A Computer Model for Estimating the Response of Sprinkler Links to Compartment Fires With Draft Curtains and Fusible Link-actuated Ceiling Vents

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Abstract

A computer program, LAVENT, is now available which computes the heating of fusible links due to the presence of a ceiling jet imbedded in an upper layer. An important new feature in this program is that the two-dimensional structure of the ceiling jet is taken into account such that the location of the link beneath the ceiling plays a role in the response of the link. The links can be used to activate ceiling vents such that the effect of venting the upper layer on the ceiling jet may be studied. Additional applications would include the study of upper layer containment through the use of a combination of draft curtains and ceiling vents. The geometry modeled by the program is that of a large compartment enclosed by a combination of walls and draft curtains.

Introduction

Over the past two decades, a significant effort has been directed toward modeling the heating of ceiling-mounted fusible links by a fire. Here, it is assumed that a fire-driven plume strikes and spreads over the ceiling forming a ceiling jet. The temperature and velocity of the ceiling jet depends on both the radial distance along the ceiling from the fire and the vertical distance beneath the ceiling.

In order to model this complex phenomenon, the approach generally has been to use a radially dependent model of the ceiling jet and calculate the response of a fusible link using either the maximum local ceiling jet temperature or the maximum local ceiling jet temperature and velocity at the link[1,2] or an average local ceiling jet temperature.[3] This approach provides an estimate of activation time as a function of radial distance

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from the fire but neglects the effects produced by the vertical structure of the ceiling jet.

More recently, a two-dimensional model of the ceiling jet[4] has been developed that uses both the vertical and radial dependence of the local ceiling jet temperature and velocity to calculate the response of a fusible link. This model includes the effects of the presence of an upper layer on the properties of the ceiling jet. A computer program, LAVENT (Link-Actuated VENTs), has been written which implements the two-dimensional ceiling jet model in a framework where the activation of fusible links by the ceiling jet and the effect of ceiling venting of the upper layer on the ceiling jet can be studied.[5] The purpose of this paper is to introduce this computational tool to the fire community.

The generic fire scenario simulated by the computer program, LAVENT, is depicted in Figure 1. This scenario involves a fire in a building space with ceiling-mounted draft curtains and fusible link-actuated ceiling vents and sprinklers. The curtained area can be considered to be one of several such spaces in a single large building compartment. By specifying the curtains to be deep enough, they can be thought of as simulating the walls of a single uncurtained compartment, well ventilated near the floor.

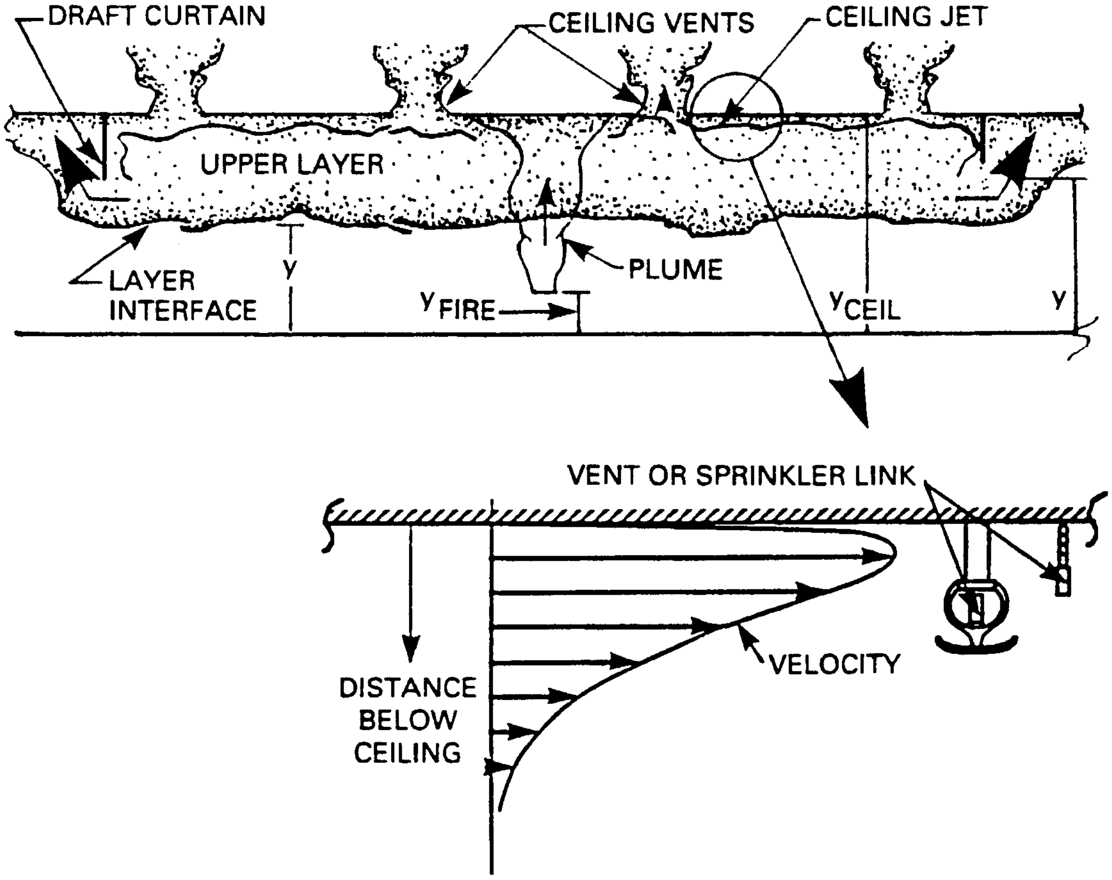

Figure 1: Fire in a building with draft curtains and fusible link-actuated ceiling vents and sprinklers.

The fire generates a mixture of gaseous and solid-soot combustion products. Because of high temperature, buoyancy forces drive the products upward toward the ceiling forming a plume of upward moving hot gases and particulates. Cool gases are laterally entrained and mixed with the plume flow, reducing its temperature as it continues its ascent to the ceiling.

When the hot plume flow impinges on the ceiling, it spreads under it, forming a relatively thin, high temperature ceiling jet. There is convective heating of the interior ceiling surface by the ceiling jet. The interior ceiling surface is also heated due to radiative transfer from the combustion zone and cooled due to re-radiation to the floor of the compartment. The compartment floor is assumed to be at ambient temperature. The exterior ceiling surface is cooled as a result of convection and radiation to a far-field, ambient temperature environment.

When the ceiling jet reaches a bounding vertical draft curtain or wall surface, its flow is redistributed across the entire curtained area and begins to form a relatively quiescent upper layer, which submerges the continuing ceiling jet flow activity. Away from bounding surfaces, the upper layer temperature is assumed to be uniform throughout its thickness. The thickness and temperature of the upper layer affect the upper-plume characteristics, the ceiling jet characteristics, and the heat transfer exchanges to the ceiling. For those cases where an upper layer does not form, the ceiling jet characteristics and the rate of heat transfer to the ceiling will be affected by the ambient temperature of the enclosure.

If the height of the bottom of the upper layer drops below the bottom of the draft curtain, mass and enthalpy from the upper layer will begin to flow beneath the curtain into the adjacent curtained spaces. The growth of the upper layer will be retarded by this additional loss mechanism.

Fusible links, designed to actuate the opening of ceiling vents and onset of water flow through sprinkler heads, are deployed at specified distances below the ceiling and at specified radial distances from the plume/ceiling impingement point. These links are submerged within the relatively high-temperature, high-velocity ceiling jet flow. Since the velocity and temperature of the ceiling jet vary with location and time, so would the heat transfer to and time-of-fusing of any particular link design. The fusing of a ceiling vent link leads to the opening of all vents "ganged" to that link. Once a ceiling vent is open, mass and enthalpy from the upper layer will flow through the vent retarding the growth of the upper layer.

Overview of the Computer Program, LAVENT

The computer program simulates a two-layer, single compartment, zone model where the upper layer is uniform in density and temperature.

A ceiling jet separates the upper layer from the flat ceiling. The compartment is assumed rectangular in floor space and is enclosed by a combination of walls and draft curtains. The ceiling contains fusible links and their associated ceiling vents with the ceiling vents opening in response to the fusing of the links. The rate of heating of the fusible links depends on both the local velocity and temperature of the ceiling jet.

The fire is characterized by a time dependent, heat release rate and either a constant fire diameter or a variable fire diameter characterized by a heat release rate per unit area. Given in Reference 4 are the physical models used to describe the mass and enthalpy flow of the fire plume and ceiling vents, the flow of mass and enthalpy under the draft curtains, the ceiling jet with its associated convective heat loses to the ceiling, and the heating of the fusible links by the ceiling jet. A detailed description of the program inputs and outputs is found in the computer users' guide.[5]

The basic differential equations upon which the upper layer calculation is based are the conservation of upper layer energy,

$$d\,[(y_c - y)\ \rho T A C_v]\ /\, dt = \Sigma\, q_i + pA\ dy/dt \qquad (1)$$

and the conservation of upper layer mass,

$$dm\,/\,dt = \Sigma\, m_i \qquad (2)$$

where y_c is the ceiling height, y is the layer height above the floor, A is the ceiling area, p is the absolute pressure at the layer interface (which is approximately equal to the ambient pressure since the space is assumed to be well ventilated), T is the upper layer temperature, and C_v is the specific heat at constant volume. Also, the q_i are the enthalpy flow rates to the layer from the plume, from the ceiling vents, from under the draft curtains, and from ceiling heat transfer, the latter being the result of convective heat transfer between the ceiling and the ceiling jet. Finally, the m_i are the mass flow rates to the layer from the plume, ceiling vents, and from flow under the draft curtains. The gas in the layer is assumed to obey the ideal gas law and to have a pressure that is assumed to approximate the ambient pressure. Using the ideal gas law, Equation 1 can be rewritten in the form of

$$dy\,/\,dt = -\,\Sigma\, q_i\ /\ (A C_p\, \rho_a\, T_a) \qquad (3)$$

where ρ_a is the ambient density, T_a is the ambient temperature, and C_p is the specific heat at constant pressure. Equations (2) and (3) make up the set of differential equations used to describe the upper layer.

The details of the plume model used to describe the flow of mass and enthalpy from the fire to the upper layer are found in Reference 6. For this model, the heat release rate and fire diameter specify the flame height and entrainment of the fire. The user may choose to specify the fire as having a constant fire diameter or if the heat release rate per unit area is known for the burning fire, a variable diameter fire may be specified using the fire's heat release rate and heat release rate per unit area. The plume model has a few limitations. The flame height model has been shown to be approximately valid for $Q^{2/5}/D$ in the range of 7–700 $kW^{2/5}/m$. Here Q is the heat release rate of the fire and D is the fire diameter. While this range should be sufficient for most applications, the user must exercise some caution if the heat release rate of the fire lies outside this range since the plume entrainment rate and therefore the development of the upper layer and heating of the fusible links may no longer be accurately represented. The heat release rate and the fire diameter or heat release rate per area are user inputs, and the heat release rate as a function of time is part of the program output, hence the user should be able to determine when a calculation is being computed outside of the range of validity for the plume model. Since the computer program allows fires to start from zero heat release rate, a default value of 1 mm for the flame height is used for small heat release rates where the flame height model would predict a negative flame height. The entrainment portion of the plume model is valid only if in-depth combustion is not substantial. In-depth combustion is taken to mean that the fuel load is involved throughout its volume and the fire can no longer be adequately represented by surface combustion.

Mass flow from the upper layer is driven through the ceiling vents by the cross-vent hydrostatic pressure difference. Bernoulli's equation is applied across the vent, and it is assumed that away from and on either side of the vent, the environment is relatively quiescent. The cross-vent pressure difference is computed by calculating the hydrostatic pressure difference between equal columns of gas at the ambient and upper layer density with each column having a thickness equal to the depth of the upper layer. A vent flow coefficient of 0.68 is used to complete the calculation.[7] The flow of enthalpy through the vent is then just the mass flow through the vent multiplied by the product of the upper layer temperature and the specific heat of the gas at constant pressure.

Mass flow beneath the draft curtains is calculated in a similar manner except that the cross-vent hydrostatic pressure difference across the flow is no longer a constant as it is for the ceiling vents and now depends on height. A flow coefficient of 1.0 is used to model this vertical flow.[4]

The thermal response of the ceiling involves convective heating from the ceiling jet, radiative heating from the fire, convective cooling between the outer ceiling surface and ambient conditions, and re-radiation from both inner and outer ceiling surfaces to ambient conditions. Re-radiation is calculated in the standard manner using the black body radiation equation with emissivities equal to one.

The convective heating and cooling calculations are done by assuming that the rate of heating or cooling is directly proportional to the temperature difference between the surface and the local conditions. The temperature difference used for the lower ceiling surface is equal to the difference between a characteristic temperature and the temperature of the lower ceiling surface. The characteristic temperature is equal to the temperature measured adjacent to the ceiling surface if the ceiling was adiabatic. For the upper ceiling surface, the temperature difference is equal to the difference between the upper ceiling surface temperature and ambient temperature. The convection coefficient for the inner and outer ceiling surface is given by Reference 8 and Reference 9, respectively.

The fraction of the fire's energy radiated from the combustion zone is taken to be independent of the fuel burned and assumed to be 0.35. Both the upper and lower layers are assumed to be transparent to radiation.

To calculate the temperature response of the ceiling, the ceiling area, which includes the draft curtains and walls as an extended ceiling, are cast into an equivalent cylindrical geometry with the fire located at the center. The area of the equivalent cylindrical ceiling equals the sum of the rectangular ceiling area and the area of the wall surfaces and draft curtains down to eighty percent of the height of the enclosure. The ceiling is divided into a number of annuli not exceeding 50. Each annulus is treated as an independent ceiling segment with the net heat flux to upper and lower surfaces determining the in-depth temperature distribution. To determine the temperature profile in the ceiling, one-dimensional heat conduction calculations must be performed for each annulus at each time-step using the standard partial differential equation formalism.[10] It is assumed that radial gradients in temperature are sufficiently small that radial heat flow within the ceiling is negligible.

The ceiling jet model used in the computer program is relatively complex. A detailed description of the model, which includes comparisons with experimental data, appears in Reference 11. This model is valid for values of radial distance from the plume impingement point divided by the distance of the equivalent fire source beneath the ceiling, r/H, of order 1 or less. For values of r/H less than 0.2, which is in the plume stagnation region, the values of ceiling jet temperature and velocity are assumed equal to the values calculated at r/H equal to 0.2. For this reason, the user should exercise some caution about using the computed results for the ceiling temperature when r/H is less than 0.2.

The heating of the fusible links is calculated using the convective heating model developed in Reference 12. Here, the heating of the fusible links is given by

$$dT_L/dt = (T_{CJ} - T_L)\, V_{CJ}^{1/2} / RTI \qquad (4)$$

where T_L is the link temperature, T_{CJ} and V_{CJ} are the temperature and velocity of the ceiling jet at the position of the link, and *RTI* is the response time index of the fusible link. Heat losses, which include conduction along the link to the ceiling and re-radiation from the link, are neglected in this model.

The computer program compares the instantaneous link temperature against a user-selected temperature at which the link actuates and sets a switch when the link temperature reaches the user-selected temperature. This switch is then used by the program to open a ceiling vent or activate a sprinkler head. The calculated time required for a fusible link to actuate will in general be shorter than the actual time since the model for the ceiling jet is quasi-steady and assumes that the ceiling jet instantaneously covers the ceiling. The transient time required for the ceiling jet to initially flow across the ceiling is ignored. The user can make a crude estimate of the magnitude of this transient time by taking the distance from the plume center to the fusible link, adding the ceiling height, and dividing the resulting sum by the local ceiling jet speed at the link.

The computer program is designed to accept either English or SI units for input and output but all calculations within the program are performed in SI units.

Simulation of a Typical Large Compartment Fire

The following fire scenario is used to demonstrate the capabilities of the computer program, LAVENT. A compartment 84.0 ft × 84.0 ft with a ceiling located 30.0 ft above the floor is enclosed by a draft curtain 11.0 ft in depth, which completely surrounds and defines the compartment. The ceiling is constructed of a thin sheet-steel lower surface that is well-insulated from above.

The curtained compartment has four, uniformly spaced, 48 ft^2 ceiling vents (see Figure 2 on p. 120) with a total area of 192 ft^2, or 2.7 percent of the ceiling area. Opening of the ceiling vents is actuated by quick-response fusible links with RTIs of 50.0 $(\text{ft}\cdot \text{s})^{1/2}$ and fuse temperatures of 165.0°F. The links are located at the centers of the vents and 0.3 ft below the ceiling surface.

Fusible link-actuated sprinkler heads are deployed on a square grid with 12.0-ft spacing between heads. The links have RTIs of 400.0 $(\text{ft}\cdot \text{s})^{1/2}$ and fuse temperatures of 165.0°F. The heads and links are mounted 1.0 ft below the ceiling surface.

The choice of RTI value and location beneath the ceiling of the two sets of fusible links was made in order to permit the link-controlled ceiling

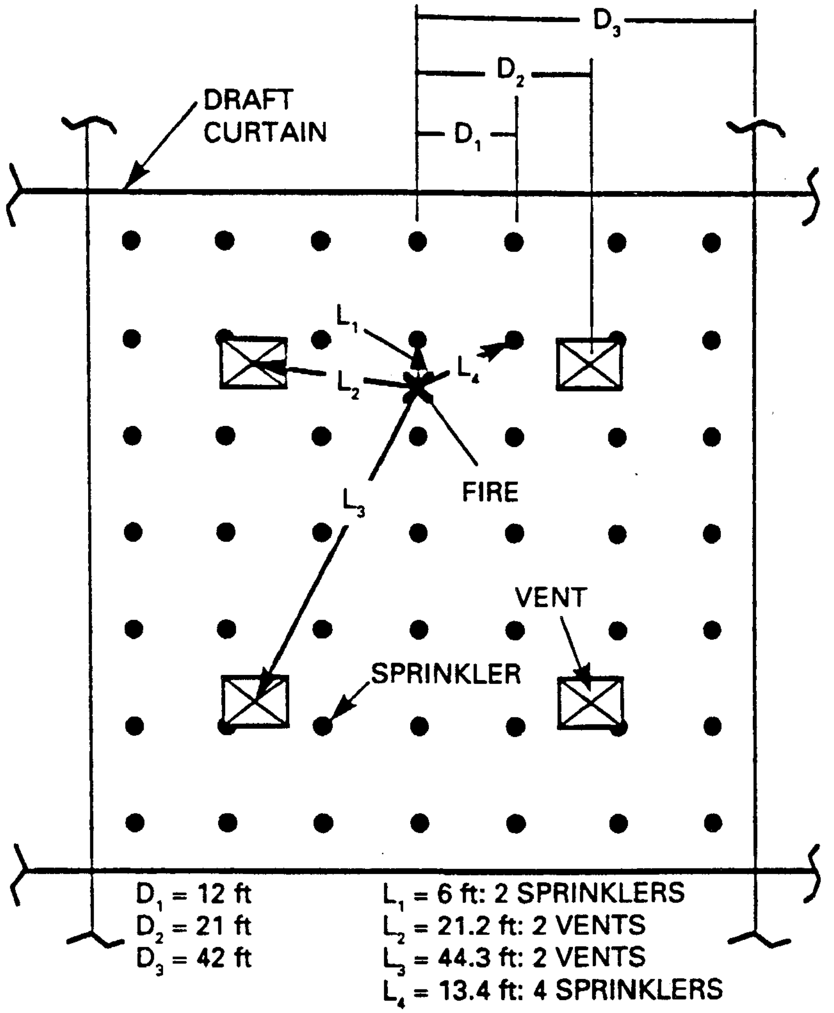

Figure 2: Vent and sprinkler spacing and fire location.

vents to actuate prior to the actuation of the link-controlled sprinkler heads. The sequence of link actuations depends on the location of the links and their relative RTI values. By using different sets of values, the sprinkler links may be made to actuate before the ceiling vent links.

The simulation fire involves four abutting 5.0-ft-high stacks of 5.0-ft × 5.0-ft wood pallets. The combined grouping of pallets makes up a combustible array 10.0 ft × 10.0 ft (100 ft^2 in area) on the floor and 5.0 ft in height. It is assumed that other combustibles in the curtained compartment are far enough away from this array that they will not be ignited in the time interval to be simulated.

The total heat release rate of the simulation fire, Q, grows from ignition, at time $t = 0$, in proportion to t^2 as

$$Q = 1000.\ [t/(130)]^2\ BTU/s \qquad (5)$$

where t is in seconds. The fire grows at this rate until the combustibles

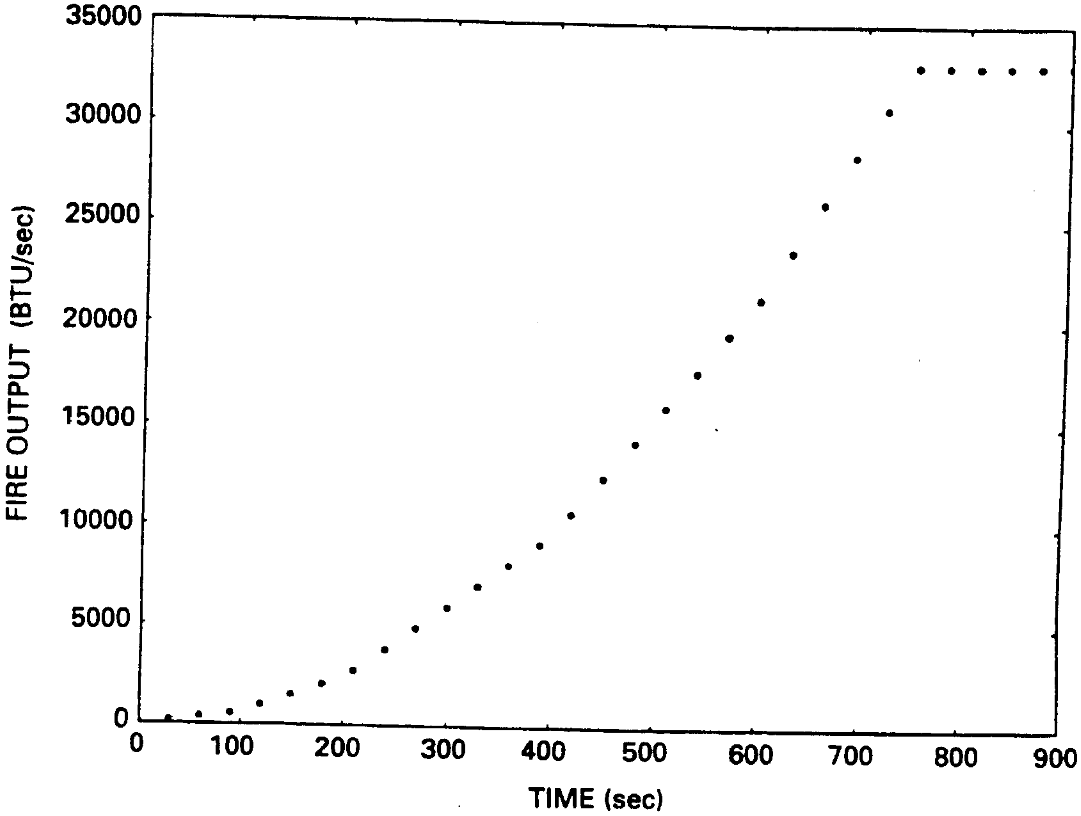

Figure 3: Energy release rate vs. time for the fire.

are fully involved. Then it is assumed that the heat release rate becomes constant at the fully involved value, which is 33000. BTU/s for this simulation. A plot of the fire growth according to the above description is presented in Figure 3. In the actual calculation, the fire's instantaneous heat release rate is estimated by interpolating linearly between a series of input data points defined by user-specified values using the above heat release rate equation.

The position of the center of the fire is identified in Figure 2. In terms of this figure, the fire is assumed to be located at the midpoint of a 12.0-ft line between two sprinkler links, at a distance of 21.2 ft from each of the two closest equidistant vents (total vent area of 96.0 ft^2), and at a distance of 44.3 ft from the remaining two equidistant vents (total vent area of 96.0 ft^2). Of the sprinklers and associated links, two are closest and equidistant to the fire-plume axis at radial distances of 6.0 ft. Note from Figure 2 that the next closest group of sprinkler heads and links is at radial distance from the fire of 13.4 ft (four heads and links). In the simulation, opening of each of the four vents occurs, and flow out of the vents is initiated at the simulated time of fusing of their associated links. Also simulated in the calculation is the thermal response, including time-of-fusing, of the pair of sprinkler links closest to the fire. As a

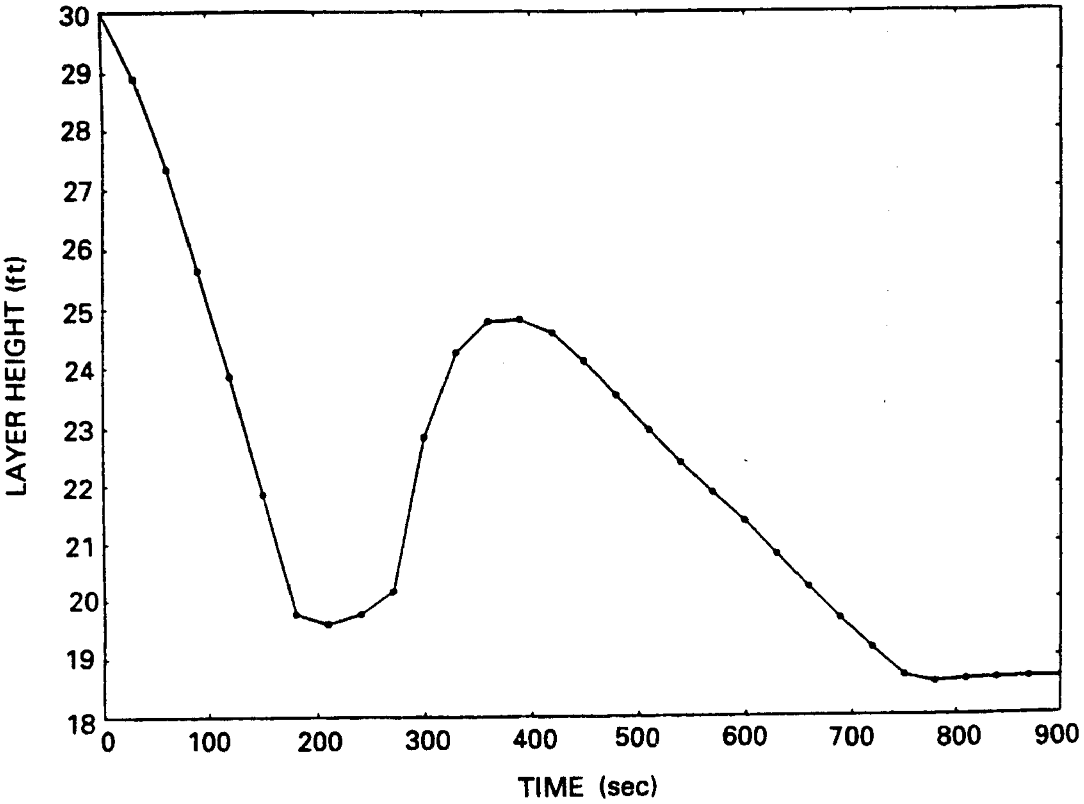

Figure 4: Plot of the height of the smoke layer interface vs. time.

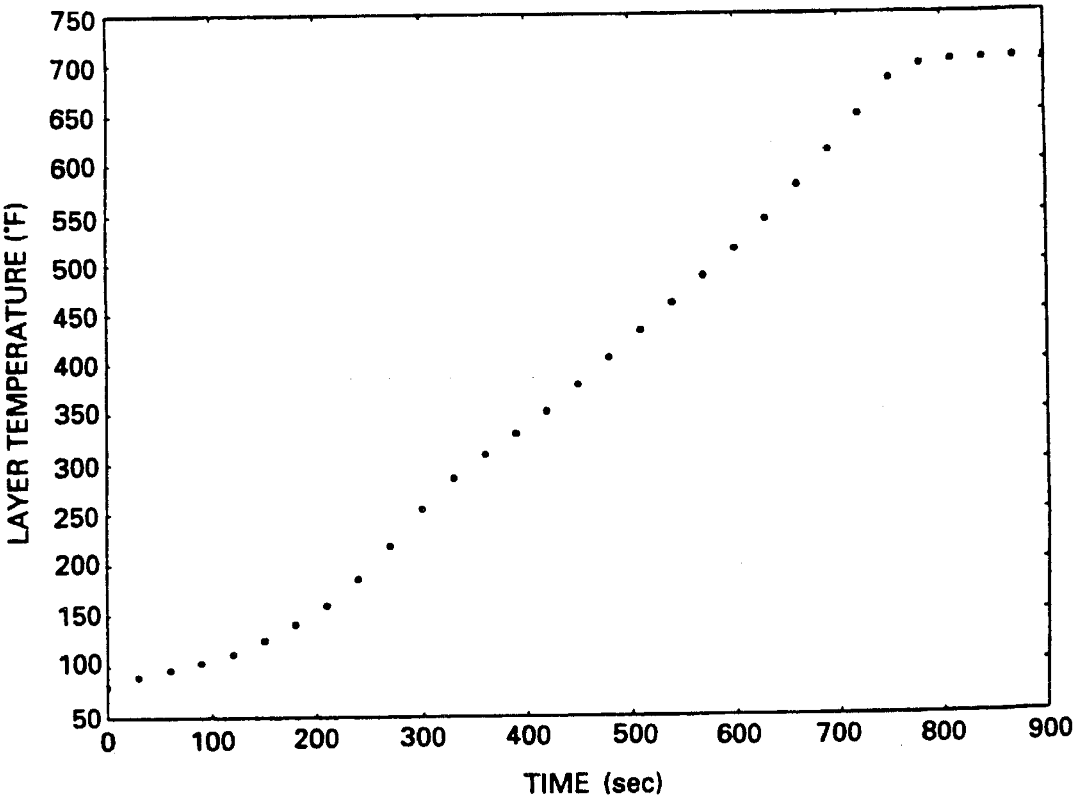

Figure 5: Plot of the temperature of the smoke layer vs. time.

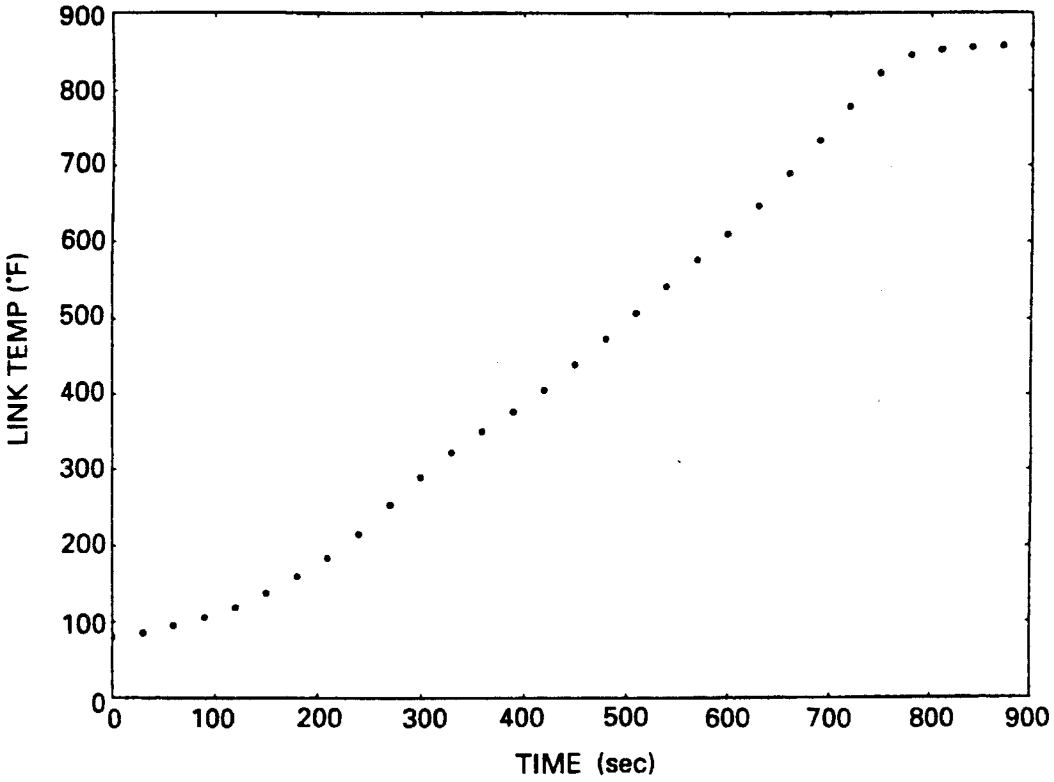

Figure 6: Plot of the closest (R = 21.2 ft) vent-link temperatures vs. time.

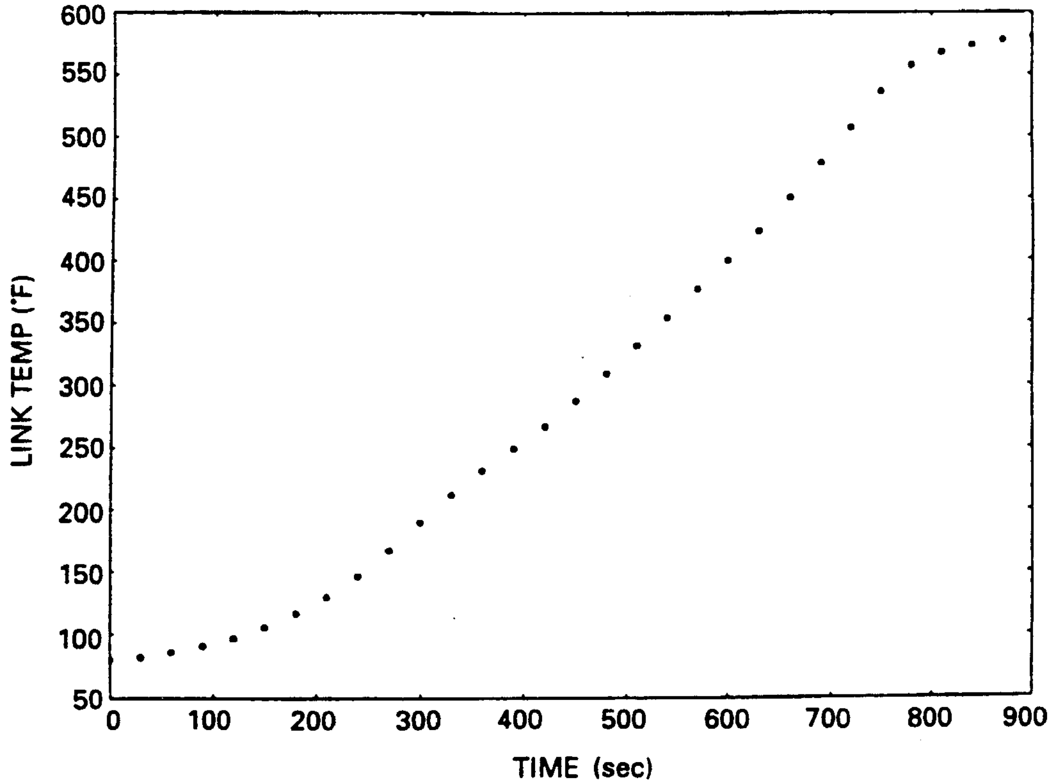

Figure 7: Plot of the far (R = 44.3 ft) pair of vent-link temperatures vs. time.

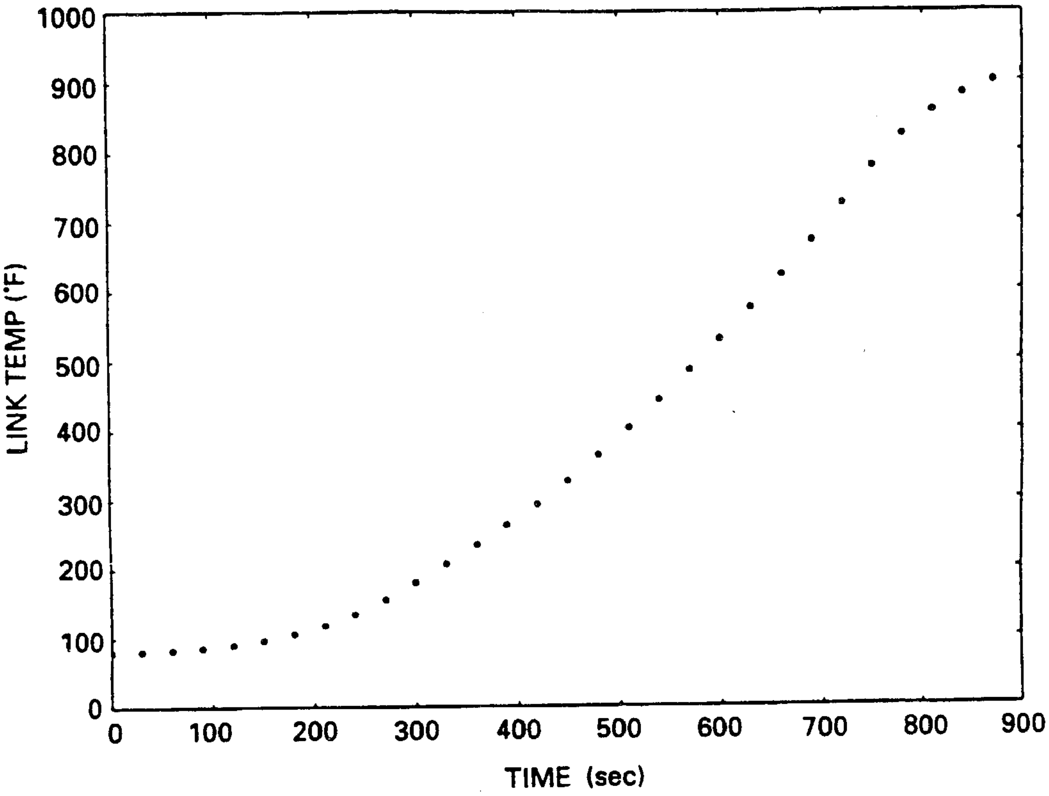

Figure 8: Plot of the closest (R = 6.0 ft) sprinkler-link temperatures vs. time.

final specification of the fire, it is assumed that the characteristic elevation of the fire remains at a fixed value, 2.5 ft above the floor, at the initial mid-elevation of the array of combustibles.

Results of the Fire Simulation

The growth of the layer and the increase in its temperature in response to the growing fire are presented in Figures 4 and 5, respectively. Plots of the thermal response of the two pairs of vent links and the pair of sprinkler links closest to the fire are presented in Figures 6–8, respectively. The links controlling the near pair of vents fuses at 187 s, the links controlling the far pair of vents fuses at 267 s, and the links controlling the nearest pair of sprinklers fuses at 282 s. Although the links controlling the sprinkler are closer to the fire than any of the links controlling the vents, and although all the links have the same fuse temperatures, the simulation predicts that the sprinkler links fuse after all of the vent links. There are two reasons for this. First, the RTI of the sprinkler links is larger than those of the vent links and, therefore, slower to respond thermally. Second, the two sprinkler links are far enough from the ceiling as to be below the peak temperature of the ceiling jet, which is relatively thin at the 6-ft radial position (see the lower sketch of Figure 1).

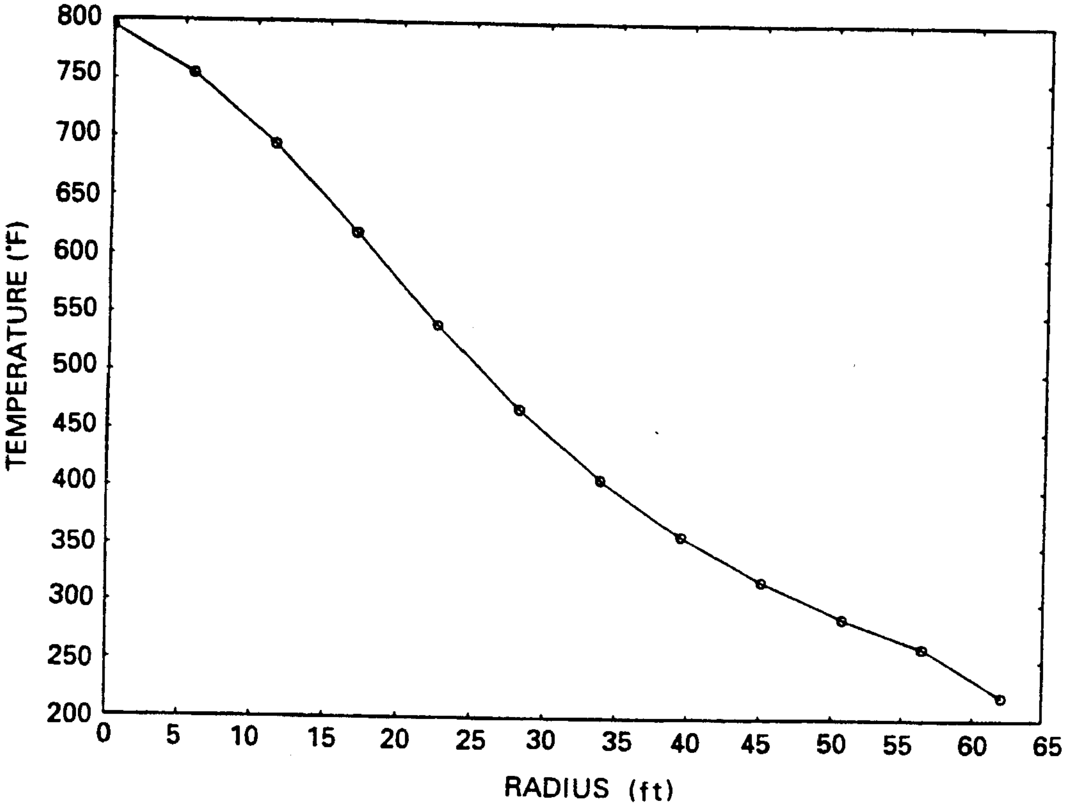

Figure 9: Plot of the ceiling temperature as a function of distance from the plume impingement point at 900 s.

The effect of layer growth on the fusing of the two pairs of vent links and opening of their corresponding vents at 187 s and 267 s can be noted in Figure 4. Note that the opening of the first pair of vents effectively stops the rate of increase of layer thickness and the opening of the second pair of vents leads to a relatively rapid rate of decrease in the layer thickness. All of this, of course, is occurring at times when the energy release rate of the fire is growing rapidly.

While the links controlling the sprinklers would have fused at 282 s, it's assumed that the sprinklers did not discharge water and the simulation was continued to 900 s. This was done to demonstrate the containment of the upper layer by the draft curtain in the absence of operating sprinklers. Had the sprinklers operated, they would have severely modified the fire growth with the resulting layer growth after 282 s being substantially different from what is presented here. At present, LAVENT does not have the capability to model the effects of sprinkler operation.

As seen in Figure 4, up to about 750 s of simulation time, the combination of ceiling vents and draft curtains is effective in preventing the upper layer from spilling into the adjacent compartments. The growing fire finally overwhelms the venting system and the upper-layer gases spill under the draft curtain. The ceiling vent system has managed to delay the escape of upper-layer gases to adjacent compartments by approximately 500 s.

The computed temperature distribution of the inner ceiling surface as a function of radial distance from the plume impingement point at 900 s is shown in Figure 9. In this simulation, the computer program divided up the ceiling into 12 annuli as shown by the open dots on the figure. The heating at each of these annuli was calculated using the radiative and conductive heat fluxes present at these points. The resulting temperature distribution across the ceiling falls off fairly rapidly as a function of radial distance, reaching a value of about half the peak value at 30 ft from the plume impingement point.

Summary

The computer program, LAVENT, provides a computational tool to investigate the response of fusible links to a ceiling jet in an environment where there is sufficient ventilation to maintain the compartment pressure below the smoke layer at approximately ambient conditions. Venting of the fire produced smoke layer as a function of ceiling vent area and fusible link response time may also be studied.

Work is presently underway to incorporate sprinkler interaction with the upper layer. With this enhancement, fire scenarios may be simulated numerically, which will include the actuation of more than one sprinkler link.

Acknowledgments

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