THE INTERACTION OF AN ISOLATED SPRINKLER SPRAY AND A TWO-LAYER COMPARTMENT FIRE ENVIRONMENT: PHENOMENA AND MODEL SIMULATIONS

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ABSTRACT

A general desription of the interaction of sprinklers and compartment-fire-generated smoke layers is presented. Various possible aspects of the interaction phenomena (upper-layer smoke entrainment into the sprinkler spray, momentum and mass exchange between droplets and entrained gas, gas cooling by evaporation, buoyancy effects, and others) are discussed in the context of a two-layer-type of description of the fire environment. Inputs and outputs for a mathematical submodel which simulates the phenomena are discussed. The submodel is suitable for general use in any two-layer, zone-type, compartment fire model.

Results of exercising the submodel are presented. These example calculations simulate the interaction between the spray of a real sprinkler device and a range of two-layer fire environments. The calculations reveal an important generic interaction phenomenon, namely, an abrupt and large change in the growth rate of an upper layer that would accompany an increase in upper layer thickness beyond a critical thickness (for a given upper layer temperature) or an increase in upper layer temperature beyond a critical temperature (for a given upper layer thickness). Exceeding critical values would lead to very large rate of growth of upper layer thickness, a growth that could lead to rapid and complete smoke filling of even the largest compartments of fire origin.

Key Words: building fires; compartment fires; computer models; fire models; mathematical models; vents; sprinklers; sprinkler response; zone models

INTRODUCTION

The overall objective of this work was to develop a model to predict the interaction of sprinklers and compartment-fire-generated smoke layers, and to include the effect in an enhanced version of the compartment fire model computer code LAVENT (Link Actuated Vents) [1 - 3]. The resulting new computer code would be capable of simulating the combined effects of sprinklers and ceiling vents on time-dependent compartment fire environments.

The present paper describes the sprinkler/smoke-layer interaction part of the problem. First the basic phemomena are described within the context of a mathematical model that was developed and described in detail in [4]. Then results of example model simulations are presented.

QUALITATIVE DESCRIPTION OF THE SPRAY/LAYER INTERACTIONS

Consider a compartment fire. Assume a two-layer-type description of the fire-generated environment, where the thickness of the layers (i.e., the elevation of the layers' interface) and the assumed-uniform layer properties are known.

Depicted in Figure 1 are generic interactions between two-layer fire-generated environments and an operating sprinkler. In Figures 1a and 1b, the upper elevated-temperature layer submerges the sprinkler nozzle, whereas in Figure 1c, the layer interface is at or above the elevation of sprinkler deployment.

In the Figure 1a and 1b scenarios, the sprinkler spray entrains, drives downward (by aerodynamic drag on the spray drops), humidifies, and cools (by drop evaporation) gases from the high temperature upper layer. A jet of downward-moving gases is formed. Following experimental observations of isolated sprinklers operating in an ambient environment [5]*, the downward jet is assumed to be confined to a fixed and specified spray zone of influence, a spray cone envelope.

The gases penetrate and emerge from the upper-layer/lower-layer interface as a downward-moving jet of gases. This jet is typically upward-buoyant in the lower layer because of the fact that below the interface the jet gases are usually warmer and less dense than the relatively cool lower layer environment. It is also possible for the penetrating jet to be cooler and more dense than the lower layer environment.

Once in the lower layer, upward buoyant forces on the jet gases would act in a manner as to reduce their downward velocity. Also, downward drag forces and spray evaporation and cooling continue as in the upper layer, albeit with reduced intensity.

In developing the mathematical model it was convenient to divide the lower layer gas jet flows into three major categories depicted in Figures 1a, 1b, and 1c. These categories involve a total of six different flow conditions identified as ICOND 1, ICOND 2, ..., ICOND 6, respectively. As noted, the Figure 1c scenario involves the flow condition designated as ICOND 1. The defining features of each of these flow conditions will be described below.

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*Numbers in brackets refer to the list of REFERENCES at the end of this paper.

The Sprinkler-Spray/Lower-Layer Interaction of Figure 1a

Consider the jet gases as they penetrate the layer interface. The sprinkler-spray/lower-layer interaction of the Figure 1a involves scenarios where: 1) there is an upward buoyancy body force on the jet gases immediately below the interface which is strong enough to overcome the downward spray drag force (i.e., the net force on the gases is upward); and 2) the net upward force is strong enough to lead to a jet mass flow which decreases with decreasing elevation (i.e., instead of entrainment from the lower layer environment into the spray cone envelope, immediately below the interface there will be lateral outflow of gases from the spray cone.

Define** $\dot{M}$ as the mass flow rate of all gas entrained into the spray cone between the sprinkler nozzle elevation and an elevation of interest. Then the Figure 1a scenarios involve cases where $d\dot{M}/dx \leq 0$ immediately below the layer interface. As a result, the downward velocity of the jet gases will decrease with decreasing elevation. The velocity may go to zero above the floor at a jet-penetration depth, $\delta_p = x_\delta - x_{INT}$, as in shown in the figure (also depicted as ICOND 4 in Figure 2), or the jet may maintain its downward motion until it actually impinges on the floor (depicted as ICOND 3 in Figure 2). Note that within the zone of the spray envelope, evaporation and cooling of jet gases takes place even as they decelerate.

From the layer interface to the elevation of jet penetration, jet gases flow laterally outward from the spray cone axis. The buoyant forces acting on the jet gases as they leave the spray envelope drive them upward, back toward the upper-layer/lower-layer interface. The now-upward-moving plume-like flow, which surrounds the downward-penetrating jet, entrains the relatively cool lower-layer gases. The original, downward-penetrating jet gases, the entrained lower-layer gases, and all the water that was evaporated in the spray cone from the spray drops are assumed to be deposited finally into and mixed with the upper-layer.

Suppose, as depicted in Figure 1a and in the top of Figure 2, that jet velocity does go to zero above the floor elevation, i.e., ICOND 4. Then, at the penetration-depth elevation the drops of the spray cone emerge from below the upward-buoyant jet. With their remaining downward momentum and with the now-enlarged spray cone cross-sectional area, the drops would initiate a new spray cone gas jet by entrainment from the far-field lower-layer environment. This new jet eventually impinges on the floor. The new jet is analogous to the original jet initiated at the elevation of the sprinkle nozzle. The phenomena associated with the new jet would also be completely analogous to the phenomena described below in association with the Figure 1c scenario.

The Sprinkler-Spray/Lower-Layer Interaction of Figure 1b

The sprinkler-spray/lower-layer interaction of the Figure 1b involves scenarios where immediately below the interface the mass flow of the penetrating jet is increasing with decreasing elevation, i.e., $d\dot{M}/dx > 0$, even though upward buoyancy may lead to a net upward force on the jet gases. Also, in some non-zero interval below the interface the $d\dot{M}/dx > 0$ condition persists as in the upper layer. This is an interval of entrainment into the spray cone of relatively low-temperature lower layer gases.

**A list of NOMENCLATURE is included at the end of this paper.

The generic Figure-1b scenario includes those cases where the lower layer temperature is greater than the temperature of the penetrating jet. In such cases, the buoyancy force on the jet in the lower layer is initially downward, enhancing the downward-directed drag force and remains so until the jet reaches the floor; the jet dynamics in the lower layer are completely analogous to the original flow in the upper layer. The situation involves a flow conditions designated as ICOND 6 and depicted in Figure 3. In general, the distinguishing feature of the ICOND 6 scenario is that $d\dot{M}/dx > 0$ throughout the entire depth of the lower layer.

Consider cases in the present category of flow where the jet gases are upward buoyant as they penetrate the interface. These cases are designated as ICOND 2 or 5 and are depicted in Figure 3. It is possible that below the interface $d\dot{M}/dx$ decreases with decreasing elevation and goes to zero at some elevation above the floor. At still lower elevations, the jet velocity would then be reduced with further decreases in elevation. As can be seen in Figure 3, ICOND 5 is distinguished by the fact that the $d\dot{M}/dx = 0$ condition occurs and the velocity actually goes to zero at an elevation above the floor. Flow conditions where: 1) $d\dot{M}/dx = 0$ at some elevation, but where the velocity does not go to zero above the floor; or 2) where there is no elevation where $dM/dx = 0$, are both included in ICOND 2. The former of these two flow conditions are depicted in the ICOND 2 sketch of Figure 3.

Note that in the Figure 3 depiction of ICOND 5 scenarios, spray drops emerge from the elevation of zero velocity and initiate a new downward-directed jet of gases entrained from the lower-layer environment. This is completely analogous to the previously discussed new lower layer jet of the ICOND 4 flow condition.

Eventually the jet gases impinge on the floor. It is assumed that they are then all deposited in and mixed with the rest of the lower layer. Thus, for the scenarios of Figures 1b and 3, whatever the conditions of the jet development in the lower layer, the flow entrained into the spray cone in the elevation interval immediately below the interface is assumed to "shield" the upper layer from the potential entry from the lower layer of any possible upward-buoyant gases driven from the spray cone at lower elevations.

Note that throughout the entire depth of the lower layer an understanding of the dynamics of the gases in the spray cone is required in order to be able to predict the cooling and humidification that takes place there. Thus, along with an estimate of the flow of spray cone gases penetrating the interface and being deposited in the lower layer it is also necessary to estimate the amount of enthalpy and water vapor added to the gases in the lower layer spray cone envelope, since these are also deposited in the lower layer.

The Sprinkler-Spray/Lower-Layer Interaction of Figure 1c

Figure 1c depicts the ICOND 6 flow condition. Here the sprinkler is below or at the layer interface. The upper layer is assumed to be unaffected by sprinkler operation. The dynamics of the spray-induced jet of gases in the lower layer is completely analogous to the spray/upper-layer interaction of a Figure 1a scenario, where the upper layer fills the compartment. In this Figure-1c scenario it is again important to predict the net cooling and humidification of jet gases which are deposited into and mixed with the lower layer.

THE MATHEMATICAL MODEL: INPUTS AND OUTPUTS

A mathematical model which simulates all aspects of the above-described phenomena was developed in [7]. This provides a description of the sprinkler/fire-environment interaction which results when an operating sprinkler head, with specified flow characteristics, elevation, and water flow rate, is imbedded in any instantaneous fire environment, described in terms of the two-layer approximation.

Model Inputs: The Fire Environment and the Sprinkler Characteristics

Specifying the Two-Layer Fire Environment. Refer to Figure 1. The elevations of the ceiling, floor, and layer interface above some datum elevation, y_{CEIL}, y_{FLOOR}, and y_{LAYER}, respectively are specified. The upper and lower layers are assumed to have specified densities and absolute temperatures, ρ_U, ρ_L and T_U, T_L, respectively, where $T_U > T_L$, $\rho_U < \rho_L$, and specified mass fractions of water vapor [(kg of H_2O)/(kg gas layer)], $c_{H2O,U}$, $c_{H2O,L}$ and other products of combustion [(kg of product k)/(kg gas layer)], $c_{k,U}$, $c_{k,L}$ which are taken account of in the simulation (here, the water is both a product of combustion and a product of evaporation from the sprinkler spray drops).

All of the above-mentioned fire environment decriptors are required inputs to the model.

When implementing the model equations in a compartment fire model, the specification of layer product concentrations, including the water concentration, would be required only when such concentrations are actually being predicted in the overall fire model simulation. Thus, the present sprinkler/layer interaction model does not depend on specification of the instantaneous upper- and lower-layer concentration of water. This is in spite of the fact that: 1) the model predicts, among other parameters, the rate of water evaporation and cooling from the sprinkler spray drops; and 2) such evaporation is generally a function of the humidity of the gases entrained into the zone of influence of the water spray. The reason that specification of water concentrations is not required is that the models used here for predicting the rate of evaporative cooling [6] and the aerodynamic drag [7] of evaporating water droplets are based on the assumption that the relative humidity of the gases in the water spray envelope is negligible. This is expected to be a reasonable assumption since most of the evaporative cooling is expected to occur at gas temperatures at least several tens of degrees K above ambient conditions. At such temperatures, high relative humidity conditions would require the gases to have unrealistically high mass fractions of water.

Specifying Sprinkler Head Characteristics. Beside the elevation of the sprinkler nozzle outlet above the datum, y_{SPRINK}, and its instantaneous volumetric water discharge rate, $\dot{V}_N$, the model requires inputs to describe the flow characteristics of the particular sprinkler head whose performance is to be simulated. Following [5] and [8] the sprinkler head is characterized by the diameter of its nozzle, D_N, the characteristic total cone angle of the sprinkler spray, θ, and two other measureable device parameters, r and C_M, related, respectively, to: 1) the mean-volume diameter of the sprinkler spray droplets after fragmentation of the nozzle flow, d,

$$d = r(D_N/u_N)^{2/3} \tag{1}$$

and 2) the momentum of the water flow immediately after nozzle flow fragmentation

$$C_M = \text{(momentum of water flow immediately after fragmentation)/} \quad \text{(momentum of the water flow as it exits the nozzle)} \tag{2}$$

Typical standard sprinklers have r values of 0.084 $m/s^{2/3}$ and a representative C_M value of 0.4 [5].

The above sprinkler parameters complete the required inputs to the model.

Model Outputs

Consistent with earlier description of the phenomena portrayed in Figures 1 - 3, the model outputs of interest here are: the flow condition, ICONDN; $\dot{M}_{ENT}$, mass rate of entrainment of the reversed plume flow from the lower layer; x_δ; and $\dot{Q}_d(x) \leq 0$, $0 \leq x \leq x_{FLOOR}$, the rate of heat transfer from the drops to the gas in the spray cone, where

$$x_{FLOOR} = x \text{ at floor} = y_{SPRINK} - y_{FLOOR} \tag{3}$$

In the model, these results are then used to provide the additional outputs: net rates of flow to the upper and lower layer of: mass ($\dot{M}_U$ to the upper layer, $\dot{M}_L$, to the lower layer); enthalpy ($\dot{Q}_U$ and $\dot{Q}_L$); evaporated water ($\dot{P}_{H2O,U}$ and $\dot{P}_{H2O,L}$); and other products of combustion ($\dot{P}_{k,U}$ and $\dot{P}_{k,L} = - \dot{P}_{k,U}$ for k other than H_2O).

The latter outputs are the ones required of a stand-alone submodel algorithm which is suitable for integration into a general two-layer compartment fire model, e.g. LAVENT.

EXAMPLE CALCULATIONS

Simulated Interactions Between Two-Layer Fire Environments and a Rockwood T-4 Spray Nozzle Flow

This section presents results of using the present model to simulate the interactions of a sprinkler and a two-layer fire environment. The scenarios simulate the operation of the Rockwood T-4 spray nozzle used in the experiments reported in [5]. This device, like automatic sprinklers used for fire protection, generates a spray by employing a deflector beneath the device to intercept and fragment the solid water jet which flows from the nozzle [5]. The calculations simulate the effects of the sprinkler discharging near the top of the hot upper layer of conjectured two-layer fire environments.

The Rockwood T-4 spray nozzle has the following characteristics [5]:

$$C_M = 0.41; \quad r = 0.096 m/s^{2/3}; \qquad D_N = 0.00635 m \tag{4}$$

For the test of [5] with the highest nozzle pressure, the flow rate was $0.107m^3/s$ and the measured spray envelope had a diameter of 2.0m, 2.7m, and 3.1m at 1.52m, 3.04m, and 5.78m below the nozzle, respectively. Based on this, the spray envelope for all of these elevations is simulated here by a 45^o cone angle. The following operating condition will be adopted for all calculations

$$\theta = 45^o; \ \dot{V}_N = 0.00107m^3/s \qquad (5)$$

For all calculations the apex of the spray cone is assumed to be at a nozzle exit located 10m above the floor. The lower layer is always assumed to be at the ambient temperature T_{REF}.

Two sets of calculations are carried out. In the first set the upper layer temperature is fixed and the layer interface elevation varies between the 10m elevation of the nozzle and the zero elevation of the floor. In the second set of calculations, the layer interface elevation is fixed and the temperature of the upper layer is varied over a wide range of values.

The Spray Nozzle Operating in a 600K Upper Layer. The model was used to simulate the interaction of an operating Rockwood T-4 spray nozzle and a two-layer fire environment with a 600K upper layer and a $T_{REF} = 293K$ ambient temperature lower layer. The results for $\dot{M}_{ENT}$ and x_δ are plotted in Figure 4 as functions of the distance of the interface below the spray nozzle, x_{INT}. The ICOND numbers corresponding to the flow conditions of Figures 2 and 3 are also indicated in Figure 4.

$x_{INT} = 0$ corresponds to a fire scenario where the interface is at the elevation of the spray nozzle. This leads to an ICOND 1 condition with no effect on the upper layer.

For $0 < x_{INT} \leq 1.0m$, an ICOND 2 flow condition is predicted. As in Figure 3, here there is an upward buoyant flow that is established in the lower portion of the lower layer and this impinges on the floor, i.e., $x_\delta = 10m$. However, because of the "shielding" provided by the far field entrainment into the spray cone immediately below the interface, the lower layer mass entrained into the plume-like lower-layer flow does not return to the upper layer i.e., $\dot{M}_{ENT} = 0$.

For $1.0m < x_{INT} < 4.3m$ the model predicts an ICOND 5 flow condition (see Figure 3). As in the ICOND 2 flow condition, the flow penetrating the interface is all mixed into the lower layer . Here, the upward buoyant plume in the lower layer lifts off the floor and x_δ becomes less than 10.m. However, as required by definition of the geometry, x_δ is always greater than x_{INT}. As with the ICOND 2 flow condition, the upward buoyant plume flow in the lower layer is still prevented from entering the upper layer and the $\dot{M}_{ENT} = 0$ result persists.

For $4.3m < x_{INT} \leq 8.9m$ the model predicts an ICOND 4 flow condition (see Figure 2). At this stage all upward buoyant flow in the lower layer, involving a relatively large entrained mass flow rate ranging from approximately $\dot{M}_{ENT} = 8$ to 37 kg/s, is predicted to return to the upper layer. Therefore, for the specified upper layer temperature and for the assumed characteristics of the spray device, the model predicts an abrupt and relatively massive growth of the upper layer as the upper layer thickness grows beyond 4.3m.

For $8.9m < x_{INT} < 10.m$ the model predicts an ICOND 3 flow condition (see Figure 2) where all the penetrating flow and the flow entrained from the lower layer is returned to the upper layer. Here the magnitude of $\dot{M}_{ENT}$ continues to increase with continued increase in the upper layer thickness. Note that in this range the upward buoyant plume again impinges on the floor and, as before, x_δ = 10m.

<u>The Effect of the Nozzle Spray Penetrating a 5.m Thick Upper Layer.</u> The model was also used to simulate the interaction of an operating Rockwood T-4 spray nozzle and a two-layer fire environment with a 5m upper layer thickness and with different upper layer temperatures ranging from 600K to 300K. The lower layer temperature is again fixed at T_{REF} = 293K. The results for $\dot{M}_{ENT}$ and x_δ are plotted in Figure 5 as functions of the upper layer temperature. As in the presentation of the previous results, the ICOND numbers corresponding to the flow conditions sketched in Figures 2 and 3 are also indicated in the figure.

For 300K $\leq T_U <$ 425K, ICOND 2 or 3 flow conditions are seen to prevail and none of the upward buoyant flow entrainment in the lower layer is returned to the upper layer, i.e., $\dot{M}_{ENT}$ = 0. As the upper layer temperature increases beyond T_U = 425K, the situation changes abruptly as upward buoyant flow in the lower layer is able to enter the upper layer. As seen in the figure, for the specified parameters, when the upper layer goes beyond this "threshold" temperature a significant flow rate of approximately $\dot{M}_{ENT}$ = 8 kg/s of entrained lower layer flow is predicted to be deposited into the upper layer. As T_U rises from 425K to 600K, $\dot{M}_{ENT}$ increases to approximately 11kg/s and the flow condition remains at ICOND 4.

Summary of the Example Calculations - Ceiling Venting to Enhance the Effectiveness of Sprinkler Systems

The above example calculations illustrate some of the important effects of the interaction of a sprinkler spray and a two-layer fire environment. The phenomenon highlighted by the calculations is the abrupt and large change in sprinkler/layer interaction that comes about as an upper layer increases in thickness beyond a critical thickness (for a given upper layer temperature) or increases in upper layer temperature beyond a critical temperature (for a given upper layer thickness). When the layer does not exceed the critical values the sprinkler spray is predicted to have a relatively small effect on the upper layer. In particular, the model predicts that the spray simply entrains and extracts a relatively small flow of upper gases and deposits it into the lower layer. When the critical values are exceeded, the model predicts that a very large rate of relatively cool lower layer gases, of the order of several tens to a few hundred kg/s in the example calculations, is entrained and transferred to the upper layer. This would be accompanied by a redeposition into the upper layer of all of those upper layer gases, cooled and humidified by spray drop evaporation, which are continuously extracted from the upper layer by the action of the spray cone entrainment there.

The net result of the above predicted sprinkler/layer interaction would be a very large rate of growth in the thickness of the upper layer, a growth that in practice could lead to rapid and complete smoke filling of even the largest compartments of fire origin.

From the above results and discussion, it would appear that control or delay of the temperature and/or thickness of the upper layer to below-critical levels would lead to predictable design-response sprinkler/fire interactions, i.e., sprinkler/fire interactions which do not significantly deviate from design conditions. For example, it is possible that the relatively prompt use of ceiling venting could provide the suggested desirable smoke layer control. Indeed, use of ceiling venting to provide such control, without significant smoke logging, could be the basis of a strategy of co-ordinated sprinkler/vent design leading to effective fire control/suppression in compartments of fire origin.

USING THE SPRINKLER/LAYER INTERACTION MODEL IN LAVENT

The full implications of the sprinkler/layer model developed here can only be assessed within the context of simulations involving a complete compartment fire model. One likely candidate model is the two-layer zone compartment fire model computer code LAVENT (Link Actuated VENTs) [1, 2]. LAVENT simulates the development of the fire environment in a compartment of fire origin outfitted with fusible-link-actuated ceiling vents and sprinklers. LAVENT simulates the environment in the fire compartment up to the time that the first sprinkler link fuses and the water flow from the actuated sprinkler nozzle is initiated.

By including the present sprinkler/layer interaction model in LAVENT, the revised compartment fire model would be able to simulate the fire environment beyond the time of first sprinkler operation, including the effects of subsequent actuation of additional ceiling vents and/or sprinkler nozzle flows. A prototype version of such a revised LAVENT fire model is now under development. The new fire model will be called LAVENTS (Link Actuated VENTs and Sprinklers).

SUMMARY AND CONCLUSIONS

A mathematical model was developed to simulate the interaction of an isolated operating sprinkler and a two-layer fire environment under arbitrary conditions of sprinkler-nozzle elevation, and upper- and lower-layer thickness and temperature. The sprinkler is characterized by water flow rate, nozzle diameter, and three other measurable device parameters related to: the drop size of the water flow after fragmentation of the nozzle flow stream, the momentum of the stream after fragmentation, and an effective cone angle of the sprinkler spray. The model takes account of all effects of the sprinkler spray as it entrains, drives downward (by aerodynamic drag on the spray drops), humidifies, and cools (by drop evaporation) gases from both the high temperature upper layer and the relatively cooler lower layer.

A specific objective of the model was to provide a means of predicting the rates of flow of mass, enthalpy, products of combustion, and evaporated water to each of the two layers as a result of sprinkler operation. An algorithm for such predictions was presented. This is suitable for general use in two-layer zone-type compartment fire models.

The model was exercised in example calculations which simulate the interaction between the spray of a real sprinkler device and both fire and non-fire environments. Limited validation of the model was achieved in the simulation of experiments involving the operation of a spray nozzle flow operating in a uniform, ambient-temperature, non-fire environment [5, 8]. Model validation in experiments involving operating sprinkler in fire environments is required.

Example calculations simulated the interaction of an operating Rockwood T-4 spray nozzle and a variety of two-layer fire environments in a 10m high space. An important generic phenomenon identified in these calculations was the abrupt and large change in sprinkler/layer interaction that comes about as an upper layer increases in thickness beyond a critical thickness (for a given upper layer temperature) or increases in upper layer temperature beyond a critical temperature (for a given upper layer thickness). When the layer does not exceed the critical values, the sprinkler spray is predicted to result in relatively little mixing between the layers. However, when the critical values are exceeded the model predicts that a very large flow of lower layer gases is transferred to the upper layer by entrainment into the upward buoyant flow that is driven out of the upper layer by direct action of the water spray. The net result of the latter predicted sprinkler/layer interaction would be a very large rate of growth in the thickness of the upper layer, a growth that could lead to rapid and complete smoke filling of even the largest compartments of fire origin.

The above calculation results suggested that control or delay of the temperature and thickness of the upper layer to below-critical levels could be useful in guaranteeing sprinkler/fire interactions, without smoke logging (smoke filling of the entire space), which do not significantly deviate from design conditions. It is possible that the relatively prompt use of ceiling venting could provide the suggested desirable smoke layer control.

The model developed here can only be assessed within the context of a full compartment fire model simulation. Toward the development of such a simulation capability, the sprinkler/layer interaction model is being included in a revised version of the compartment fire model LAVENT (Link Actuated VENTs) [1 - 3]. The new fire model will be called LAVENTS (Link Actuated VENTs and Sprinklers).

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NOMENCLATURE

$c_{H2O,U}$, $c_{H2O,L}$	mass fraction of H_2O in upper, lower layer [(kg of H_2O)/(kg layer)]
$c_{k,U}$, $c_{k,L}$	mass fraction of product k in upper, lower layer [(kg of product k)/(kg layer)]
C_M	ratio of initial momentum of the spray to momentum of the water flow in the sprinkler nozzle (estimate as 0.4).
D_N	sprinkler nozzle diameter
d	volume-mean diameter of the spray drops
$\dot{M}_U$, $\dot{M}_L$	net rate of mass flow to the upper, lower layer as a result of sprinkler operation
$\dot{M}_{ENT}$	mass rate of entrainment of the reversed plume flow
$\dot{M}$	mass rate of layer gases entrained into the spray cone from x_W to x
$\dot{M}_d$	mass rate of water evaporation from all drops in the spray cone between x_W and x
$\dot{P}_{k,U}$, $\dot{P}_{k,L}$	net rate of flow of product of combustion k to the upper, lower layer as a result of sprinkler operation
$\dot{Q}_U$, $\dot{Q}_L$	net rate of flow of enthalpy plus heat transfer to the upper, lower layer as a result of sprinkler operation
$\dot{Q}_d$	rate of heat transfer from the drops to the gas in the spray cone between x_W and x
r	drop size parameter, Eq. (3); estimate to be [0.084 $m/s^{2/3}$]
T_U, T_L	T of upper, lower layer
$\dot{V}_N$	volumetric water discharge rate of the nozzle
x	distance below the spray cone apex located approximately at y_{SPRINK}
x_{FLOOR}; x_{INT}; x_δ	x at floor, $y_{SPRINK} - y_{FLOOR}$; layer interface, $y_{LAYER} - y_{FLOOR}$; jet penetration depth
y	elevation above a datum elevation
y_{CEIL}; y_{FLOOR}; y_{LAYER}; y_{SPRINK}	y of the ceiling; floor; layer interface; sprinkler nozzle outlet

δ_p	jet penetration depth, x_δ - x_{INT}
θ	sprinkler spray angle
ρ_U, ρ_L	density of upper, lower layer

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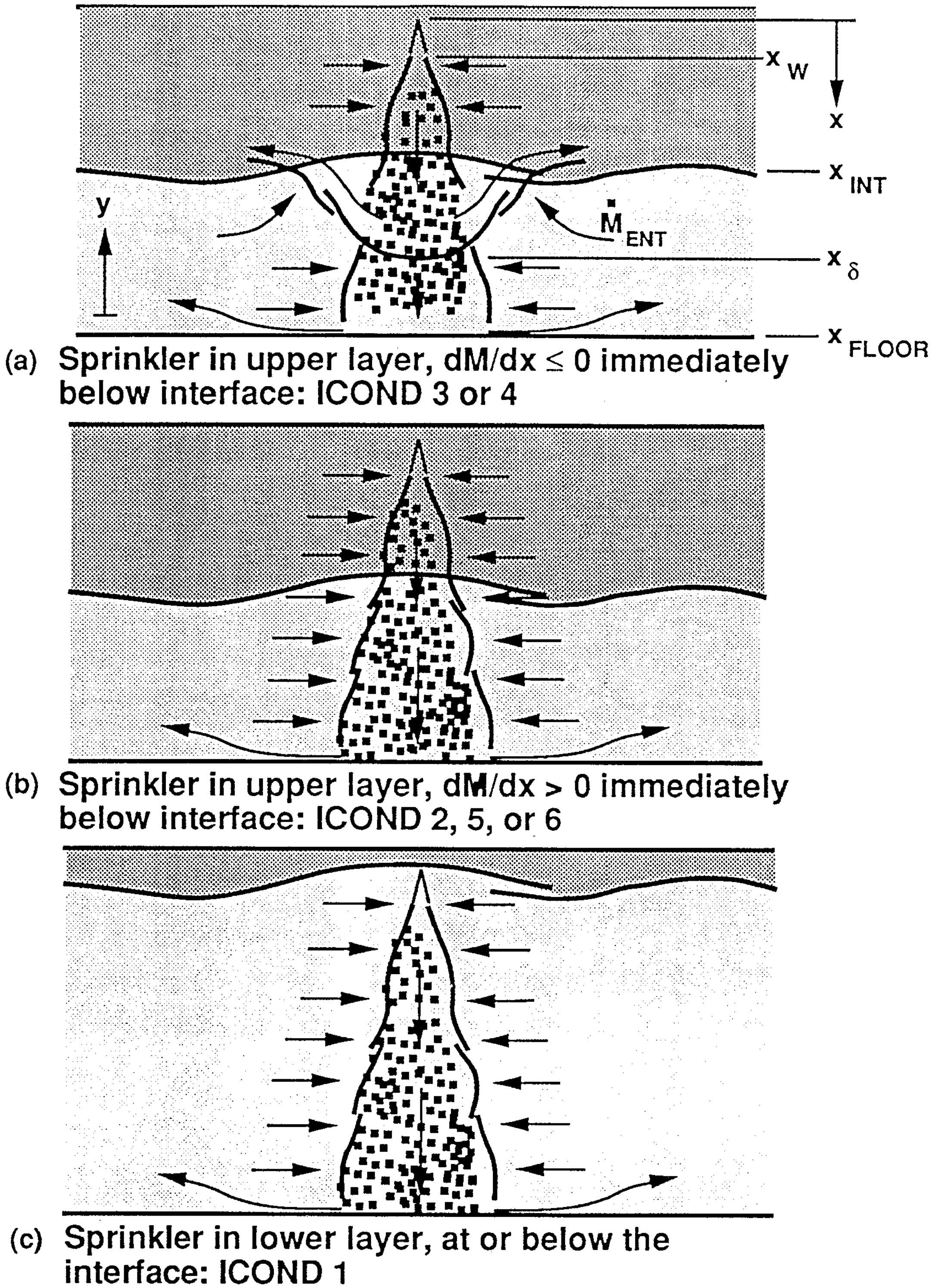


Figure 1. The three generic scenarios for interaction of an operating sprinkler and a two-layer fire environment.

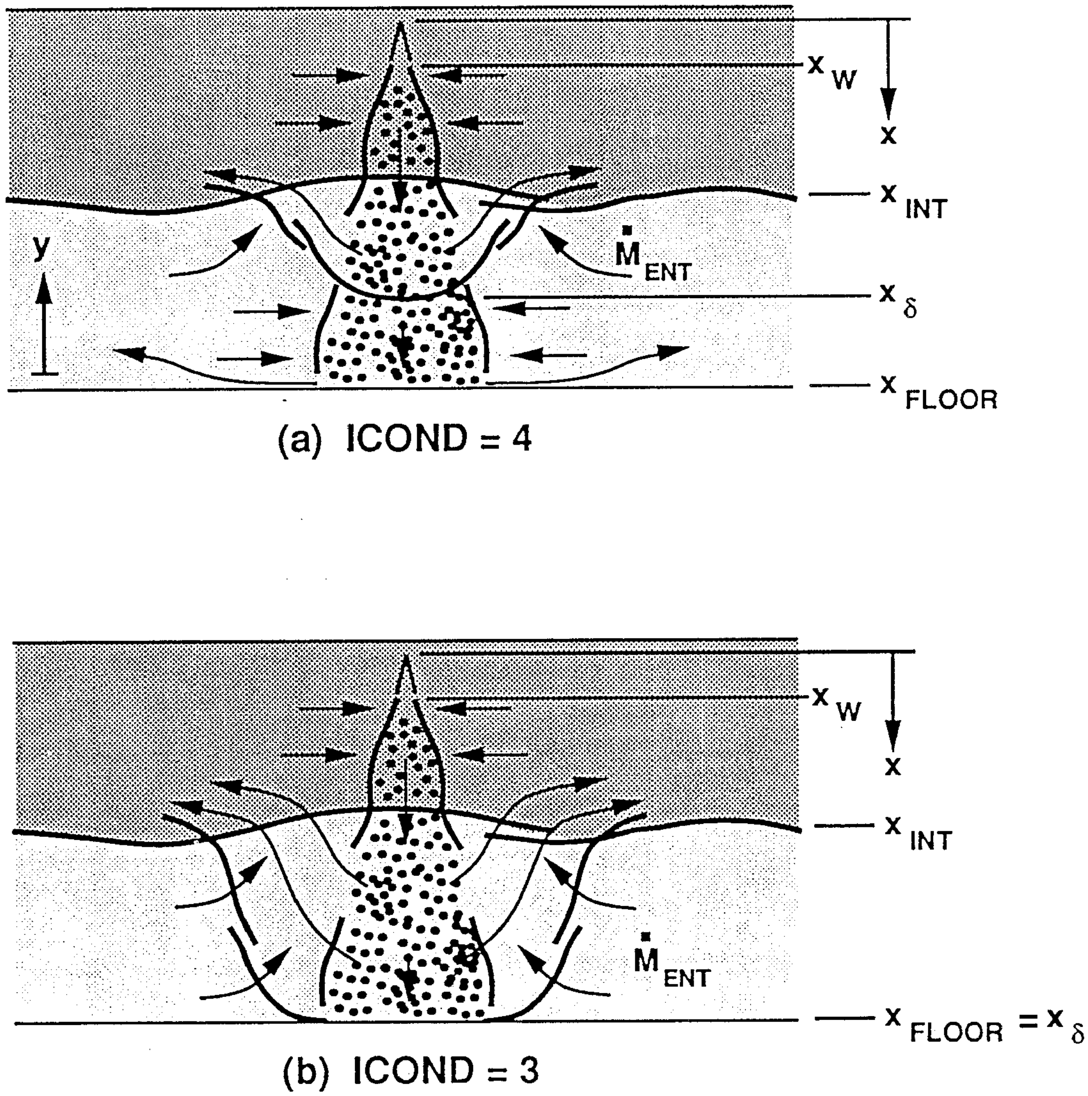
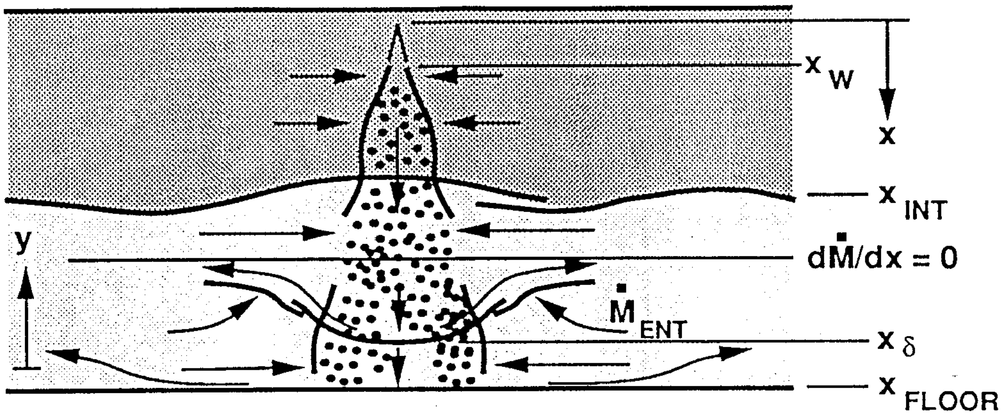
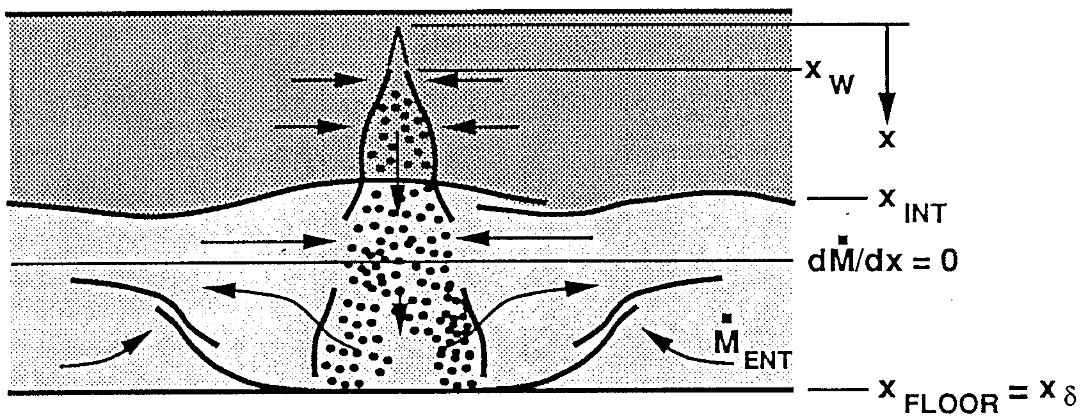


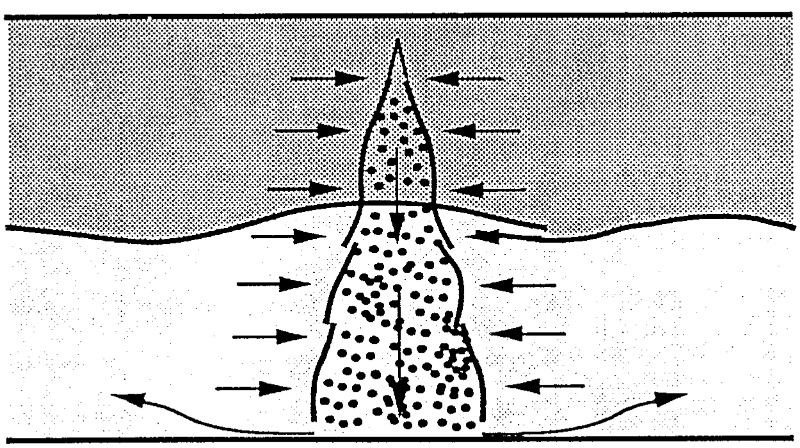
Figure 2. Flow conditions of Figure 1a: ICOND 3 and 4.



(a) ICOND = 5



(b) ICOND = 2



(c) ICOND = 6

Figure 3. Flow conditions of Figure 1b: ICOND 2, 5, or 6.

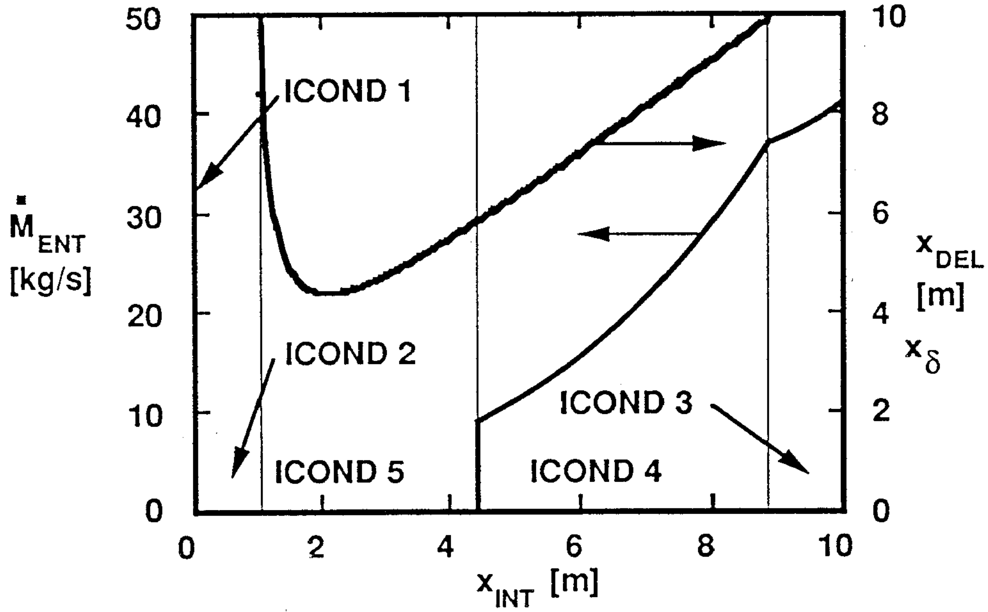


Figure 4. Predictions of $\dot{M}_{ENT}$ and x_δ vs interface elevation for a spray nozzle operating in a two-layer fire environment with a 600K upper layer and a 293K lower layer.

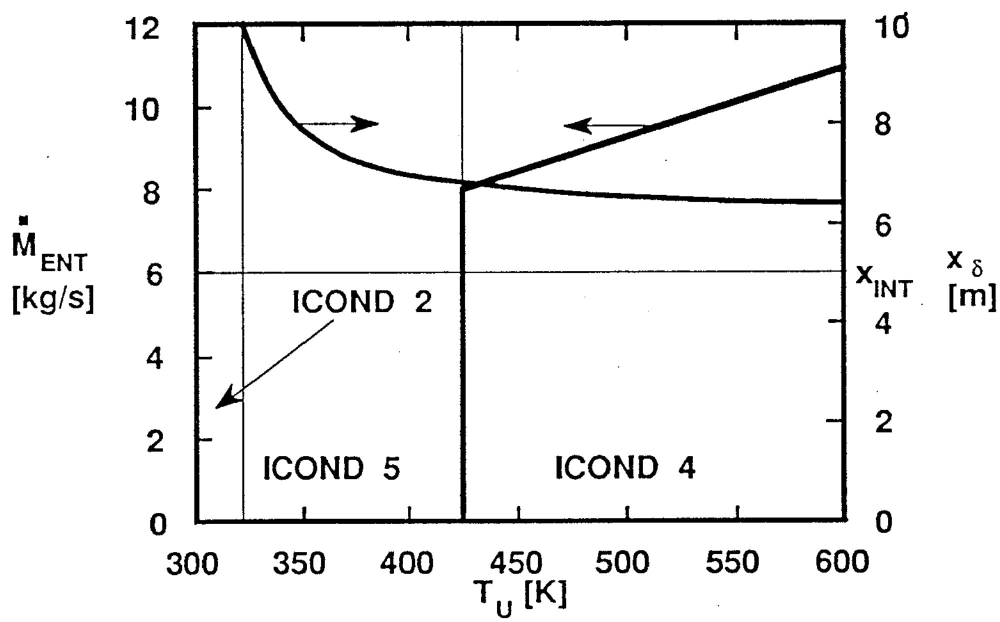


Figure 5. Predictions of $\dot{M}_{ENT}$ and x_δ vs upper layer temperature for a spray nozzle operating above a two-layer fire environment with a 5m thick upper layer and a 293K lower layer.