the #yes/#no values shown near each point). The continuous curve shown in the plot represents the theoretical critical total flow rate as determined by empirical fit (eyeball) of equation 14 to the data. The equation as shown with the droplet diameter given in microns is

$$M_w(\text{gpm}) = 0.0059\ D^2 \tag{16}$$

or in cgs units with the droplet radius given in cm,

$$M_w(\text{gm/sec}) = 1.5\text{x}10^7\ r_d 2 \tag{17}$$

The 'observed' theoretical constant coefficient is about an order of magnitude smaller than that calculated equation 15).

The vertical dotted line in figure 5 represents the 'observed' theoretical critical droplet diameter for extinguishment by rapid quenching. From the literature (reference 1) a linear oil burning rate of about 0.01 cm/sec might be expected for the pool sizes used in these fire tests. This would yield a calculated critical droplet diameter of 250 micron (equation 11) which is about 30% less than the 'observed' theoretical value. It is noted that if the data of figure 5 was based on the root-mean square diameter of the actual droplet size distribution rather than the $Dv_{0.9}$ value, it would probably have resulted in a smaller "observed" critical drop diameter, and in better agreement with the calculated value of 250 microns.

It should be noted that the above results are based on the 52 fire tests, independent of the fire location and pool size parameters. Visually from figure 5, there doesn't seem to be any clear trends to be noted other than those based on droplet size and/or the total flow rate, at least for the case of the rapid quench process. This conclusion is also indicated from similar data plots where the size and location parameters have been sorted (figures 6-11). Unfortunately, sorting the data this way reduces the number of fire tests in a given category, and hence, the significance of any observation. However, from the sorted plots it is seen that the 'observed' theoretical results from all the fires are reasonably consistent with the sorted data.

An argument to support these finding might be that the rapid quench mechanism as depicted in the model depends solely on there being an adequate supply of suitably sized water droplets in the air surrounding the fire. The pool fire itself will cause the

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[1] From the functional form of equation 15, it would be appropriate to plot gpm versus the root-mean square diameter of the droplet size distribution as produced by the various nozzles. Unfortunately, the size distribution data was not available at this time.

water droplets to enter the plume as it entrains the air needed to maintain the combustion processes. As long as the critical water droplet size and water concentration in the air can be maintained, rapid quenching should be promoted. It might be expected that, except for the potential complications of a hot surface acting as a flame holder, rapid quenching of pool fires should be somewhat independent of obstacles in the room containing the pool fire.

By reasons of the same argument given above, it might be easier to extinguish large pool fires by a rapid quench process than small fires. The horizontal air flows generated by small pool fires would likewise be small, and possibly require a critical droplet size too small to be produced by commercial mist spray nozzles. For example, from equation 11, a small pool fire having a linear burning rate of 0.0001 cm/sec, would require nozzles capable of producing an adequate supply of 25 micron diameter water droplets. In this case, it might be better to extinguish the fire by direct injection of large water droplets into the fire plume, a process that would have greater chance of success when aerodynamic forces generated by the fire plume are relatively weak.

CONCLUSION

The parametric approach to rapid extinguishment of pool fires that is presented here is reasonably consistent with the extinguishment results for fuel oil pool fires interacting with water mists produced by a variety of spray nozzles. The order of magnitude agreement between calculated and observed critical total water flow rates and critical water droplet sizes is quite encouraging for the simple approach taken; however, further testing of the predictive capabilities of the model needs to be validated through more realistic pool fire/obstacle scenarios. An important aspect of a simple parametric approach to fire extinguishment is that it could be a starting point for a more realistic treatment of the coupling of pool fires with the water mists, but perhaps more significant is that a simple parametric model can be a starting point for design of pool fire tests as well as the approach to analysis of the extinguishment results.

REFERENCES

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3. Seeger, P. G., On the Combustion and Heat Transfer in Fires of Liquid Fuels in Tanks, Ch.3 in Heat Transfer in Fires, P. L. Blackshear, ed., Wiley & Sons, New York (1974) pp. 92-128.

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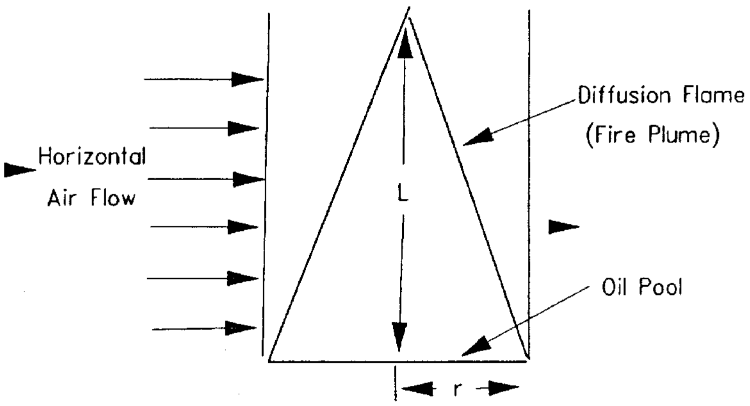

Figure1. Representation of an oil pool fire.

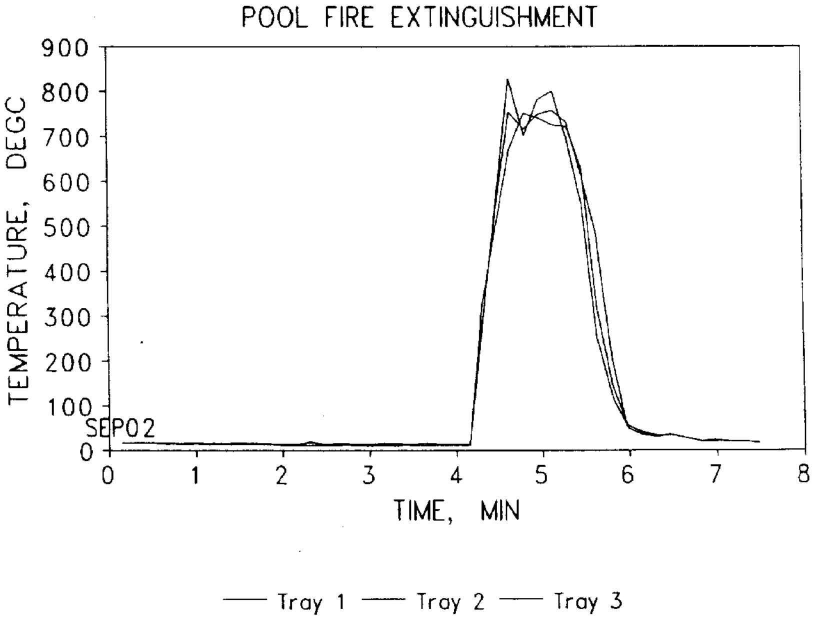

Figure 2: Example of a 'yes' rapid quench extinquishment.

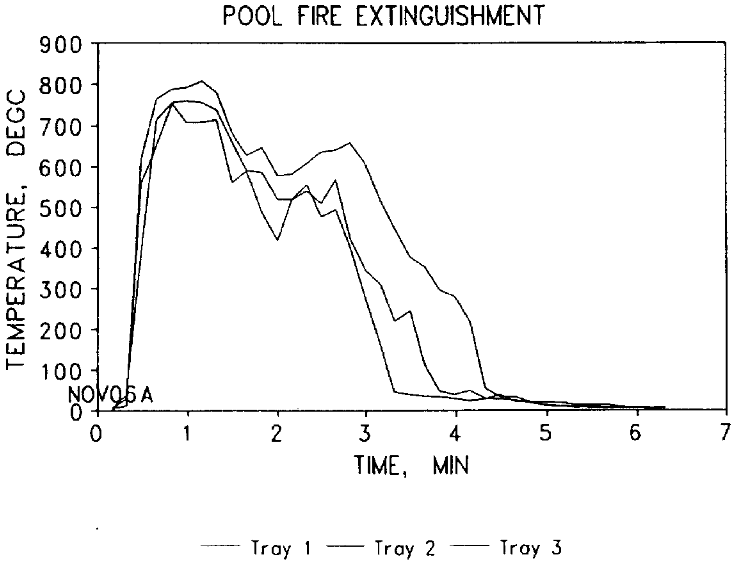

Figure 3: Example of a 'no' rapid quench extinguishment.

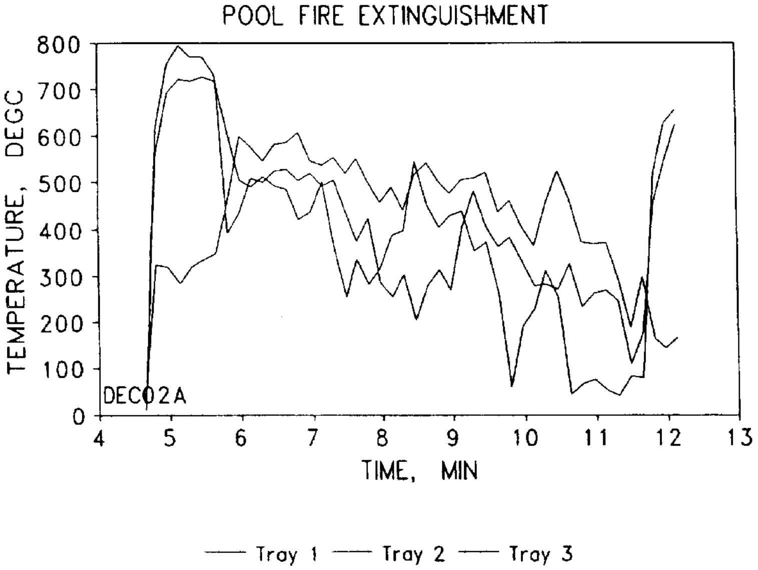

Figure 4: Example of non-extinguishment; also a 'no' rapid quenching result.

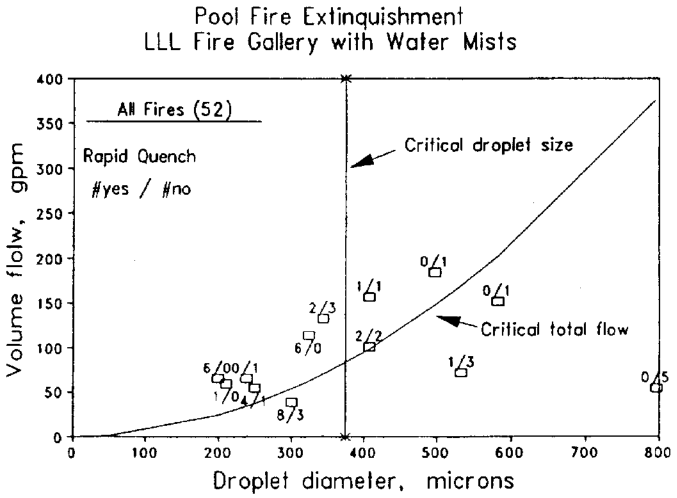

Figure 5: Rapid quenching results for all fires.

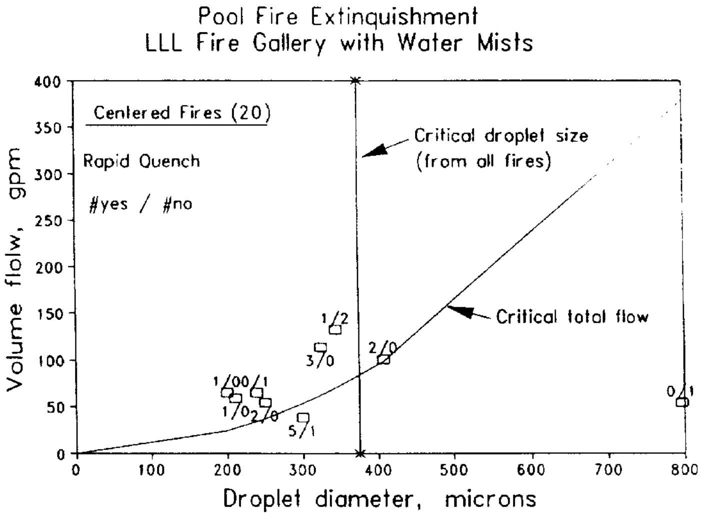

Figure 6: Rapid quenching results for centered fires.

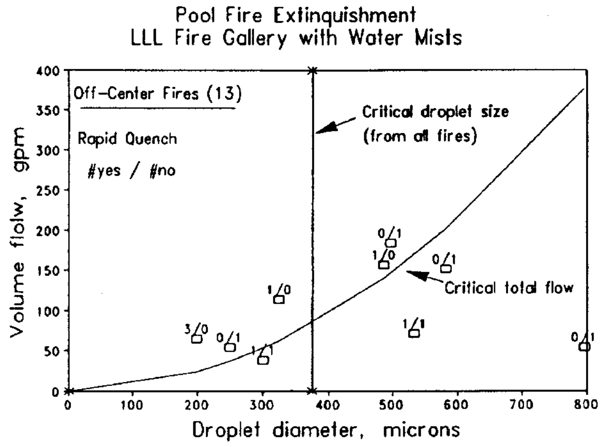

Figure 7: Rapid quenching results for off-centered fires.

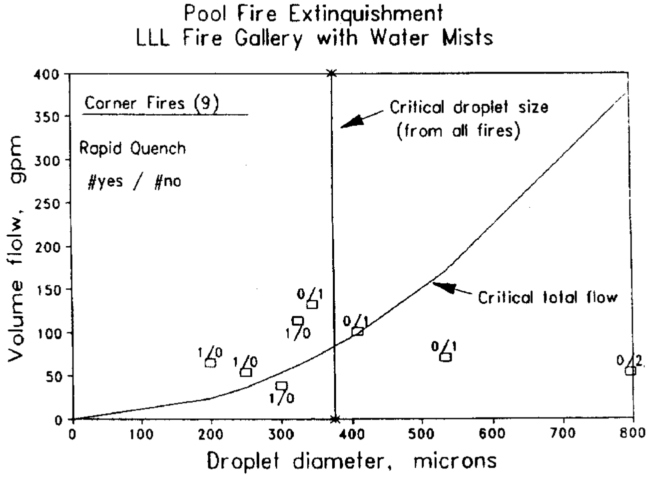

Figure 8: Rapid quenching results for corner fires.

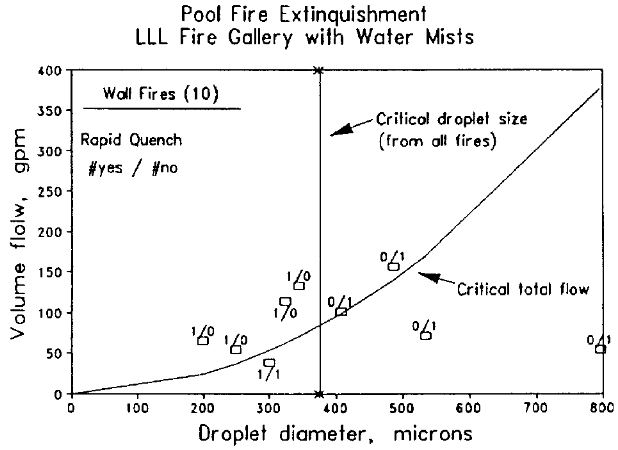

Figure 9: Rapid quenching results for wall fires.

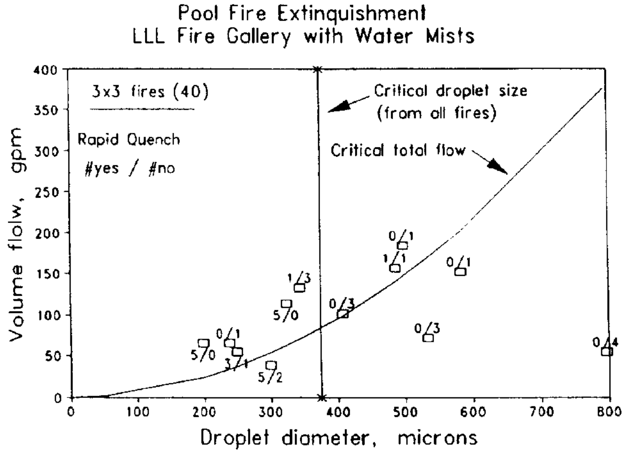

Figure 10: Rapid quenching results for 3x3-ft pool fires

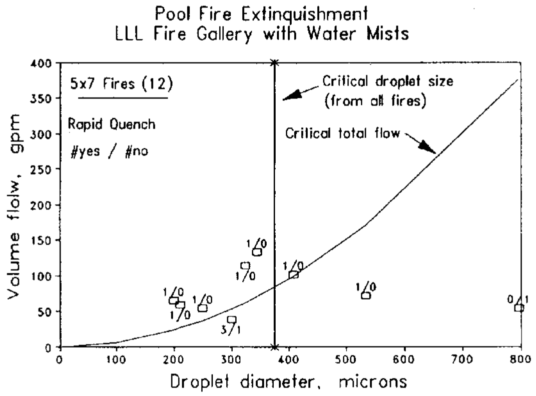

Figure 11: Rapid quenching results for 5x7-ft pool fires.