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Nuclear Power Plant Fire Protection - Ventilation (Subsystems Study Task 1)

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ABSTRACT

This report examines the role of compartment ventilation from the standpoint of nuclear power plant fire protection safety. Based on a review of numerous design standards which consider the influence of controlled ventilation on reducing fire severity, the report concludes that current standards and regulatory guidelines inadequately define criteria for design of ventilation systems and their operation under fire emergencies. To resolve this deficiency, the report evaluates four candidate design bases for ventilation systems: smoke removal, smoke dispersion control, fire spread control, and fire temperature control. It is concluded that the lack of existing fire technology precludes the implementation of all but one of these criteria--fire temperature control. On this basis the report presents an example design calculation for applying the temperature control criterion.

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NUCLEAR POWER PLANT FIRE PROTECTION - VENTILATION (SUBSYSTEMS STUDY TASK 1)

Introduction

Background

An earlier Sandia Laboratories fire protection study[1] surveyed the guidelines and standards pertaining to nuclear power plant fire protection and the investigative reports which followed in the aftermath of the Brown's Ferry Nuclear Power Plant fire of March 22, 1975. The purpose of that survey was to establish a firm basis for future activities in assessing the adequacy and development of improved design criteria for nuclear power plant fire protection systems. One of the conclusions reached in the study was that further work should be undertaken to develop more comprehensive guidance for the design of ventilation systems.

Based on this and several other considerations, the NRC Office of Standards Development funded a new program to carry out a more detailed investigation. In particular, the following tasks were identified for study:

- Task 1 Ventilation Systems
- Task 2 Fire Detection Systems
- Task 3 Fire Barriers
- Task 4 Fire Hazards Analysis

This report addresses the first of these subjects, Ventilation Systems.

Task 1 Description

It was the objective of this task to examine the role of compartment ventilation as it affects nuclear power plant fire protection safety. To do this, the following general approach was used:

- Review and compare existing standards for ventilation systems to evaluate the adequacy of the guidance provided;
- Develop technical bases for ventilation system functions and performance in fire emergencies and identify topics requiring further investigation or testing; and
- Recommend changes or additions to existing guidance to clarify intent and define design criteria.

Technical Approach

The existing guidelines and standards, as they apply to the effect of ventilation systems on fire protection in nuclear power plants, were reviewed from the point of view of a design organization attempting to bring a facility into compliance. Specific criteria were listed and examined to determine if they were adequate to evaluate and specify system designs.

Current literature in the fire protection field was surveyed to locate investigative research reports on ventilation-related aspects of fire phenomenology. Particular attention was directed to reports dealing with the effects of variable ventilation rates on the growth of compartment fires and burning rates in fully developed compartment fires.

Information gathered from the review of the standards and the literature search was used in formulating and evaluating four candidate technical bases for ventilation system design. Each candidate basis was examined to determine whether or not it fully met the intent of the guidelines and standards. The question of feasibility was also addressed in each case, with regard to equipment design, plant layout implications, and the availability of data upon which to base design parameters. From the four candidates, a single design approach was selected and examples of its application are given.

Review of Existing and Proposed Guidelines and Standards

Documents Considered

The following documents were considered representative of the available guidance which exert substantial influence upon the nuclear power industry in the area of fire protection. They represent the position of national and international regulatory agencies or are statements of requirements for insurability:

1. Proposed Regulatory Guide 1.120, "Fire Protection Guidelines for Nuclear Power Plant," U.S. Nuclear Regulatory Commission Office of Standards Development. Several revisions of this document dating from June 1976, through November 1977, were included in the review. (RG 1.120)

2. "International Guidelines for the Fire Protection of Nuclear Power Plants," National Nuclear Risks Insurance Pools and Associates, February 1974. (IGL)

3. "Property Loss Prevention Standards for Nuclear Generating Stations," Nuclear Mutual Limited, September 1975. (NML)

4. "Basic Fire Protection for Nuclear Power Plants," Nuclear Energy Liability Property Insurance Association, April 1976. (NEL-PIA)

5. "Safety Guide on Fire Protection in Nuclear Power Plants," International Atomic Energy Agency, January 1976. (IAEA)

6. ANSI N 18.10, "Generic Requirements for Nuclear Power Plant Fire Protection," American National Standards Institute, February 1977. (ANSI N 18.10)

7. NFPA 803 "Standard for Fire Protection for Nuclear Power Plants," National Fire Protection Association, 1977. (NFPA 803)

Guidance for Ventilation System Design

The review of the above documents indicates that the ventilation system as a subsystem in the total fire protection program in a nuclear power plant should function:

- To assure accessiblity to fire-involved areas for manual fire fighting operations
- To prevent the spread of smoke and toxic gases to other areas of the plant
- To limit damage to electrical equipment and structural features caused by corrosive products of combustion
- To assure continued habitability of areas normally occupied by operating personnel
- To prevent smoke infiltration into routes of emergency egress
- To remove heat which could result in serious structural damage
- To control the release of radioactive contaminants from fire-involved controlled areas.

The IGL includes the most extensive section dealing with ventilation system design. It not only states the underlying philosophy in each of the areas of guidance, but, in most cases, gives specific minimum standards for compliance with the stated requirements. In some areas in which specific criteria are given, alternative courses of action are also given.

In general, however, the existing guidance for ventilation systems is brief, nonspecific, and lacking in sufficient detail to judge the adequacy of a particular system or to specify system designs for compliance with the standards. In those documents where specific criteria do appear, no basis for the criteria is given nor is its source referenced. For instance, RG 1.120 states that smoke and heat vents should be provided for the control room, cable spreading rooms, diesel oil storage areas, switchgear rooms, and other areas where the potential exists for heavy smoke conditions. RG 1.120 then references NFPA 204, "Guide for Smoke and Heat Venting," for additional guidance. However, neither RG 1.120 nor NFPA 204 (see page 19) provides sufficient design information or design bases for judging the adequacy of a particular smoke venting system design. Furthermore, no information is provided to identify "... areas where the potential exists for heavy smoke conditions." Although some specific locations are identified in RG 1.120, system design guidance for these locations is lacking.

A preference for separate smoke and heat venting facilities is stated in several of the documents. If design criteria are stated for these vents, they are generally given as a ratio of vent to floor area of the compartment. Since the capacity to remove smoke and heat is the true measure of adequacy of such a system, as opposed to the physical size of a vent opening, it is conceivable that a system fully capable of functional compliance could be rejected because of its physical measurements.

No consideration is given to the extent of modification that might be required in existing facilities to bring them into compliance with newly promulgated standards. Because of the capacities needed to meet the stated ventilation objectives, the physical size of the equipment required could preclude their installation in a plant which has many internal compartments. In such cases, the only practical alternative is to waive ventilation standards in favor of detection and suppression systems of a specified reliability level.

In the following section, four candidate approaches for the design of ventilation systems to meet the intent of existing guidance are presented. The discussion is intended to develop an understanding of the significance of ventilation in fire development in the light of current technology. A design criterion is proposed which could aid both in system design and evaluation of compliance with the guidelines.

Smoke Removal

Specific reference is made in three of the guidelines (RG 1.120, IGL, ANSI N 18.10) to the use of ventilation as a means of assuring access for manual fire fighting. From a practical point of view, regardless of whether or not a fixed fire suppression system is provided, access to the fire area must eventually be gained to allow mop up and damage assessment.

Access to a fire area could be precluded by three factors: toxicity of smoke and gases, heat, and visibility. The hazard posed to fire fighting personnel by toxic products of combustion is acknowledged in all of the guidelines reviewed by the requirement for self-contained breathing apparatus and the training of the fire brigade in its proper use. The removal of heat from the fire area is discussed under Temperature Control below. The impairment of visibility by dense smoke is the primary concern of this section.

The reduction of visual range by dense smoke in a fire area presents an obvious impairment to manual fire fighting efforts. In order to effectively extinguish a fire, the suppression agent must be delivered to the source of the fire. If smoke is so dense that it obscures the location of visible flame, then efficient delivery of the suppressant becomes impossible. The difficulty of directing the manual fire fighting effort is further increased if the involved area possesses a high degree of mechanical congestion, which is typical of many areas in nuclear power plants. In such areas, the obstructing machinery makes it necessary to approach the fire closely for direct application of the hose stream. These obstructions also serve to mask the fire location and present obstacles which impede the progress of the fire brigade. Since early arrest of fire development is an important factor in limiting the extent of involvement, impaired visibility can severely limit fire fighting effectiveness.

Besides acting as an impediment to effective manual fire fighting, smoke and gases represent potential damage mechanisms which can cause losses beyond the area of actual fire involvement. The deposition of heavy soot in adjacent areas obviously exacerbates postfire cleanup and salvage problems. The presence of corrosive chemicals in the products of combustion can also propagate equipment failures beyond the damaging range of the flames. Electrical control equipment, such as relay racks and switchgear, are particularly susceptible to damage caused by corrosive chemicals evolved by cable fires. Therefore, the prompt removal of smoke can serve to limit the extent of damage and the cost of salvage operations.

It should also be recognized that smoke production is a time dependent phenomenon. A practical smoke venting system might be designed for a given fire area which would be capable of ensuring adequate visibility in the early stages of fire development, but which would be totally incapable of coping with a fully developed fire. Similarly, a smoke venting system could be designed to satisfactorily vent smoke and gases after successful operation of a fixed suppression system and allow manual mop up operations and damage assessment, but which would be totally inadequate if the suppression system should fail. Thus, the design basis for smoke removal is closely coupled with the speed and reliability of detection, the expected response time of the fire brigade given detection if manual suppression is the primary defense, or the effectiveness and reliability of a fixed suppression system.

Smoke Production -- No definitive means of quantifying smoke production from a fire is currently available. NFPA 258 sets forth a standardized test method and apparatus for the measurement of smoke generated by solid materials.[2] A. F. Robertson presents an analytical approach for the application of data derived from this test to the estimation of smoke production in fires within buildings.[3] The latter reference discusses in considerable detail the criticality of assumptions made in smoke production analysis, and the uncertainties in the applicability of laboratory smoke measurements to the prediction of smoke production under full-scale fire conditions.

Several observations made by Robertson are pertinent to this discussion. One of the most important uncertainties encountered in this analysis was the relationship between smoke production and the rate and extent of fire involvement. Although total smoke potential may be indicated by the test performed per NFPA 258, the optical density within the confined area as a function of time will be highly sensitive to how fast the fire develops. The rate of development is also influenced by the ventilation rate which, in turn, fosters open flaming conditions under which smoke can be consumed by the fire in the same fashion that an afterburner functions to reduce air pollution. This type of combustion is typical of cellulosic materials or simple hydrocarbons. However, materials which contain inorganics such as fire retardants often release aerosols that are noncombustible and are, therefore, not consumed. Finally, Robertson observes that even a small fire in a confined cell can rapidly reduce the visual range to a few feet. This leads him to conclude that the most effective means of limiting smoke production involve the confinement, control, and early extinguishment of fires.

Some of the questions raised by Robertson have been investigated in the work of E. E. Smith.[4-6] The data derived from tests such as NFPA 258 for smoke production and ASTM E-84 for flame spread rating are intended to be used for comparison purposes in arriving at appropriate choices of construction and furnishing materials. The data are taken under carefully prescribed conditions of thermal flux exposure, but generally at a single exposure level. Smith suggests that the measurement of a single parameter at a single exposure level does not provide sufficient information for design purposes. Further, it is pointed out that cellulosic and non-cellulosic materials exhibit very different hazard producing properties when exposed at levels other than those specified in the standardized test procedures. In Reference 4, Smith has proposed a test procedure in which the rates of heat, smoke, and toxic gas release are measured over a range of exposures. Smoke release rates at various exposures are reported for both cellulosic and noncellulosic materials. These results show that the smoke production rates from synthetic materials, in this case PVC and ABS pipe, are much higher than those of red oak at the same exposure levels.

Since synthetics dominate the fuel loading in many power plant settings, particularly those which include electrical cables, smoke could be produced at rates which practically preclude the maintenance of visibility.

Methods of Smoke Removal -- The means of smoke removal suggested by the guidelines and standards include dedicated smoke vents (both natural convection and power assisted), use of the normal HVAC system, and portable smoke ejectors. The smoke and gases are to be removed to a "safe location," which generally means outdoors. However, in those cases where the potential for radioactive contamination exists, the venting must be monitored and, if permissible radiological maximums are exceeded, the smoke must be directed to the gas treatment system or released at a controlled rate. Of the three suggested options for smoke removal, the dedicated or separate smoke venting system is listed as the preferred approach by most of the documents, although normal HVAC systems may be used provided appropriate design precautions are taken to ensure that:

1. HVAC equipment temperature limitations are not exceeded;
2. HVAC filters are demonstrated to be compatible with the expected quantity and quality of vented smoke or are appropriately bypassed during smoke venting operations;
3. HVAC ducting shared with other plant areas is isolated to prevent the spread of heat and smoke.

The generally accepted design basis for power plant HVAC systems is the control of normal equipment and personnel heat loads. Consequently, air-change rates range from one to perhaps four changes per hour in all but the most heavily heat loaded areas of the plant. By comparison, for smoke removal purposes, the IGL suggests air change rates of 5 to 10 changes per hour with a note that up to 50 changes may be required if the start of smoke venting is delayed. It can be concluded that these criteria and the observations made by Smith[4] of smoke produced by burning synthetics that normal HVAC systems: (1) could be capable of efficient smoke removal from incipient fires; (2) would be of little use as a means of smoke removal from well-established fires, or during active fire suppression activities, when smoke production is at a maximum; and (3) could be useful in conjunction with portable smoke ejection for clearing a space of smoke following fire extinguishment.

There are also requirements for fire area isolation which preclude the use of normal ventilation systems for smoke venting. The duct systems must be equipped with rated fire and smoke dampers to prevent the spread of fire and smoke to other areas through the ducting. These dampers are generally of the type which are actuated by excess heat in the duct by means of a fusible link. Once closed, these dampers must be manually reset. Since closed dampers would normally be within the fire area, the normal ventilation system would be unavailable for smoke venting of the fire area.

In compartments equipped with gas flooding extinguishing systems, the area must be sealed off before and during system actuation to allow the required agent concentrations to be reached and maintained for adequate soak times. Electrically closed dampers are usually installed in the ductwork for this purpose with no provision for remote reopening.

Additional complications are encountered in those plant areas where radioactive materials may be entrained by smoke. For these areas a reliance on smoke venting to facilitate manual fire fighting or control fire severity seems ill-advised. Venting from these areas would require some means of preventing high-efficiency radiological filters from being plugged with dense smoke and of monitoring radiological effluent concentrations to prevent excessive discharges to the environment. In addition, smoke leakage to other plant areas would need to be controlled during times when fire fighters gain access to the contaminated area.

Under these conditions, a more reasonable fire protection philosophy would emphasize the use of automatic detection and suppression systems, while isolating and monitoring the burning area. Through remote monitors (e.g., video, radiological, or temperature devices), the success of the automatic extinguishing systems can be judged by the fire brigade and plant operators without entering the fire area. Only after the fire has been extinguished or the automatic extinguishing systems prove inadequate would the fire area be entered by a fire brigade. These and similar concerns are being considered in detail by a combined committee of the American Nuclear Society (ANS 59.2) and the American National Standards Institute (ANSI N189) in conjunction with drafting a new standard, entitled "HVAC Systems, Important to Safety, Located Outside Primary Containment."

The use of portable smoke ejectors will generally serve to reduce smoke density in a fire area by spreading the smoke to other areas of the building unless a duct system or direct access is provided to route the products to outdoor areas. Since high concentrations of corrosive gases can be attained in fire areas, ejection to other parts of the building could result in extensive damage to equipment not involved in the fire.

As mentioned earlier, separate venting systems are preferred by the guidelines. The IAEA document states that "fire venting shall predominantly be of the underpressure-venting type where a separate smoke/gas fan is provided to evacuate the smoke." IGL, NML, NEL-PIA, and NFPA 803 give vent-to-floor-area ratios for various areas of the plant which range from 0.005 to 0.04, depending upon combustible loading. NFPA 204 is also referenced as a source of smoke and heat venting design criteria. This document seems to be the source of the vent area ratios specified, but the criteria by which the ratios were determined are neither stated nor referenced in the text. It is interesting to note in the introductory paragraph of NFPA 204 that the document was inspired by a trend toward construction of large single-area, one-story buildings of light construction. In the section entitled "Application and Scope," it is further stated that many of the features suggested by the guide would be difficult or impractical if applied to multistory buildings. This is understandable since the proposed vent configurations are intended, at least in part, to provide access for hose streams to fight the fire from above.

Since a range of vent area ratios is stated by the standards, some criterion of adequacy is implied. The IGL publication alone provides insight into what the design basis might be by associating volume change rates with the venting process. The stated venting capacity is to be determined by the smoke production of the materials within the fire area and the number of air changes per unit time needed to sweep the smoke from the volume enclosed. Rather than a given ratio of vent-to-floor area, the basic measure of venting adequacy is clearly stated to be volumetric capacity of the system that can be brought to bear upon the fire area.

G. T. Tamura and C. Y. Shaw have proposed a design basis for smoke venting shafts in multistory buildings.[7] Their paper describes the mechanism of "stack action" in tall buildings by which smoke is spread throughout the upper floors through existing service shafts. A method is developed for the design of smoke venting shafts to prevent this from occurring. The calculations presented are based on the venting of a low temperature fire with a temperature difference of 75°F between interior and outside air providing the stack draft. Losses due to friction, velocity pressure, and leakage are considered. A table of minimum smoke shaft sizes for a range of floor areas and building heights at several leakage rates is also given. The minimum sizes are indicative of volume change rates of two to four per hour at the bottom floor of the building.

The work of Tamura and Shaw provides insight into the design of natural convection smoke vents for multistory buildings, presumably of residential or office occupancy. The selection of a low temperature fire and a relatively low air change rate would be indicative of this type of combustible loading. To be applicable to nuclear power plants, the shaft sizes would have to be increased to provide much higher flow rates to accommodate greater smoke production from synthetic materials.

Smoke Control

As used here, smoke control is defined as the prevention of smoke migration from the involved fire area to other parts of the building. The IGL lists the confinement of smoke and gases as a specific point for consideration in the design of enclosures for fire areas. Several of the standards specifically list the stairwells as areas for which special measures should be taken to prevent smoke infiltration, generally by means of overpressure ventilation, to assure a positive pressure inside the escape routes relative to other building areas.

The movement of combustion products toward the upper floors of high rise buildings has been recognized as cause for concern because these gases can result in serious visibility and toxicity hazards long before fire reaches the area. The use of differential pressure to control infiltration has been applied successfully as a solution to the problem. Fung has reported the results of full-scale smoke movement experiments conducted in the 36 story Seattle Federal Building and the 42 story Chicago Federal Building.[8] Both facilities employ the "systematic pressurization" concept in which the structures are divided into vertical zones, of several floors each, served by separate air handling systems. In a fire emergency, the systems can be switched to smoke control mode by simultaneously placing the fire zone in full exhaust condition and the adjacent zones in full supply operation. Thus air is forced to flow toward the fire from all directions.

An approach such as this could conceivably be adapted for use in a nuclear power plant, but only at the expense of severely complicating HVAC system design. In the high rise situation, the fire zones are arranged vertically with entire floors being considered single fire areas. To consider a single floor or group of floors as a separate air distribution zone follows naturally from the high rise configuration. In the power plant, however, the arrangement is primarily one of horizontal expanse with much subdivision of a single level. An arrangement of ductwork and remotely controlled dampers which would allow any given area to be aligned for exhaust and all surrounding compartments to supply mode would pose substantial problems both in design and operational reliability.

Typically nuclear power plant layouts incorporate a great deal of totally internal compartmentalization with very few or no exterior windows. Large open areas are also included in buildings, such as the turbine hall, which have considerable vertical extent, unsealed floor openings, and extensive open grating. The combustible loading and smoke production potential of many plant areas is also much higher than the typical office and residential occupancies of the buildings in which this system has been successfully implemented.

The air handling facilities for power plants generally incorporate both supply and exhaust fans. It might, therefore, be opted to seal off the involved fire area with fire dampers, and shut down the exhaust fans but continue operating the supply fans of adjacent compartments. This approach may provide sufficient differential pressure to confine smoke during the very early stages of fire development. But unless some means of venting the fire's combustion products to the outside air is provided, pressure will rise very rapidly in the heated compartment and soon overcome the differential.

It is therefore concluded that for differential pressurization to be effectively and economically used as a means of smoke control in power plants, it must be accompanied by a properly designed smoke venting system to provide pressure relief. The option to independently control supply and exhaust fans could, however, prove to be an asset during fire emergencies.

Fire Control

Intuition and Fire Phenomenology -- The concept of "control" over a phenomenon can have many different meanings depending largely upon the nature and intended application of the event being observed. For example, to many motorists, the term "controlled skid" may seem to be a contradictory use of words. Yet when viewed from the premise that a skid has occurred and the problem is now that of limiting undesirable consequences, the fact that an effective degree of control can be exerted on the situation can be significant to the eventual outcome.

The term "fire control" can be viewed in a similar way. Given that fire, in the context of this work, is an undesirable event, one "control" might be the elimination of fire as a possiblity. Another course might be to provide for the immediate and decisive extinguishment of any fire occurrence so that no fire can get "out of control." The difficulty inherent in these approaches is that neither can be applied with absolute certainty. One is therefore forced to assume that a potentially destructive fire has occurred and to investigate practical means by which the extent of damage might be limited. More specifically, in this section, the discussion is concerned with the role of ventilation in the development of the fire and its influence upon the eventual confinement of damage.

Most people have acquired some familiarity with fire phenomena. However, because of the potential for destruction, most first-hand knowledge is based on observation of fire in controlled circumstances. If, for instance, a fire is not physically confined, we have learned that its size can be controlled by regulating the amount and geometry of the fuel. For confined fires, say in a wood stove, the amount and arrangement becomes less important since the supply of oxygen can be regulated to control the burning rate. In either case, it is necessary to deal with the question of ventilation, particularly in the initial stages of development, since we become intuitively aware of the difficulties of starting a fire in a strong breeze. On the other hand, we have also encountered the situation in which, because of the arrangement or moisture content of the fuel, it is necessary to direct a stream of air to the fire in order to sustain burning.

It is perfectly natural to extrapolate acquired intuition from these controlled small-scale encounters and apply the same principles to large-scale destructive fires. Thus, a forest fire could be viewed as a large-scale campfire, and a fully developed compartment fire as a larger version of one in a wood stove. The fact is, however, that for all of our long-time association with fire, the actual phenomenology is, at best, poorly understood. The complexity of burning and the multiplicity of parameters involved preclude all but a cursory understanding of the events which occur during a fire. Because of this, the use of various scaling theories which have been developed to predict large-scale fire phenomena from small-scale experiments appear to be of questionable value and, therefore, the study of fire phenomenology becomes a complex and expensive endeavor involving large-scale experiments whose results, often, violate intuition.

Confinement of Compartment Fires -- The work of T. Z. Harmathy is noteworthy, not only for reporting the effect of ventilation rates on compartment fires but also as a source of detailed description of the processes and parameters influencing the course of destructive fires.[9-11] A basic premise of this work is that if a fire can be confined to the compartment of origin, then the goal of effective fire safety design has been met. Thus, if buildings could be designed so that a fire cannot propagate beyond the first set of barriers, even in the absence of active intervention, then the ultimate limits of destruction have been set. Active intervention could then be expected to further limit fire loss and provide an extra measure of protection.

A potential application of this philosophy would be in nuclear facilities in which redundant safety systems are physically separated from each other by fire barriers. If this were the case, and if compartment barriers could be shown to be the ultimate limit of propagation, then fire fighting, whether manual or automatic, could be directed toward limiting the extent of damage within the cell of origin. Fire would therefore pose no threat to the ultimate safety of the reactor system.

It must, however, be pointed out that Harmathy's work applies to relatively light fire loadings, as would be encountered in office and residential occupancies. The compartments modeled are typically limited in depth and ventilated through windows on at least one side. Further, the expressions developed are based on results of tests employing only cellulosic materials. These qualifications preclude the direct application of the results to the power plant setting. The theoretical framework and the method of analysis should, nevertheless, be valid for any compartment fire, given an appropriate experimental data base. In some regards, the analysis of the power plant problem by this technique may be more tractable than the one addressed in the referenced material. Since the ventilation rate is of primary importance in the analysis, a closed compartment with a well defined ventilation system should be more easily modeled. The class of combustibles available for involvement in a power plant is much more limited and more clearly defined than those in residential and office applications. Therefore a more coherent set of experimental data should be obtainable for evaluation of the various parameters. Finally, a power plant is designed as a single-use facility, and by its very nature is a more carefully controlled environment during operation. The uncertainties inherent in the analysis of human occupancies would thus be minimized.

The main thrust of Harmathy's work is toward the development of a set of expressions which are sufficiently comprehensive to match theoretical predictions to existing experimental data. Since the objective was to arrive at a measure of fire severity that could be applied in the evaluation of the barriers which form the boundaries of the compartment, only fully developed fires were considered. The burning rate was found to be a function of the flow rate of air and the free surface area of the combustible materials. A critical value of air flow rate is defined below in which the rate of burning is determined by the air flow rate and the fire is said to be "ventilation controlled." At air flows above this value, the rate of burning is determined by the available free surface of the involved fuel and is termed "fuel surface controlled." Conclusions reached for cellulosics indicate that fires in the ventilation-controlled regime (i.e., low ventilation rates) tend to be of longer duration and reach higher peak compartment temperatures than those which are surface-controlled. This can be attributed, in part, to the cooling effect of the excess air at high ventilation rates. The ventilation rate, therefore, not only governs the rate of burning of the involved combustibles, but it also determines the duration and peak temperature attained in fully developed compartment fires.

Harmathy's approach to the analysis of compartment fires involves consideration of the fire and its confining barriers as elements of a total fire system. By formally accounting for the differences between unconfined and confined burn test results and fitting the expressions developed to compartments of various geometries, a method of interpreting burn test data in the context of compartment hazard analysis is provided. The analysis also provides insight into the relative importance of the various parameters in the total fire cell chronology. This information could therefore be used to structure a fire testing program for the acquisition of the requisite data in specific applications.

Unfortunately, many of the conclusions reached by Harmathy apply to cellulosic-fueled fires in relatively light combustible load settings. These are unlike the conditions typically occurring in nuclear power plants and, therefore, a program of carefully designed confirmatory compartment burn tests would probably be required. It should also be noted that this approach to fire safety requires that, as a last resort once a compartment fire has developed, the fire is allowed to run its course, thus consuming the entire contents of the compartment. In many existing plants where spatial separation is used as a means of limiting the extent of fire damage, such a premise could not be tolerated.

Temperature Control

Where separate venting is discussed in the guidelines, the terminology used is generally "smoke and heat venting." The design bases for smoke venting and heat venting are quite different, so the two functions are considered separately in this report. This section deals with temperature control, which can be equated with "heat venting."

The work of Tamura and Shaw,[7] which was discussed under Smoke Removal, is concerned with smoke removal by means of separate shafts. The motivation for considering separate smoke venting systems is at least twofold: (1) The capacity of normal HVAC systems is not sufficient to support the required flow rates, and (2) the high particulate concentration of smoke rapidly degrades the capacity of the air handling system because it clogs the exhaust filters.

As was the case for smoke venting, the normal HVAC system is generally of insufficient capacity to handle the flow rates required for heat venting. In this case, however, the design criteria imposed on the heat exhaust system are much more demanding than those for the normal air handling function. The temperatures that could be attained by the effluent from a compartment on fire are very much higher than those of normal exhaust air. The ductwork must therefore not only be noncombustible, but must be capable of retaining structural integrity at elevated temperatures. The high-temperature gases also threaten the integrity of exhaust filter systems and exhaust fans. Indeed, the charcoal filters used to filter radioactive effluent are a secondary fire hazard when exposed to high temperature.

Harmathy has proposed the use of "fire drainage systems" in connection with his studies of fully developed compartment fires.[10] These systems are actually heat vents designed to remove combustion products by natural convection at flow rates compatible with the fuel surface controlled fire regime. This method of ventilation was proposed to contend with large areas or deep compartments in which ventilation through broken peripheral windows could not be relied upon.

A compartment fire model has been presented by J. Quintiere which deals with the early stages of fire development, namely that period from ignition up to room flashover.[12] Flashover can be defined as the critical point in fire growth within a cell which marks the difference between a fire that stays relatively small and confined to its initial surroundings and a fire that reaches its fully developed state, i.e., total room involvement. Quintiere's work is therefore complementary to Harmathy's in that the two models taken together address the entire history of a compartment fire. The two models are also functionally complementary since the same course of corrective action is indicated by both models, specifically the design of effective heat venting systems.

Quintiere has modeled conditions within a door-ventilated compartment with a centrally located fire source. The model is quasi steady state in nature, primarily because the history of turbulent mixing within the cell is not well defined. Because of this limitation, the predicted behavior is probably more accurate in the early stages of fire development when mixing has less influence on room conditions.. The ventilation rate is determined by the size and proportions of the door opening in a fashion similar to Harmathy's use of exterior windows. The features considered which are involved in the rate of fire spread are the fire plume itself and a layer of hot gases confined in the upper portion of the room. The inclusion of this gas layer was inspired by the observations of Waterman from a series of experiments performed to determine the conditions supporting room flashover.[13] These experiments led him to observe that the ability of fire to jump the intervening space between widely separated fuel packages is traceable to the heating of the remote combustibles by convection and radiation from the upper portion of the room, not propagation directly from the source fire. J. B. Fung has observed average temperatures in this upper gas layer in excess of 600°C (1110°F) resulting from confined wood crib fires.[14] The model suggests that compartment flashover and the onset of fully developed fire could be significantly delayed, or perhaps precluded, if the maximum temperature of this hot gas layer could be limited. It can also be observed that the rate of fire growth in the early stages following ignition is dependent upon thermal feedback to the source fuel. Thus, if the immediate environment of the source fire is cooled by ventilation, radiative and convective losses from the source fire increase, thereby slowing its growth.

It should be noted that, if the combustible loading is spatially continuous, the fire can spread along the material directly. Even in this case, however, the growth rate can be slowed by ventilation since the materials are not preheated to the same extent by convection. In fuel configurations which have a vertical arrangement, materials near the ceiling can be heated to their ignition temperatures by envelopment in the hot gas layer. The extent of this envelopment may also be limited by removal of the hot gases.

In summary, by venting heat from a burning room to reduce compartment temperatures several benefits can be realized. These include:

- Slowing the growth rate of a fire in early stages of development
- Limiting the extent of fire involvement by delaying or preventing flashover to remote fuel packages by radiative or convective heating from the upper portion of the room

- Reducing peak temperatures within the compartment with consequent reduction of threat to the integrity of structural members and fire barriers

- Controlling the spread of combustion products to other areas by reduction of pressure within the fire cell, whether by natural convection or power assisted ejection

- Improving accessibility for manual fire fighting by reduction of both compartment temperature and smoke concentrations.

Relative Merits of Candidate Design Bases

The preceding sections have discussed the role of ventilation as a subsystem of fire protection in nuclear power plants from four different points of view. The objective of this discussion has been to consider each of these viewpoints in the light of existing guidance and current fire protection technology to determine which approach or combination of approaches could be sufficiently quantified to generate design criteria. Taken in the order of appearance in the above discussion, the relative merits of the candidates are addressed in this section.

Smoke Removal -- Considered as a separate design goal, the removal of smoke to facilitate manual fire fighting is poorly defined. Minimum requirements for visibility and maximum allowable temperature in the involved compartment are not known. Even if they were, no definitive data is available to predict either the total amount or the rate of smoke production. Therefore, no specific design criteria can be identified to establish firm design bases.

Smoke Control -- The use of a systematic pressurization technique to confine smoke and gases to the involved fire area by realignment of the normal HVAC system is not a practical design basis unless some means of pressure relief is available in the fire cell. When considered in conjunction with a separate venting system, however, the option to continue the operation of supply fans to surrounding compartments following closure of fire dampers in the ductwork serving the fire area could be used to advantage to assure flow of air toward the fire source.

Fire Control -- This concept of allowing a compartment to reach full fire development while supplying excess air to limit temperatures and insure survival of compartment barriers is currently developed only for cellulosic combustibles in relatively light fire loading occupancies. Since many nuclear power plant areas contain high concentrations of non-cellulosic combustibles, it is questionable whether sufficient air can be supplied to a room to achieve a surface-controlled, fully developed fire. Without first reaching surface-controlled conditions, additional air will increase, instead of limit, fire temperatures. However, since additional air will reduce a fire's duration, it may be possible to balance increased room temperatures and reduced fire durations in a manner compatible with compartment barrier survival.

Temperature Control -- The concept of heat removal from a burning compartment embodies desirable features of all of the proposed technical bases. Heat removal obviously will remove smoke as well as heat and will lower the pressure within the involved compartment, thereby controlling the spread of smoke and gases by differential pressurization. In addition, a properly designed path for heat removal will ensure fire control by balancing peak room temperatures and fire durations to the capabilities of installed fire barriers.

It is therefore concluded that temperature control is the most reasonable and effective technical basis for designing a ventilation fire protection subsystem, because existing fire technology insufficiently quantifies design criteria for smoke removal, smoke control, and fire control. Although temperature control appears to represent the best basis for integrating controlled ventilation into an overall fire protection scheme, no evaluation has been made in this or any other study of the importance of controlled ventilation relative to other fire protection measures (e.g., automatic suppression, automatic detection, or separation). Such a relative evaluation needs to be made on the basis of both the benefits and detriments resulting from the use of a temperature control ventilation system in nuclear power plants. Further consideration of a controlled ventilation scheme in this report presupposes that the relative merit of a temperature control system will be demonstrated before any serious consideration is given to its implementation. The task of demonstrating the relative merit of fire protection options lies outside the scope of this present study.

Design of Heat Venting Stacks

On the basis of the conclusion reached in the preceding section, that temperature control represents the best technical basis for designing a ventilation fire protection subsystem, it was decided to outline here one possible design approach for accomplishing temperature control. It should be recognized, as stated earlier, that the relative merit of a temperature control ventilation system to overall fire safety should be demonstrated before any serious consideration is given to implementing the design technique presented in this section.

The venting of heat from a fire can be accomplished by the use of a heat venting stack designed specifically to channel the gases directly from the compartment involved to the atmosphere. Since gases flowing in this duct could reach high temperatures, material used in its fabrication must be capable of withstanding a high temperature environment for extended periods of time and maintaining its structural integrity for the duration of the fire. For the reasons discussed earlier, it is unlikely that the normal HVAC ductwork, filters, and fans would have the capacity or the high temperature capability required. Therefore, a vent stack dedicated to this purpose should be considered.

The driving force to carry the gases to the outdoors could be either natural or power-assisted convection. The use of natural convection is attractive in that no external power need be supplied during the fire emergency. The disadvantages of the passive system are that a temperature differential must exist for the stack to function and, since the velocities created by the buoyant forces are relatively low, fairly large cross-sectional areas are required to provide the necessary flow rates. Since the purpose of the stack is the removal of heat, the temperature differential will exist when the system is called upon. However, if the fire is a relatively low-temperature, smoldering fire with heavy smoke production, the smoke removal function could be too slow to maintain good visibility. This problem could be overcome by the attachment of exhaust blowers at the roof level.

The size of the stack must be determined by the maximum flow rate that it must provide to fulfill its intended function. The starting point for the analysis would be to determine the maximum heat generation rate of the compartment served by the stack. The maximum permissible temperature must then be specified for the compartment. The flow of air necessary to carry away sufficient heat to limit the temperature to the acceptable value can then be calculated. The required flow up the stack would then be the calculated air flow rate at that temperature. Provision, of course, must be made to assure that an equivalent mass flow of air at ambient temperature can be supplied to the compartment during the venting.

Applying this calculational sequence, a design equation was developed as described in the Appendix. This equation relates the stack's flow rate, diameter, and height to the temperatures in a burning compartment. By solving this equation for a variety of conditions (see Appendix) it was found that, for specified venting rates and temperature limits, the required stack diameter varies considerably with the availability of make-up air entering the burning compartment or with the extent of air leakage along the stack length. If room openings are too few or too small, make-up air to the burning room will be restricted. Also, if any air leaks into a stack through dampers from other rooms, the natural draft characteristics of the stack will be reduced. Either of these shortcomings would require an increase in stack diameter to ensure adequate flow rates for temperature control.

In addition to these findings, it was shown for an example case (a 5 ft^2 gasoline fire in a 37 500 ft^3 compartment) that the stack size required to limit peak temperature to a relatively low value is indeed reasonable: a 3-ft diameter stack would limit the peak to 400°F. It was also observed in this same example that the required airflow rates were quite high compared to those normally handled by an HVAC system. This supports the statement made earlier that normal plant air handling systems lack the capacity to provide adequate heat removal. Finally, it was found that the compartment air change rates, particularly for the low-temperature cases, are high enough to remove appreciable amounts of smoke from the fire area. Therefore, such a system would also serve to facilitate manual fire fighting.

Although a number of factors which could require that vents be made larger were neglected in the calculations, including resistances to make-up airflow occurring upstream of the compartment opening, other factors should be mentioned that could have the opposite effect: no heat losses to the contents or walls of the compartment were included. These losses would have the effect of reducing the required air flows. No mention has been made of the role of suppression systems in the removal of heat. A fixed water suppression system is capable of delivering water at a rate of about 0.25 gal/ft^2-min or 2.0 lb/min-ft^2. Given the heat of vaporization at atmospheric pressure of 1150 Btu/lb, the heat removal capability of a sprinkler system could be 2300 Btu/ft^2-min if all water were vaporized. In the 2500 ft^2 compartment used in the examples, this represents a heat removal capability of 5.75×10^6 Btu/min. In actuality, total vaporization of the water is neither achieved nor desirable in sprinkler system design. But the heat removal capability of a sprinkler system could substantially reduce the required capacity of the heat venting system.

Another point which must be considered in the design of heat venting facilities is the handling of radioactive effluent. Smoke and gases from areas of the plant which have potential for radioactive contamination must be monitored to make sure nuclide concentrations do not exceed permissible limits. If limiting concentrations are detected, the effluent must be directed to the normal plant gas treatment system or the rate of release controlled. This suggests that heat venting and normal HVAC system dampers in the ductwork servicing radiologically controlled areas must be capable of continued remote operation. If both types of venting capability were available, it could be possible to limit the heat and smoke load imposed on the gas treatment system.

Results and Recommendations

As stated in the section titled Technical Approach, the technical position taken in this study was that of the designer whose goal is to bring the ventilation system of a nuclear power plant into compliance with the referenced standards. By virtue of the current state of the art in fire protection technology, this approach leads to the conclusion that the technical design basis for the fire protection design of ventilation systems should be that of heat removal from the involved fire area for purposes of controlling fire temperatures. Examination of the ventilation system design parameters generated by this approach reveals that all but one of the roles listed under Guidance for Ventilation System Design would be fulfilled. The single exception is control of radioactive release from controlled areas of the plant.

The control of entrained radioactive substances presents a ventilation design problem in that the normal HVAC system, which is equipped to remove these substances, is generally incapable of handling the particulate concentrations and temperatures associated with fire generated effluent. NFPA 803 states that, for radioactive substances, the options are either confinement or release under controlled conditions. The IGL suggests using the normal gas-treatment system, provided that filters are suitably protected by the installation of prefilters or scrubbers and demisters to cope with smoke, heat, and corrosive gases. Presumably, the IGL suggestion meets the "controlled conditions" requirement of NFPA 803; however, another option might be the regulation of the removal rate through the vent which could lower the entrainment rate if the radioactive substances are being picked up by high-velocity flow patterns within the compartment. The confinement of smoke and gases, however, is clearly not a viable option unless the fire is arrested in its early stages of growth.

If a system of prefilters were added to the normal filter banks serving the controlled areas, the particulate concentration of contaminated smoke could be reduced to manageable levels. The addition of an upstream water curtain and demister, as suggested by IGL, would reduce temperatures and corrosive properties before filtration. The design or backfitting of all of the associated exhaust ductwork to withstand high-temperature gas flows remains a formidable problem.

As previously mentioned, the extinguishment of a fire in its early stages and the cooling effect of fixed water suppression systems greatly reduces the smoke and heat load on the ventilation system. Therefore the practical approach to fire protection in plant areas with high potential for radioactive contamination may be increased emphasis on early detection and automatic fixed suppression systems with attendant relaxation of ventilation requirements. Plant areas in this category might include the reactor building, radiation waste treatment areas, fuel handling facilities, and some emergency pump rooms. A potential problem with this approach arises in the case of the BWR, for which the turbine building and main steam tunnels are included as controlled areas. It is most probable, even in this case, that radioactive concentrations in these areas would be within acceptable limits for direct venting during fire emergencies in the absence of the simultaneous occurrence of a pipe break.

The selection of "heat removal for temperature control" as the fire ventilation system design basis implies a close systems relationship with other phases of the fire protection program. Sizing of venting facilities is determined by potential heat production rates identified for fire areas in the fire hazards analysis. The cooling capabilities of fixed suppression systems can also enter into the ventilation requirements as well as the performance capabilities of the fire detection system. The maximum permissible temperatures for which the venting system must be designed are governed by the ignition temperatures of the materials confined within the vented area, and by the thermal and structural characteristics of the fire barriers which form the boundaries of the compartment.

The results of this investigation can be summarized in the following conclusions and recommendations:

- An evaluation needs to be made of the benefits and detriments of a heat removal fire ventilation system relative to other available fire protection measures (e.g., automatic suppression, automatic detection, or separation). This effort should be completed before serious consideration is given to implementing a temperature control ventilation scheme in nuclear power plants.

- If the use of a heat removal fire ventilation system is evaluated as worthwhile, the technical design basis for the fire venting system should be the required rate of heat removal from involved fire areas.

- Existing guidelines and standards are generally lacking in sufficient detail to function as criteria for the design of ventilation systems as an integral part of the fire protection system.

- Current fire protection research activities are directed primarily toward the solution of light fire loadings, which are not typical of all areas of a nuclear power plant setting. Experimental programs should be proposed to provide basic fire performance data on combustibles normally found in critical areas of power plants.

- In areas of the plant which involve high probability for entrainment of radioactive containments in the smoke and gases and in backfitting of existing facilities, emphasis should be placed on the design and reliability analysis of fire detection and suppression systems with accompanying deemphasis on venting requirements.

- To allow sufficient flexibility of operation during fire emergencies to adequately control the spread of smoke and provide makeup air for fire vented compartments, the fans, isolation dampers, and their associated power supply and control cables should be protected from fire damage. Manual remote operation capability should be provided so that regulation and realignment of the systems can be accomplished as the particular fire situation demands.

APPENDIX

Sizing of Heat Venting Stacks for Natural Convection

The design of heat venting stacks can be approached by considering the stack operation as a steady flow process. A general energy balance for the system between state 1 at the stack entrance and state 2 at the stack exit then takes the form[15]

$$(P_2 - P_1) + (K_2 - K_1) + (Wf_2 - Wf_1) + (U_2 - U_1) = Q - W , \qquad (1)$$

where

$(P_2 - P_1)$ = potential energy change

$(K_2 - K_1)$ = kinetic energy change

$(Wf_2 - Wf_1)$ = system flow work

$(U_2 - U_1)$ = internal energy change

Q = heat input to the fluid

W = work done by the fluid.

In order to evaluate this energy expression, it is necessary to cast each term in a form appropriate to the physical system being considered. Accordingly, it can be observed that the gases flowing in a stack produce no useful work, thus eliminating the work term. The potential energy change is defined in terms of the force required to overcome the gravitational field in changing the elevation of the fluid from points 1 to 2. This requires accounting for the buoyancy of the flue gases. For a given volumetric flow rate F, a unit volume of air is displaced by each unit volume of flue gas. The bouyant mass flow then can be written as

$$w = F\,(\gamma_g - \gamma_a) = \frac{w_g}{\gamma_g}\,(\gamma_g - \gamma_a) ,$$

where

γ_g, γ_a = specific weight of flue gas and air, lb/ft^3

w, wg = mass flow rate, lb/min

F = volumetric flow rate, ft^3/min.

The potential energy term then becomes

$$(P_2 - P_1) = \frac{w_g}{\gamma_g} (\gamma_g - \gamma_a) (Z_2 - Z_1) \ ,$$

where

Z_1, Z_2 = elevation of points 1 and 2, in feet.

The change in kinetic energy in the stack is then written in terms of the velocities

$$(K_2 - K_1) = \frac{w_g}{2g_0} \left(v_2^2 - v_1^2\right) \ ,$$

where

g_0 = standard gravitational acceleration, ft/sec^2

v_1, v_2 = velocity at points 1 and 2, ft/sec.

Flow work is a consequence of the movement of the gases against pressure at the two reference points in the system. It is expressed as

$$(Wf_2 - Wf_1) = w_g \left(\frac{P_2}{\gamma_2} - \frac{P_1}{\gamma_1}\right) ,$$

where

p_1, p_2 = pressure at points 1 and 2, lb/ft^2.

Substitution in Eq (1) gives

$$\frac{w_g}{\gamma_g}(\gamma_g - \gamma_a)(Z_2 - Z_1) + \frac{w_g}{2g_0}\left(v_2^2 - v_1^2\right) + w_g\left(\frac{p_2}{\gamma_2} - \frac{p_1}{\gamma_1}\right)$$

$$+ w_g (U_2 - U_1) = Q \ . \qquad (2)$$

This is the expression for the general energy balance of the stack under steady flow.

Some further conditions can be imposed on Eq (2) to put it in a form that will be useful for stack design. The expression is for steady state operation of the stack, which implies that stable flow has been established and that initial transients have died out. Thus, it is reasonable to assume that the wall temperature of the stack has approached that of the flue gases. It can also be assumed that the stack would not be exceedingly high and that the time required for the gases to pass through the stack is therefore relatively short. The heat loss from the flue gases to the walls should consequently be small compared to the total heat carried by the gases. Accordingly, the heat transfer term, Q, can be set to zero. The same arguments applied to the third term lead to the assumption that the density change of the gases between points 1 and 2 is minimal. Thus, γ_g can be substituted for γ_1 and γ_2. This is equivalent to an assumption of incompressible flow in the stack. Equation (2) can then be recast in this form:

$$(\gamma_g - \gamma_a)(Z_2 - Z_1) + \frac{\gamma_g}{2g_0}\left(v_2^2 - v_1^2\right) + (p_2 - p_1)$$

$$+ \gamma_g (U_2 - U_1) = 0 \ . \qquad (3)$$

The change in internal energy can be attributed to friction losses within the stack. In order to obtain a practical expression for friction losses as well as to include consideration of other configuration-related losses of the stack system, it is appropriate to introduce some of the techniques used in the design of duct systems into Eq (3).[16] In duct design, friction losses are usually expressed in terms of the velocity of the flowing fluid and the Moody friction factor:

$$p_f = \left(\frac{\gamma v^2}{2g_0}\right)\left(\frac{fL}{D}\right) = p_v\left(\frac{fL}{D}\right)$$

where

p_f = pressure loss due to duct friction, lb/ft^2

f = Moody friction factor, dimensionless

L = length of duct, ft

D = diameter of duct, ft

p_v = velocity pressure, lb/ft^2.

The Moody friction factor is a function of the relative roughness of the duct and the Reynolds number indicative of the degree of turbulence of the flow. Its value can be found by reference to a generalized flow resistance diagram.[17]

Duct configuration losses, such as bends and entrance and exit losses, are accounted for by inclusion of an empirical loss coefficient for each fitting. The product of this coefficient and the local velocity pressure gives the pressure loss due to flow through the feature being considered. Chapter 31 of the ASHRAE 1977 Fundamentals Handbook[18] tabulates a number of fitting loss coefficients, including those applicable to the stack design problem. In applying the loss coefficients it is necessary to carefully observe the velocity to which each given coefficient is referred. For the purposes of this work, it is assumed that the stack is one of constant cross section, which, in turn, implies that a constant gas velocity applies from entrance to exit. The applicable ASHRAE coefficients are such that the reference velocity is that of the stack gases. Consequently, a combined friction and system configuration pressure loss expression can be written as

$$p_L = \frac{\gamma v^2}{2g_0}\left(\sum_i C_i + \frac{fL}{D}\right), \tag{4}$$

where

p_L = combined pressure loss, lb/ft^2

C_i = individual configuration loss coefficients.

The second term of Eq (3) represents the change in kinetic energy during stack transit. If the velocity of the gases in the vented compartment at some point near the entrance to the stack is assumed to be small compared to the velocity in the stack, then v_1 can be taken as zero and v_2 becomes the gas velocity in the stack. Thus, the term represents the exit pressure loss with an implied coefficient of unity which is appropriate for a stack exit without a tapered diffuser section. Combining the kinetic and internal energy terms of Eq (3) in the form of Eq (4), and noting that $(Z_2 - Z_1)$ and L are equal to the stack height, yields

$$H\,(\gamma_g - \gamma_a) + \frac{\gamma_g v_g^2}{2g_0}\left(\sum_i C_i + \frac{fH}{D}\right) + (p_2 - p_1) = 0\ , \tag{5}$$

where

H = stack height above entrance, ft.

This result is more conveniently applied to the present problem if the stack velocity is stated in terms of the volumetric flow rate, using

$$v_g = \frac{Q_g}{15\pi D^2} ,$$

where

v_g = flue gas velocity, ft/sec

Q_g = stack flow rate, ft^3/min

D = stack diameter, ft.

Substitution in Eq (5) and rearranging gives

$$(p_2 - p_1) = H(\gamma_a - \gamma_g) - \frac{\gamma_g Q_g^2}{450\pi^2 g_0 D^5} \left(D\sum_i C_i + fH\right) . \tag{6}$$

Solving this expression for the volumetric flow rate results in:

$$Q_g = \left\{\frac{450\pi^2 g_0 D^5}{\left(D\sum_i C_i + fH\right)\gamma_g} \left[H(\gamma_a - \gamma_g) - (p_2 - p_1)\right]\right\}^{1/2} . \tag{7}$$

Evaluation of this equation is inconvenient because of the presence of the gas densities. These can be expressed in terms of temperature if the air and flue gases are considered ideal gases by invoking the Ideal Gas Law in the form[15]

$$\gamma = \frac{p}{RT} ,$$

where

p = gas pressure, lb/ft^2

R = gas constant, ft-lb/lb-°R

T = absolute gas temperature, °R.

The gas pressures throughout the system are essentially atmospheric. It is further noted that the equivalent molecular weights of air and flue gas are very nearly identical,[19] which allows the use of a single gas constant for both constituents. Making the substitutions for γ_a and γ_g in Eq (7) gives the following:

$$Q_g = \left\{ \frac{450\pi^2 g_0 D^5}{\left(D\sum_i C_i + fH\right)} \left[\frac{H(T_g - T_a)}{T_a} - \frac{RT_g}{p_a}(p_2 - p_1) \right] \right\}^{1/2} , \qquad (8)$$

where

p_a = atmospheric pressure, lb/ft^2.

Now examine the significance of the second term in the bracketed expression. Reference to Eq (2) shows that p_1 and p_2 are the pressures at the inlet and outlet of the stack, respectively, during steady flow conditions. If, by some means, the fire compartment were to be supplied with air by a completely unrestricted path, then both the inlet and outlet of the stack would be at atmospheric pressure and the term would vanish. This could be done, for example, by supplying air at exactly the right flow rate through a fan powered input duct system. A more likely scenario, however, would involve drawing the air into the compartment from an adjacent plant area through an open door or some other opening. In this case, the pressure in the compartment would be subatmospheric, i.e., $p_1 < p_2$, and the system flow rate would be reduced by this term.

Assuming a single opening into the compartment and considering it a square-edged orifice, the pressure drop across the opening can be written as

$$(p_2 - p_1) = \frac{C_o \gamma_a v_a^2}{2g_0} , \qquad (9)$$

where

C_o = orifice coefficient referred to the velocity through the orifice

v_a = velocity of air through the orifice, ft/sec.

Since the underlying premise of the heat venting system is that sufficient excess air is provided to the fire compartment to limit peak temperatures, it will be assumed that the flow rate of combustion air into the fire is small compared to the total air flow. The mass flow rate into the compartment must then equal the outflow and

$$Q_a = Q_g \frac{\gamma_g}{\gamma_a} = Q_g \frac{T_a}{T_g} \; . \tag{10}$$

Now expressing the orifice velocity in terms of the stack flow rate and the orifice area gives:

$$(p_2 - p_1) = \frac{C_o p_a T_a Q_g^2}{7200 A_o^2 g_0 R T_g^2} \; ,$$

where

A_o = area of air supply opening, ft^2.

Substituting this result in Eq (8) and solving again for the volumetric flow rate of the stack gases yields the final expression:

$$Q_g = \left\{ \frac{450\pi^2 g_0 D^5 H(T_g - T_a)}{T_a \left[\left(D\sum_i C_i + fH \right) + \frac{C_o \pi^2 D^5 T_a}{16 A_o^2 T_g} \right]} \right\}^{1/2} \; , \tag{11}$$

where

H = stack height, ft

Q_g = stack flow rate, ft^3/min

g_0 = standard gravitational acceleration, ft/sec^2

D = stack diameter, ft

T_a, T_g = absolute air and flue gas temperatures, °R

f = Moody friction factor, dimensionless

C_o = orifice coefficient of compartment air supply opening, dimensionless

C_i = individual configuration loss coefficients, dimensionless

A_o = area of compartment air supply opening, ft^2.

Evaluation of Eq (11) for a range of stack heights and diameters, stack configuration, compartment air supply conditions, and ambient and peak temperatures produces a corresponding range of stack flow rates. Estimates of the potential heat production in a fire area can then be used to determine the stack flow rate required to limit peak temperatures to acceptable values. The appropriate combination of stack parameters can then be selected, based on the required flow rate. The presence of the Moody friction factor in the equation requires that some degree of conservatism be introduced by selection of a suitably high value for this parameter. A check on the validity of the assumed value can be made as a secondary calculation once the velocity of the stack gases is determined for a given design situation.

Tables 1 and 2 give the stack flow rates resulting from evaluation of Eq (11) for stack diameters from 1 to 10 ft, stack heights from 50 to 200 ft, and gas temperatures from 200° to 800°F. Table 1 represents the case in which make-up air is somehow supplied to the compartment at a rate which maintains the compartment at atmospheric pressure. As such, the flow rates are the maxima attainable by natural stack action. The values in Table 2 include the assumption that air is being drawn into the room by stack action through an opening of 20 ft^2, approximately that of a fully opened door. The expression is quite sensitive to the inlet area assumption so the tabulated results should be viewed only as indicative of passive air supply. A constant friction factor, $f = 0.025$, was assumed for both sets of calculations. Over the range of stack flows obtained, this is a conservatively high value representative of a stack liner of relatively rough concrete. The assumed configuration is that of a centrally located stack with dampered openings of the same cross-sectional area as the stack into each of the compartments served. The loss coefficients were taken from Reference 16 and the orifice coefficient for the doorway is from Reference 18.

It should be noted that no leakage losses were included in the calculations. Tamura and Shaw have shown that leakage can reduce the flow rates by a factor of two if the total leakage fraction is as little as 3% of the stack flow.[7] If a central stack were to be designed to vent several compartments, only the damper in the fire cell would be actuated, while all others would remain in their normally closed condition. All of these dampers must be very carefully designed to assure minimum leakage.

Table 1

Predicted Smoke Vent Flow Rates*
(Unlimited Inlet Area)

Stack Height = 50 ft

Diam (ft)	Flow Rate (cubic feet/minute) at 200°F	400°F	600°F	800°F
1	634	1 035	1 320	1 553
2	2 765	4 515	5 756	6 773
3	6 426	10 494	13 377	15 741
4	11 620	18 975	24 189	28 463
5	18 348	29 962	38 194	44 943
6	26 609	43 453	55 392	65 180
7	36 405	59 450	75 784	89 175
8	47 735	77 952	99 370	116 928
9	60 600	98 959	126 149	148 439
10	74 998	122 472	156 122	183 708

Stack Height = 100 ft

Diam (ft)	Flow Rate (cubic feet/minute) at 200°F	400°F	600°F	800°F
1	781	1 276	1 627	2 105
2	3 587	5 859	7 468	10 001
3	8 535	13 938	17 768	24 218
4	15 642	25 543	32 562	44 866
5	24 913	40 684	51 862	71 982
6	36 352	59 363	75 673	105 585
7	49 959	81 583	103 998	145 683
8	65 734	107 344	136 837	192 280
9	83 679	136 647	174 191	245 379
10	103 792	169 492	216 061	304 983

Stack Height = 150 ft

Diam (ft)	Flow Rate (cubic feet/minute) at 200°F	400°F	600°F	800°F
1	859	1 403	1 789	2 105
2	4 083	6 667	8 499	10 001
3	9 887	16 145	20 581	24 218
4	18 316	29 910	38 128	44 866
5	29 386	47 988	61 173	71 982
6	43 105	70 390	89 730	105 585
7	59 474	97 122	123 807	145 683
8	78 498	128 186	163 406	192 280
9	100 175	163 586	208 532	245 379
10	124 509	203 322	259 186	304 983

Stack Height = 200 ft

Diam (ft)	Flow Rate (cubic feet/minute) at 200°F	400°F	600°F	800°F
1	908	1 483	1 891	2 225
2	4 422	7 221	9 205	10 832
3	10 358	17 731	22 603	26 597
4	20 296	33 143	42 249	49 715
5	32 766	53 507	68 209	80 261
6	48 283	78 847	100 511	118 271
7	66 855	109 175	139 171	163 762
8	88 486	144 497	184 199	216 746
9	113 178	184 820	235 600	277 230
10	140 934	230 145	293 378	345 218

*Ambient Air Temperature = 80°F; Friction Factor = 0.025

Loss Coefficients: Entrance = 0.5; Exit = 1.0; Stack Tee = 1.2

Table 2

Predicted Smoke Vent Flow Rates*
(Limited Inlet Area)

Stack Height = 50 ft

Diam (ft)	Flow Rate (cubic feet/minute) at 200°F	400°F	600°F	800°F
1	634	1 035	1 319	1 553
2	2 744	4 489	5 729	6 746
3	6 178	10 178	13 048	15 413
4	10 319	17 281	22 393	26 654
5	14 205	24 359	32 096	38 680
6	17 156	30 138	40 451	49 466
7	19 105	34 214	46 658	57 826
8	20 311	36 863	50 865	63 700
9	21 047	38 535	53 600	67 622
10	21 502	39 591	55 362	70 197

Stack Height = 100 ft

Diam (ft)	Flow Rate (cubic feet/minute) at 200°F	400°F	600°F	800°F
1	781	1 276	1 627	2 105
2	3 565	5 830	7 439	9 972
3	8 242	13 567	17 381	23 818
4	14 031	23 451	30 348	42 464
5	19 597	33 523	44 090	63 149
6	23 909	41 906	56 144	82 347
7	26 791	47 897	65 222	97 643
8	28 583	51 817	71 424	108 583
9	29 677	54 296	75 469	115 953
10	30 353	55 861	78 077	120 807

Stack Height = 150 ft

Diam (ft)	Flow Rate (cubic feet/minute) at 200°F	400°F	600°F	800°F
1	859	1 403	1 789	2 105
2	4 060	6 639	8 470	9 972
3	9 582	15 759	20 179	23 818
4	16 569	27 648	35 738	42 464
5	23 442	40 010	52 537	63 149
6	28 868	50 491	67 531	82 347
7	32 540	58 080	78 978	97 643
8	34 836	63 083	86 865	108 583
9	36 241	66 255	92 028	115 953
10	37 108	68 259	95 362	120 807

Stack Height = 200 ft

Diam (ft)	Flow Rate (cubic feet/minute) at 200°F	400°F	600°F	800°F
1	908	1 483	1 891	2 225
2	4 401	7 194	9 178	10 805
3	10 553	17 346	22 202	26 198
4	18 493	30 814	39 793	47 249
5	26 465	45 078	59 105	70 966
6	32 875	57 384	76 630	93 325
7	37 267	66 412	90 189	111 376
8	40 032	72 411	99 611	124 406
9	41 726	76 227	105 807	133 230
10	42 771	78 639	109 812	139 054

*Ambient Air Temperature = 80°F; Friction Factor = 0.025

Loss Coefficients: Entrance = 0.5; Exit = 1.0; Stack Tee = 1.2

Compartment Air Inlet: Area = 20 ft; Orifice Coefficient = 2.5

Examples of Vent Stack Applications

To illustrate the use of Tables 1 and 2 and to investigate the feasibility of heat removal by stack action, some sample calculations were made for a postulated fire, the results of which are presented here. The heat removal capability of air can be expressed as

$$q = wc_p (T_2 - T_1) ,$$

where

q = heat removal capability, Btu/min

c_p = specific heat of air at constant pressure, Btu/lb-°R

T_1, T_2 = initial and final air temperatures, °R

w = mass flow rate, lb/min.

The specific heat is defined by

$$c_2 = \frac{h_2 - h_1}{T_2 - T_1} ,$$

where

h_2, h_1 = enthalpy at T_2 and T_1, Btu/lb.

Making this substitution and applying the previously stated form of the Ideal Gas Law, the following expression for the required flow in the stack can be written as follows:

$$Q_g = \frac{Q_f + RT_g}{P_a (h_2 - h_1)} , \quad (12)$$

where

Q_g = required stack flow rate, ft^3/min

Q_f = heat evolved by postulated fire, Btu/min

R = gas constant, ft-lb/lb-°R

T_g = assumed allowable maximum temperature, °R

P_a = atmospheric pressure, lb/ft^2

h_2, h_1 = enthalpy of air at maximum and ambient temperatures, Btu/lb.

For purposes of estimating stack size requirements, Eq (12) can be simplified by assuming standard atmospheric pressure and R = 53.3 which gives

$$\dot{Q}_g = (2.5186 \times 10^{-2}) \frac{q_f T_g}{(h_2 - h_1)} . \tag{13}$$

The values for enthalpy of air at various temperatures can be found in standard gas tables.[20] Equation (10) can be used to estimate the required make-up airflow rate. Equation (9) will give the value of negative differential pressure in the compartment under natural stack action, when air is supplied through an assumed opening for a given supply air velocity through the inlet opening. Again using the standard air conditions stated above and an orifice coefficient of 2.5, Eq (9) becomes

$$\Delta p = -(8.2334 \times 10^{-5}) \frac{v_a^2}{T_a} , \tag{14}$$

where

v_a = inlet air velocity, ft/min.

Using these expressions, consider a 5 ft^2 gasoline fire in a compartment 50 ft square by 15 ft high. NFPA 204 gives a pool-burning heat evolution rate of 10 000 Btu/ft^2-min for gasoline, which represents a heat input to the compartment of 50 000 Btu/min. A stack height of 100 ft was assumed. Stack sizes were taken from Table 2 which implies an ambient temperature of 80°F and an air inlet opening of 20 ft^2. The results of these calculations are shown in Table 3.

Table 3

Example Heat Venting Results
(5 ft^2 gasoline fire in 37 500 ft^3 compartment)

Assumed maximum permissible temperature, °F	200	400	600
Enthalpy change, Btu/lb	29	76	126
Required gas flow in vent stack, ft^3/min	28 660	14 250	10 594
Required air flow into compartment, ft^3/min	23 450	8 950	5 397
Minimum stack diameter from Table 2, ft	8.0	3.1	2.5
Velocity in stack, ft/min	570	1 888	2 158
Velocity through 20 ft^2 compartment air inlet, ft/min	1 172	447	269
Air change rate at 80°F, vol/hr	37.5	14.3	8.6
Compartment differential pressure, in. H_2O	-0.210	-0.031	-0.011

As might be expected, very large flow rates, and hence large stacks, would be required to maintain low peak temperatures. In this example, a peak permissible temperature of 400°F results in a reasonable stack diameter and flow rates. If a stack height of 50 ft had been assumed, Table 2 suggests that the 200°F temperature could not be maintained. Reference to the flow rates in Table 1 for the 50-ft stacks shows that this latter case is governed by the limitations of the compartment air inlet.

References

1. E. A. Bernard and G. L. Cano, Report on Task I - Fire Protection Study, Sandia Laboratories, SAND76-0630 (NUREG 766516), February 1977.

2. Standard Test Method for Measuring the Smoke Generated by Solid Materials, National Fire Protection Association, NFPA 258, 1976.

3. A. F. Robertson, "Estimating Smoke Production During Building Fires," Fire Technology, Vol. 11, No. 2 (pp. 80-93) May 1975.

4. E. E. Smith, "Measuring Rate of Heat, Smoke and Toxic Gas Release," Fire Technology, Vol. 8, No. 3 (pp. 237-245), August 1972.

5. E. E. Smith, "Application of Release Data to Hazard Load Calculations," Fire Technology, Vol. 10, No. 3 (pp. 181-186), August 1974.

6. E. E. Smith, "Relation of Performance Tests to Actual Fires," Fire Technology, Vol. 12, No. 1 (pp. 49-54), February 1976.

7. G. T. Tamura and C. Y. Shaw, "Basis for the Design of Smoke Shafts," Fire Technology, Vol. 9, No. 3 (pp. 209-222), August 1973.

8. F. C. W. Fung, "Smoke Control by Systematic Pressurization," Fire Technology, Vol. 11, No. 4 (pp. 261-268), November 1975.

9. T. Z. Harmathy, " A New Look at Compartment Fires, Parts I and II," Fire Technology, Vol. 8, No. 3, (pp. 196-217), August 1972 and Vol. 8, No. 4 (pp. 326-351), November, 1972.

10. T. Z. Harmathy, "Design of Buildings for Fire Safety, Parts I and II," Fire Technology, Vol. 12, No. 2, (pp. 95-108), May 1976, and Vol. 12, No. 3 (pp. 219-236), August 1976.

11. T. Z. Harmathy, "Fire Resistance versus Flame Spread Resistance," Fire Technology, Vol. 12, No. 4 (pp. 290-302), November 1976.

12. J. Quintiere, "Growth of Fire in Building Compartments," Fire Standards and Safety, ASTM STP 614, A. F. Robertson, Ed., American Society for Testing and Materials (pp. 131-167), 1977.

13. T. E. Waterman, "Room Flashover--Criteria and Synthesis," Fire Technology, Vol. 4, No. 1 (pp. 25-31), February 1968.

14. J. B. Fung, "Fire Buildup in a Room and the Role of Interior Finish Materials" NBS Technical Note 879, National Bureau of Standards, Washington, DC, June 1975.

15. V. M. Faires, Thermodynamics, Fifth Edition, MacMillan Co., London, 1970.

16. ASHRAE Handbook of Fundamentals, 1977 Edition, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., New York, Chapter 31.

17. Marks' Standard Handbook for Mechanical Engineers, Seventh Edition, T. Baumeister, Editor, McGraw-Hill Book Co., New York, p 3-60, 1967.

18. ASHRAE Handbook of Fundamentals, 1972 Edition, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., New York, Chapter 25.

19. Steam, Its Generation and Use, 38th Edition, Babcock & Wilcox Co., New York, p 17-2, 1975.

20. P. J. Potter, Power Plant Theory and Design, Second Edition, The Ronald Press Co., New York, 1959.

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This report examines the role of compartment ventilation from the standpoint of nuclear power plant fire protection safety. Based on a review of numerous design standards which consider the influence of controlled ventilation on reducing fire severity, the report concludes that current standards and regulatory guidelines inadequately define criteria for design of ventilation systems and their operation under fire emergencies. To resolve this deficiency, the report evaluates four candidate design bases for ventilation systems: smoke removal, smoke dispersion control, fire spread control, and fire temperature control. It is concluded that the lack of existing fire technology precludes the implementation of all but one of these criteria--fire temperature control. On this basis the report presents an example design calculation for applying the temperature control criterion.

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