LAWRENCE W. HUNTER

FIRE HAZARDS OF ELECTRIC CABLES IN NUCLEAR POWER PLANTS

Mathematical models were developed at APL to describe fires in electric cable installations. The theories, in coordination with experiments at a number of other facilities, helped the Nuclear Regulatory Commission to develop fire safety guidelines for nuclear power plants. The results also have significance for the Navy, where electric cable fires are a continuing problem.

From 1977 to 1982, APL was involved in a joint effort with Sandia National Laboratories, Underwriters' Laboratories, and the University of California at Berkeley to examine fire problems in nuclear power plants. Most of the flammable material in a nuclear power plant is the plastic insulation on electric cables. Hence the research focused on the fire hazards of electric cable installations. The theories were developed at APL,[1-7] while the experiments were carried out at the other institutions. The combined effort assisted the Nuclear Regulatory Commission (NRC) in making licensing decisions and in establishing design standards.

BACKGROUND

On March 22, 1975, a major cable fire occurred in the cable-spreading room of the world's largest operating nuclear power plant, the Browns Ferry Nuclear Plant of the Tennessee Valley Authority located beside the Tennessee River near Decatur, Ala. Over 600 of the burned cables contained circuits for the safe shutdown of one or both of the two operating reactors. The direct fire loss was $10 million, and the cost of fossil fuel used to produce the replacement electricity over the next 18 months was $200 million. That incident led NRC to initiate a reevaluation of the fire potential of all U.S. nuclear power plants.

Cable fires also pose serious fire hazards to ships at sea. In the early 1970's, cable fires occurred in the aircraft carriers USS *Forrestal* and USS *Saratoga.* The cables carried the fire through bulkheads thought capable of stopping fire. In 1976 the British submarine HMS *Warspite* developed a cable fire that shut down its nuclear reactor. The burning insulation produced corrosive hydrogen chloride gas, necessitating two years of repairs. More recently, a cable fire occurred on HMS *Sheffield* in the Falklands war when the destroyer was hit by an Exocet missile. Within 15 to 20 seconds the whole working area of the ship was filled with acrid smoke, mainly from the cable runs and paint. Clearly, the results of the research for NRC have applications to ships as well as nuclear power plants.

NRC originally became interested in receiving APL's assistance as a result of earlier work at APL on basic principles of the ignition and combustion of plastics[8-15] and the suppression of flames.[16]

The work on combustion of plastics centered on identifying the combustion mechanism. A burning plastic decomposes to produce hot flammable gases that react quickly with air in a zone very near the surface (Fig. 1). Thus the reaction zone is supplied on one side by flammable gases evolving from the solid, and on the other by oxygen diffusing inward from the air. The reactions release heat, some of which

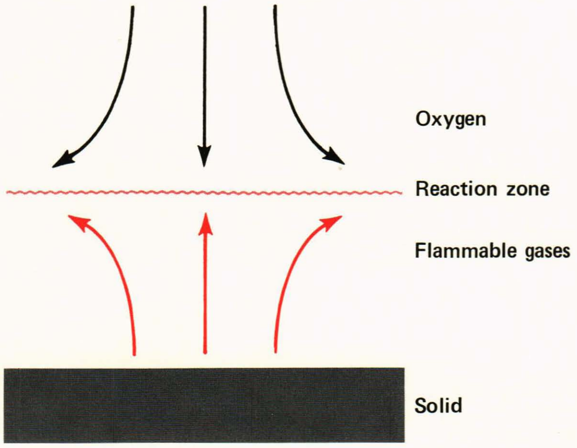

Figure 1 — A qualitative picture of the combustion of plastics. The plastic degrades thermally with production of flammable gases that react with oxygen in the gas phase. The reaction zone is only a fraction of a millimeter from the solid at normal pressures, but the distance increases at reduced pressure.

feeds back to the solid to sustain the decomposition reactions that produce the flammable gases. The consumption of oxygen in the reaction zone maintains a concentration gradient that sustains the diffusion of oxygen. At normal pressures, the reaction zone is within 0.1 millimeter of the surface. We were able to increase this distance by reducing the pressure in a special apparatus that allowed us to isolate and identify some of the flammable gases evolving from polyvinyl chloride, a common cable insulation material.

As a corollary, a plastic cannot ignite until it is hot enough to decompose and generate flammable gas. Even then, ignition is not guaranteed. Ignition requires oxygen and a spark or a pilot flame.

The suppression work focused on the chemical substance CF_3Br, a common agent in fire suppression systems for electric cable installations. We observed that CF_3Br achieves its effect by interfering with the chemical reactions in the flame. Those reactions almost exclusively involve fragments of molecules. The concentration of the fragments remains low because of their high reactivity.

While the principles of ignition, combustion, and suppression observed in a laboratory hold true with equal validity for cable installations, the application of the principles goes beyond the basic work and into uncharted areas of heat transfer, aerodynamics, and applied mathematics.

For a cable installation, the likelihood of ignition and fire spread is very sensitive to the orientation of the cables and the proximity of walls. Hence it is necessary to consider the possibilities separately. The phenomena addressed during the course of the program were as follows:

1. Ignition of horizontal cables,
2. Cable fire propagation,
3. The fire resistance of a wall penetrated by cables,
4. The fire resistance of a wall penetrated by a hole,
5. Cable fire suppression.

The results in these areas are discussed from a qualitative viewpoint in the following sections.

IGNITION OF HORIZONTAL CABLES

The work described in this section was motivated by some puzzling observations, in tests at Sandia Laboratories, of a common installation technique in nuclear power plants where cables are supported in horizontal ladder-like trays that in turn are arranged in a stack (Fig. 2). It was observed that a fire in a lower tray (the "donor fire" in tray 1) spreads upward by a peculiar leapfrog process. The next higher tray in the stack (tray 2) does not ignite directly. Instead, a gas-phase fireball develops against the underside of tray 3 and gradually grows in size until it ignites tray 2 from above.

The theoretical analysis at APL led to the following explanation of the observations. The donor fire generates hot gases, mainly depleted of oxygen, that rise because of the forces of buoyancy. Part of the plume flows through tray 2, where it heats the cables. Depending on conditions, the insulation can eventually become hot enough to produce flammable gas—but only in the middle of the plume. Since ignition cannot occur without oxygen, the flammable gas is carried upward by the plume until it reaches a recirculation zone under tray 3, where fresh air is entrained. When ignition occurs, the fireball that is formed establishes new buoyant flow patterns that sustain the entrainment of fresh air. The radiation from the fireball to tray 2 increases the evolution rate of flammable gas. Hence the fireball grows until it attaches to tray 2 from above.

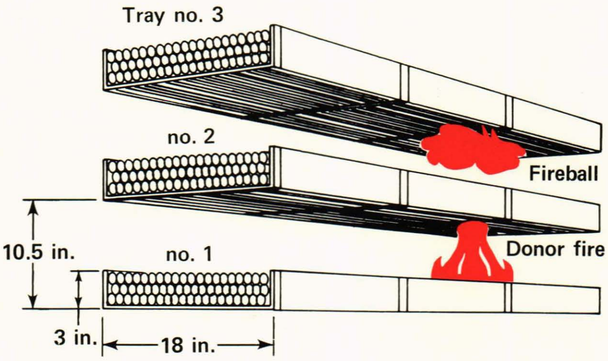

Figure 2 — Upward fire spread in a stack of horizontal open-bottom trays filled with cables. When a preexisting "donor" fire in tray 1 spreads upward through the stack, the mechanism is a leapfrog process. Flammable gas driven from tray 2 produces the fireball shown, which then ignites tray 2 from above.

A necessary condition for this whole process to be possible is that the insulation in tray 2 eventually gets hot enough to generate flammable gas. As a first approximation, flammable gas evolves when the surface of the insulation reaches a given temperature, which is dependent only on the insulation's chemical composition. Whether this condition is achieved depends on the balance between heat convection from the plume, radiation from the donor fire, radial heat conduction in the cable, axial heat conduction in the cable, and reradiation. Thus the first stage in the theoretical analysis involved solving the governing (steady-state) heat transfer equations.

More detailed (time-dependent) calculations led to the necessary delay time to the onset of flammable gas evolution. The delay time is an important factor when the donor fire is short-lived.

Another vital step in the fire spread process is the flow of plume gases through tray 2. The rate of flammable gas evolution was calculated from overall heat and mass conservation equations. The simple result is that the output of flammable gas is proportional to the throughput of plume gas. Specifically, the mass flux of flammable gas generated at the center of the plume is proportional to the mass flux of plume gas that actually penetrates the tray. Loosely packed cables allow a higher throughput of plume gas and thereby generate flammable gas faster.

Comparisons between theory and experiment gave satisfactory agreement. One of the outputs was a set of safety guidelines for designers and inspectors. When upward fire spread is estimated to be a hazard, tests confirmed that the hazard may be eliminated completely by blocking the airflow through the trays by means of fire-resistant barriers.

CABLE FIRE PROPAGATION

Once ignition has occurred in a cable installation, it is important to determine how rapidly the fire will spread over the cables. The rate of fire spread is strongly affected by the heat feedback to the unburned insulation in the path of the advancing flames. This insulation must be heated to its gasification temperature before it can ignite.

The feedback, in turn, depends on cable orientation and the proximity of walls. Consider fire spreading along horizontal cables. Here the unignited insulation is preheated mainly by axial heat conduction in the cables. This mode of heat transfer is not especially efficient, and the result is a slow propagation speed.

While horizontal orientation is common, cables are also arranged vertically and are frequently housed in conduits. Upward fire spread over vertical cables is rapid, as is fire spread through a conduit with a forced airflow. In both cases, the unignited insulation is preheated by direct contact with the fire gases.

The most rapid fire spread occurs when the heat feedback is augmented by radiation from an external fire such as an established fire on another cable installation somewhere else in the room. When the level of external radiation is itself sufficient to preheat cable insulation to the flammable gas temperature (about 2 watts per square centimeter), the concept of propagation no longer applies and the phenomenon of flashover is observed.

The overall energy balance in the duct fire (Fig. 3) is

$$Q\dot{m}_{\text{air}} = LPV + \dot{Q}_{\text{walls}} \,. \qquad (1)$$

The term on the left is the rate at which heat is chemically released by the flames, Q being the heat of combustion per unit mass of air and $\dot{m}_{\text{air}}$ being the mass flow rate of air entering the duct. Part of the heat released, given by the first term on the right, is consumed in gasifying the flammable lining in the duct. Here, L is the heat of gasification per unit mass, P is the mass of flammable lining per unit length, and V is the propagation speed of the fire. The remaining heat is conducted through the walls to the surroundings and is lost to the fire spread process.

V is unknown in advance. To find V, a set of differential conservation equations is solved for the wall temperature distribution, which then provides an expression for the loss rate, $\dot{Q}_{\text{walls}}$, in terms of V. With this information, the overall energy balance may be solved algebraically for V.

The overall mass balance gives an expression for the mass rate of smoke production by the fire,

$$\dot{m}_{\text{smoke}} = \dot{m}_{\text{air}} + PV \qquad (2)$$

in terms of the flow rate of air entering the duct and the contribution of the flammable gas evolving from the fuel lining, PV. It is also possible to write an expression for the rate of production of unburned flammable gas.

Tests at Underwriters' Laboratories and Sandia Laboratories focused on upward fire spread over vertical cables. While a few qualitative trends did emerge, quantitative reproducibility was difficult to obtain. In general, upward fire spread over vertical cables is sensitive to the original source of ignition, to small airflows in the room, and to the precise cable

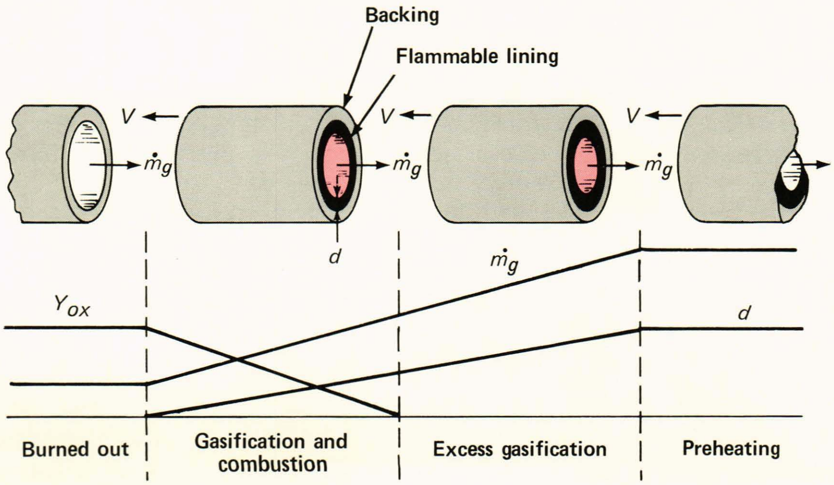

Figure 3 — The four zones in a duct fire, as seen by an observer moving to the right at the steady propagation speed V. The fire appears as a counterflow process in which the flammable lining, of thickness d, moves to the left against a flow of oxygen, of concentration Y_{ox}, moving to the right. The total mass flow rate of gas, $\dot{m}_g$, increases in the two central zones where the lining is hot enough to generate flammable gas.

arrangement, which changes randomly because of thermal expansion.

However, a system that does offer the possibility of quantitative study is a cable conduit. When a conduit connects switch boxes in two different rooms, there is generally a pressure differential and a forced flow of air through the conduit. A fire at one end of the conduit can then spread with the flow of air.

Roberts and Clough[17] reported fire tests on a duct whose inner walls were lined with a flammable solid. Quantitative results were obtained over a wide range of experimental conditions. In a conduit, the flammable material lines the cables. Nevertheless, the two problems are very similar mathematically, and it was concluded that a theory of the fuel-lined duct would provide valuable insight into the conduit problem.

Although the experiments were reported in 1967, there was no theory that predicted the results from basic principles. Hence a theoretical effort was begun on this problem at APL, and a quantitative explanation of results was obtained.

The observations were quite simple. The fire tended to propagate at a constant speed proportional to the mass flow rate of oxygen entering the duct and inversely proportional to the mass of flammable solid per unit length. The theory predicted this dependence and the value of the proportionality constant. In addition, the necessary conditions for steady propagation were calculated.

In the duct-fire test, the flow of gases was one-dimensional. While the composition and speed of the gases varied with axial position, turbulent mixing made conditions radially uniform.

Once steady propagation is established, a duct fire may be viewed from coordinate axes moving at the propagation speed. The fire then appears as a steady counterflow process (Fig. 3) in which the flammable lining and the walls of the duct appear to be moving to the left while fresh air and fire gases flow to the right. There are four distinct zones. The actual flames are confined to the "combustion" zone, where oxygen is reacting with flammable gas being generated by the lining. In the neighboring "excess gasification" zone, no oxygen remains but the lining is still hot enough to generate excess flammable gas. In the "preheating" zone, the hot combustion gases preheat the lining to the point where evolution of flammable gas can begin. In the "burned out" zone, the walls of the duct are being cooled by the flow of fresh air. In all of the zones, heat is conducted from the duct walls to the surroundings.

The unknowns in the problem include the oxygen concentration profile in the combustion zone, the gas temperature profile throughout the duct, and the solid temperature distribution in the two external zones. In the combustion and excess gasification zones, the lining is at its flammable gas evolution temperature, but the gasification rate and the thickness of the lining are unknown functions of position. Finally, the lengths of the two central zones and the propagation speed are unknown in advance.

The governing equations prescribe conservation of heat, mass, and oxygen in the solid and gas phases of the four zones. These equations are sufficient to determine all the unknowns in the problem.

The theoretical results agreed well with experiment. In addition, parameters were varied outside the range of experimental conditions to find the limits at which the calculated temperatures become negative or imaginary. Then the original assumption of steady fire spread is contradicted. The limits show where the fire accelerates or decelerates. These results led to the conclusion that heat losses to the surroundings have a stabilizing influence on the fire spread. Fire in an insulated duct tends to accelerate.

THE FIRE RESISTANCE OF A WALL PENETRATED BY CABLES

Attempts to stop fire at the ignition and propagation stages discussed above occasionally fail. When a fire involves an entire room, the walls are the next line of defense.

The walls in a nuclear power plant are generally constructed from materials that can withstand a severe fire. However, the walls are penetrated by electric cables that lessen the wall's fire resistance. When a fire heats a wall on one side, the metal conductors in the exposed cables transfer heat through the wall to the unexposed side.

The kind of installation considered here is one in which the cables are inserted through an opening in the wall and the remaining space in the opening is sealed with a fire-resistant filler material. A representative model of this situation was developed at APL for the purpose of estimating the important effects of the cables on the backface temperature. The model, shown in Fig. 4, is an array of equally sized, equally spaced metal rods through a slab heated from one side. A steady state is assumed.

Two features of the model simplify the analysis. First, the temperature in each rod is radially constant because of the high thermal conductivity of the rod. Second, between each rod and its nearest neighbors is a surface where the radial heat flux is zero ($\partial T/\partial r = 0$), as shown qualitatively in Fig. 4. Since the rods are equivalent and uniformly spaced, a useful starting approximation is that the no-flux surface is a cylinder of radius equal to one-half the distance between the nearest neighbor rods. It is then possible to focus on one rod enclosed by an annular piece of slab whose curved outer surface is insulated.

The slab and rod temperatures are governed by energy conservation equations that describe radial and axial heat conduction in the slab coupled to axial heat conduction in the rod.

The backface temperature of the slab was calculated as a function of the geometry, thermal properties, and heating intensity. These results established the usefulness under practical conditions of a simple formula based on the approximation that the rods are thermally insulated inside the slab. This formula

The steady temperatures in an electric cable penetration (Fig. 4) are given (to a good approximation) by the solution of a boundary value problem representing a single cable surrounded by an annular piece of wall whose outer curved surface is insulated. A second-order partial differential equation for the wall temperature, T_w, is coupled to a second-order ordinary differential equation for the cable temperature, T_c:

$$\frac{\partial^2 T_w}{\partial z^2} + \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_w}{\partial r}\right) = 0\,,$$

$$0 \le z \le l,$$
$$a \le r \le b.$$

$$\frac{ak_c}{2}\frac{d^2 T_c}{dz^2} = \begin{cases} -H_1(T_1 - T_c), \\ \infty < z < 0; \\ -k_w \dfrac{\partial T}{\partial r}, \\ 0 < z < l, r = a; \\ H_2(T_c - T_2), \\ l < z < \infty. \end{cases} \tag{3}$$

Boundary conditions are also applied.

In these equations, z is the axial coordinate and r is the radial coordinate. In addition, a is the cable radius, b is the outer radius of the wall annulus, and l is the wall thickness, while k_c and k_w are the thermal conductivities in the cable and the wall. Finally, H_1 and H_2 are the heat transfer coefficients on the hot and cold sides, while T_1 and T_2 are the ambient temperatures.

The solution was obtained by means of eigenfunction expansions for T_c and T_w. The two series were matched over the surface $r = a$, $0 < z < l$, to give an infinite order matrix equation for the expansion coefficients.

makes it convenient for designers and inspectors to estimate quickly the fire safety of a cable penetration.

THE FIRE RESISTANCE OF A WALL PENETRATED BY A HOLE

Rewiring operations in a nuclear power plant sometimes leave a hole through a wall where a cable or conduit has been removed. The hole can weaken the fire resistance of the wall. During a fully developed fire in a room, hot fire gases can be driven through a hole by the plant's forced ventilation system and the pressure developed by the fire. The hot gases in the hole raise the heat load in the interior of the wall. In addition, the gases can be flammable and can ignite as they emerge on the unexposed side. Unburned flammable gas is especially probable in a fully developed cable fire when the availability of oxygen is limited.

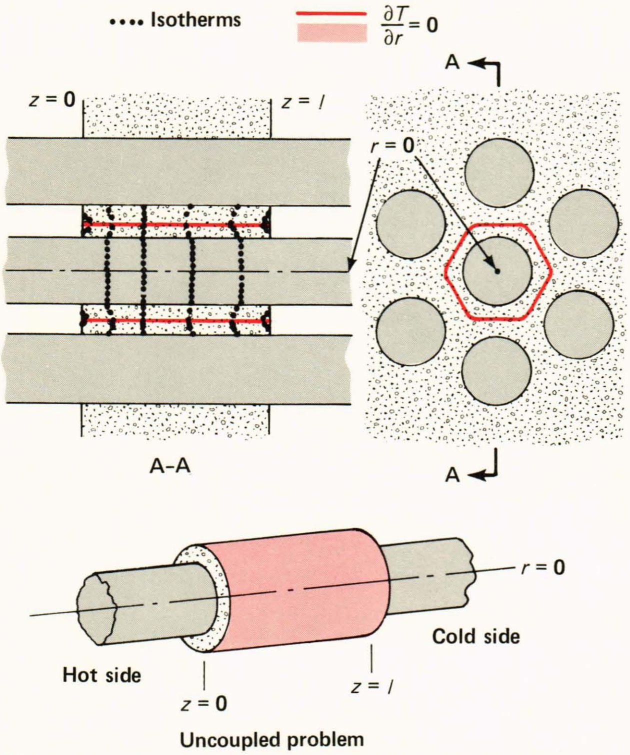

Figure 4 — An array of cables penetrating a wall exposed to a fire on one side. The symmetry of the temperature distribution leads to the approximation in which just one cable is considered, surrounded by a circular sleeve of wall material whose curved outer surface is insulated.

Experimental evidence for this hazard was obtained in fire tests at Underwriters' Laboratories and the University of California at Berkeley. In parallel work, a theory was developed at APL to identify the key parameters controlling the severity of the hazard.

The theory concerned a wall with a circular hole exposed to a fire on one side (Fig. 5). The exposed face of the wall receives radiation from remote fire sources in the room and experiences forced convection heating from the fire gases that contact the wall. In addition, the exposed face reradiates some heat back to the fire. The sides of the hole are heated convectively by the hot gases flowing through it. The heat imparted to the wall is conducted radially and axially into the interior of the wall. Finally, the backface of the wall exchanges heat by radiation and convection with the unexposed room.

The solution of the governing equations for this problem predicted the following trends. The parameters having the greatest influence on the cold side conditions are the thickness of the wall, l, and the mass flow rate of gases through the hole, $\dot{m}_g$. The gas emerging at the exit and the backface of the wall is cool when l is large or $\dot{m}_g$ is small. Both gas and wall exit temperatures can increase substantially as l decreases or $\dot{m}_g$ increases. Ultimately the gas temperature at the exit approaches its temperature at the entrance.

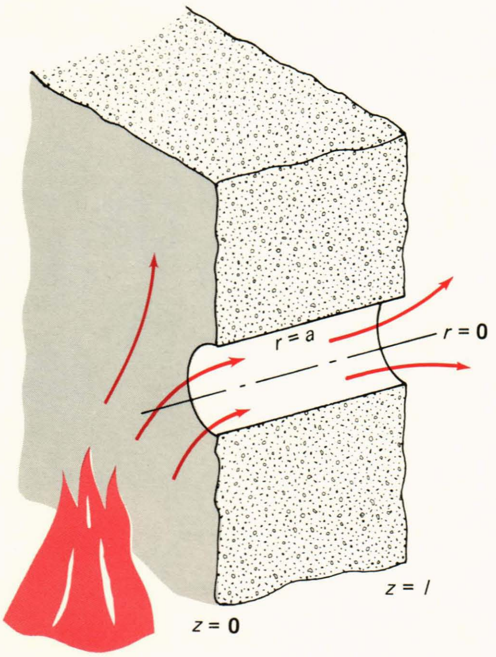

Figure 5 — A wall with a circular hole exposed to fire on one side. The hole weakens the fire resistance of the wall. The hot fire gases flowing through the hole increase the heat load in the interior of the wall and may ignite when they emerge on the unexposed side.

The key parameters l and $\dot{m}_g$ may be grouped with the gas viscosity, μ_g, to form the dimensionless quantity $\dot{m}_g / l\mu_g$, which is a combination of the Reynolds number and the diameter-to-length ratio of the hole.

The steady temperature in a wall with a circular hole exposed to a fire on one side is obtained by solving the following differential equations subject to appropriate boundary conditions:

$$\begin{aligned} &\frac{\partial^2 T}{\partial z^2} + \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) = 0, \\ &\quad 0 < z < l, \\ &\quad a < r < \infty. \\ &\dot{m}_g \hat{C}_g \frac{dT_g}{dz} + 2\pi a H_g (T_g - T) = 0, \\ &\quad 0 < z < l, \\ &\quad r = a. \end{aligned} \tag{4}$$

Thus the wall temperature, T, is coupled to the gas temperature in the hole, T_g, which must be determined simultaneously.

In these equations, the axial coordinate is z and the radial coordinate is r, as shown in Fig. 5. In addition, l is the wall thickness, a is the hole radius, $\dot{m}_g$ is the mass flow rate in the hole, $\hat{C}_g$ is the specific heat of the gas, and H_g is the heat transfer coefficient in the hole.

The solution was obtained by eigenfunction expansion methods that required rather lengthy and delicate manipulations.

When the value of this quantity is near 1, the back-face of the wall and the emerging gas are cool. They are dangerously hot when $\dot{m}_g / l\mu_g$ is near 100. As a rule of thumb, a good safety limit is $\dot{m}_g / l\mu_g \approx 13$. At this value the theory showed that the temperature of the emerging gas is about halfway between the ambient cold-side temperature and the fire temperature.

CABLE FIRE SUPPRESSION

The fire suppression systems in a nuclear power plant are an important line of defense against fire. Both Halon and water systems are used. The Halon is a gas, typically CF_3Br. The water is applied as a fine spray or mist to avoid electrical short circuits.

Halon suppression systems have a number of drawbacks. While Halon effectively suppresses the flames, it does not cool the insulation, which continues to generate flammable gas. Reignition often occurs when plant personnel open a door and inadvertently admit fresh air. While Halon itself is probably harmless to people and equipment, its chemical reaction products in flames are toxic and corrosive.

Water does not have these drawbacks. The water, which penetrates to the surface of the hot insulation, is boiled off as steam. In the process, the surface loses an amount of heat determined by the heat of vaporization and quantity of water. Thus the surface cools down and, if it cools sufficiently, flammable gas stops evolving, so that reignition cannot occur.

A very simple approach to modeling this process is based on the principle that extinction occurs when the heat absorbed by water vaporization equals the heat feedback from the flames to the surface. It follows that a sufficient condition for suppression by water is that the rate of heat absorption due to vaporization equals the entire rate of heat release of the fire,

$$L\dot{m}_w = \dot{Q} . \tag{5}$$

Here L is the heat of vaporization of water per unit mass and $\dot{m}_w$ is the mass addition rate of water, which actually vaporizes on the surface. This formula is reasonably consistent with observations.

CONCLUSIONS

With the assistance of the research program described here, the NRC has developed guidelines for fire protection in nuclear power plants. The approach is defense in depth using a combination of fire prevention, detection, containment, and suppression.

The consequences of greatest concern in a nuclear plant include radioactive contamination and economic loss. As discussed briefly in the Background section, cable fires also present hazards in ships. Here an additional concern is the ability of combat vessels to continue to perform their combat functions. Many of the shipboard cable fire problems are still unsolved.

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