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Modeling of Smoke Generation and Movement in a Nuclear Facility

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ABSTRACT

The nuclear industry is required to analyze its facilities for hazardous fire conditions, and a national laboratory has developed a computer code called FIRAC to aid in this process. FIRAC can predict the temperature, pressure, density, and mass or volumetric flow of air through a facility. The code is oriented primarily toward transport through the ventilation system, but it can be adapted to model any airflow passageway. The code includes a compartment fire model to simulate the burning of both radioactive and nonradioactive material. This model generates the smoke that subsequently is transported throughout the facility.

The FIRAC code and material transport modules are described in detail. An example hypothetical facility and fire scenario are used to illustrate the code's abilities to model smoke generation and movement.

INTRODUCTION

Safety analysts in the nuclear industry are required to determine the effects of hypothetical fires that could occur within a nuclear facility. To aid the analyst in this task, a national laboratory has developed a computer code called FIRAC to simulate the effects of a fire (Nichols and Gregory 1986). The code is applicable to nuclear facilities that use forced ventilation to bring air into, through, and out of the plant. The code models the ventilation network and the burning that occurs in fire zones. The fire zone model (a compartment model called FIRIN) has special capabilities to simulate the burning of different radioactive materials. The model provides the mass and energy produced and the radioactive and nonradioactive smoke. This output then is convected throughout the corridors, rooms, and ductwork.

The basic FIRAC code structure is discussed along with the general limitations of the code and the transport of smoke in particular. The code's capability is illustrated by calculating a sample problem that involves burning kerosene, polystyrene, and a radioactive mixed-oxide powder.

FIRAC CODE DESCRIPTION

FIRAC is one of a family of computer codes that has been developed to predict the effects of fires, explosions, and tornadoes on nuclear fuel cycle facilities. FIRAC was designed to numerically model fire-induced flows, heat transfer, and material transport within ventilation systems and other airflow pathways. In the code, fires may be represented either parametrically or by a fire compartment model called FIRIN that was developed at a national laboratory (Chan et al. 1985).

FIRAC simultaneously calculates the gas-dynamic, material-transport, and heat-transport transients that occur in any arbitrarily connected network system subjected to a fire. The network system includes ventilation system components such as filters, dampers, ducts, and blowers; these components are connected to the rooms and corridors to complete the network for moving air through the facility.

FIRAC uses a lumped-parameter method to describe the airflow system, and no spatial distribution of parameters within the network components is included in this approach. Network theory defines system elements that exhibit flow resistance and inertia, or flow potential, as branches. The ventilation system components contained in branches include dampers, ducts, filters, and blowers. The connecting points of the branches are network system elements called nodes, and they always have a finite volume. Nodes include specific network components that have a finite volume, such as rooms, glove boxes, and plenums, or the node may contain only the volume of the connecting branches. System boundaries, where the volume is practically infinite, also are specified as nodes. Fluid mass and energy storage at the internal nodes is taken into account by using the equations for conservation of mass and energy. The conservation equations are applied to the room nodes using the lumped-parameter formulation assuming a homogeneous mixture and a thermodynamic equilibrium. An implicit numerical scheme is used to solve for the pressure and density at each node. In the solution algorithm, the flow rate through branches is modeled as a function of the differential pressure and friction factors.

The material transport model in the code estimates the movement of material through the network of ventilation system components. The code also calculates material concentrations and material mass flow rates at any location in the network. This model includes convective transport, depletion by gravitational settling, entrainment from ducts,

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and filtration. No phase transitions or chemical reactions are modeled.

The code's heat-transfer model predicts how the combustion gas in the system cools as it flows through the network ducts. The model predicts the temperature of the gas leaving any section of the duct if the inlet temperature and gas properties are known. The following heat-transfer processes are modeled:

- Forced convection between the gas and the inside duct walls
- Radiation between the gas and the side duct wall
- Heat conduction through the duct wall
- Natural convection from the outside duct wall to the surrounding air
- Radiation from the outside duct wall to the atmosphere.

The total amount of energy removed from the gas as it flows through the duct is given by the solving of a set of four coupled nonlinear algebraic equations using an iterative procedure.

The fire-generated radioactive and nonradioactive source terms for FIRAC can be estimated in either of two ways. The source terms may be specified as input to the FIRAC code or may be generated by a zone-type compartment fire model. (This model is in a code module named FIRIN.) A zone-type fire compartment assumes that the gas in the room is divided into two homogeneous regions, or layers, during a fire. One layer (the hot layer) develops near the ceiling and contains the hot combustion products released from the burning material. The cold layer, which is between the hot layer and the floor, contains fresh air. FIRIN predicts the fire source mass loss rate, the energy generation rate, and the fire room conditions (temperatures of the two layers and room pressure) as a function of time. It also calculates the mass generation rate and particle size distributions for radioactive and nonradioactive particles that can become airborne for a given fire accident scenario. The radioactive release factors incorporated into the FIRIN module are primarily those developed in experimental work at the national laboratory, and the combustion product data were developed from a literature search of combustibles that commonly are found in nuclear facilities. More information on the fire and radioactive source term models and FIRIN code assumptions is available in the user's manual for FIRIN (Chan et al. 1985).

MATERIAL TRANSPORT THEORY

The material transport algorithms in the FIRAC code provide an estimate of the aerosol or gas transport within a complex network system. Using this, the code can calculate material concentrations and material mass flow rates at any location in the network. Furthermore, it will perform these transport calculations for various gas-dynamic transients. The code solves the entire network for transient flow and, in doing so, takes system interactions into account.

A generalized treatment of material transport under accident conditions in a nuclear fuel-handling facility could become extremely complex. FIRAC models only the most significant phenomena with simple models. The material transport components of the code are (1) material characteristics, (2) transport initiation, (3) convection transport, (4) aerosol depletion, and (5) filtration.

Material characteristics and transport initiation must be considered by the user as he or she begins to set up the code to solve a given problem. The code automatically calculates convective transport, aerosol depletion, and filtration. The material transport models have some limitations with regard to the physical and chemical characteristics of the material. The pneumatically transportble contaminant material can consist of any number of aerosol or gaseous species; however, no phase transitions or chemical reactions are allowed. For example, condensation and gas-to-particle conversion are not permitted. If the contaminant is an aerosol (solid particles or liquid droplets suspended in air), a size distribution can be simulated. In this case, within each size range, the material will be treated as monodisperse (equal sized), homogeneous (uniform density), spherical particles or droplets during a given code run. Both the size and density of each specie must be specified by the user. If the contaminant is a gas, then it is assumed to be inert. User guidance in the area of aerosol and gas characteristics is provided in the FIRAC user's manual (Nichols and Gregory 1986).

To calculate material transport using the code, the analyst must determine or assume the location, distribution, and total quantity of contaminant material. This material can be located or generated in rooms, internal boundary nodes representing the fire compartment, cells, glove boxes, corridors, or rectangular ductwork. (An assumption about material distribution is only necessary when the user wishes to exercise the option for calculated aerodynamic entrainment of dry powder from thick beds.) A total quantity (mass of material) must be known or assumed.

There are three options for material transport initiation: user-specified, calculated aerodynamic entrainment, and FIRIN calculated material generation. The user-specified option allows the analyst considerable flexibility but requires engineering judgment to specify input to the code. This option involves preparing a table or graph of material generation rate or mass injection rate vs. time.

The calculated entrainment option specifically refers to a subroutine designed to calculate aerodynamic entrainment of dry powder from thick beds. This subroutine can be useful for analyzing material transport initiation. It uses a semi-empirical analytical approach for calculating entrainment that takes advantage of detailed flow information produced by the gas- dynamics module. To arrive at an estimate of the mass of material entrained at each time step of the calculation, this subroutine calculates when the surface particles will begin to move, and particle, surface, and flow characteristics are taken into account. It also accounts for the aerodynamic, interparticle (cohesion), and surface-to-particle (adhesion) forces that may be acting. The calculated entrainment option can be used whenever powder beds are known or assumed to be present. However, the code must be provided with particle size and density, total mass of contaminant, and the floor area of the surface over which the powder is distributed uniformly.

The FIRIN module calculates various particulate and gaseous specie generation rates and concentrations for the fire compartment. If the user selects the FIRIN models

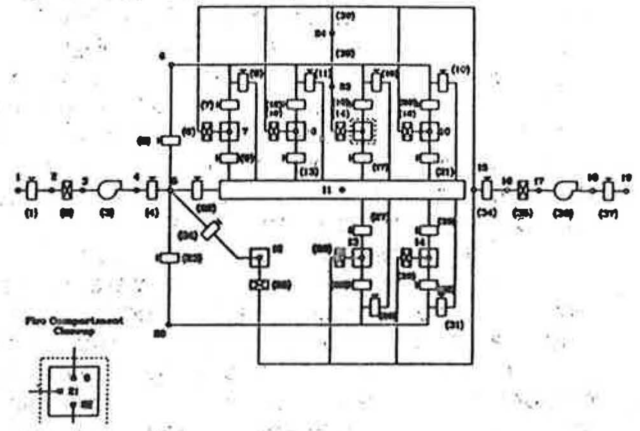

Figure 1: Example facility showing node and branch locations.

to simulate the release of particulate material, up to 13 particulate and 3 gaseous species can be transported by the FIRAC material transport models. The first two particulate species are the total smoke and total radioactive particulates. The total radioactive particulate mass released as a result of the fire has been divided into 11 particle-size distributions. These particle-size distributions are generated within the FIRIN radioactive source term subroutines and are transported as the remaining 11 particulate species.

The convective transport model is based on the assumptions that the particle size is small and its mass fraction is small relative to the gas mass in the same volume (Tang 1982). This allows us to assume that the material and the gas form a homogeneous mixture and that they are in dynamic equilibrium. In this case, the gas-dynamic aspect of the problem is not affected by the presence of the airborne material, and the particulate or material velocity is the same as the gas velocity at any location and time. Therefore, the only relation needed to describe the motion of the material is the continuity equation.

The FIRAC code calculates aerosol losses caused by gravitational sedimentation in horizontal rectangular or round ducts. Aerosol depletion can be calculated throughout the network during transient flow. The theory is based on quasi-steady-state settling with the terminal settling velocity corrected by the Cunningham slip factor. The flow in ducts and rooms is assumed to be well mixed so that the aerosol concentration is uniform within the volume. The user must supply the aerosol diameter, density, and duct height to this model, and the aerosol may consist of solid particles or liquid droplets.

A phenomenological approach to filter loading is used. The filter gas-dynamic performance can be changed by the accumulation of airborne material on the filter, which, in turn, causes an increase in flow resistance. A linear model in which the increase in resistance is linearly proportional to the amount of material on the filter is used. The proportionality constant is a function of the fuel source and filter properties. The user supplies the filter efficiency and plugging factor.

EXAMPLE CALCULATION

To illustrate how the FIRAC code can be used to model a small facility, we have chosen to model a fire in the facility shown in Figure 1. This system includes a set of steady-state flows and pressures and multiple blowers, compartments, dampers, and filter systems. The ventilation system network connections are in both parallel and series arrangement. Supply and exhaust blowers are included, and leakage around doors and other areas can be included. In addition, several pressure zones are provided with flow from the least contaminated to more contaminated zones.

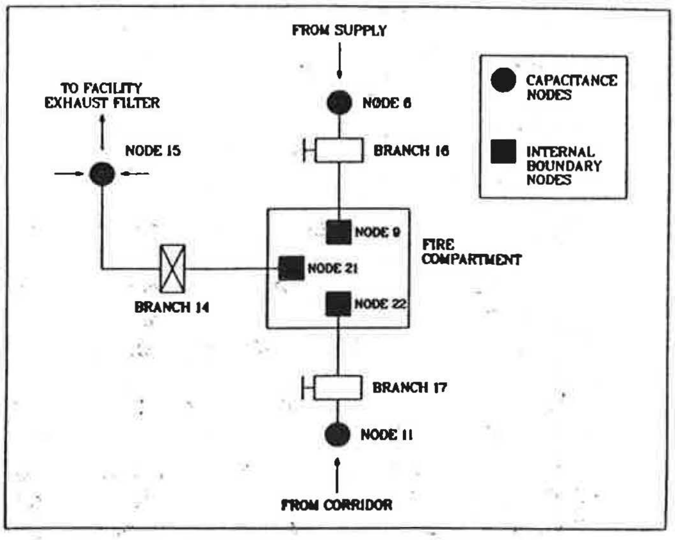

Figure 2: Close-up system schematic near the fire compartment

System Description

For this scenario, the fire is assumed to occur in the compartment represented by internal boundary nodes 9, 21, and 22, as shown in Figure 2. Three internal boundary nodes were required because the compartment has three flow connections: two in-flow (branches 16 and 17) and one out-flow (branch 14). The inlet and outlet branches (ducts) to the fire compartment have been positioned so that the general ventilation flow direction in the room is downward. Most compartment ventilation ducts in fuel cycle facilities are configured in this manner to help settle contaminated airborne particulates, which reduces the risk of contamination throughout the facility.

The fire compartment is assumed to be 39 ft (12 m) long, 39 ft (12 m) wide, and 20 ft (6 m) high. The centerline elevation of the two inlet ventilators (measured from the floor) is 18.74 ft (5.71 m), and the centerline elevation of the outlet ventilator is 3.0 ft (0.9 m). Also, the fire compartment is assumed to have a concrete floor, ceiling, and walls. The ceiling and floor are assumed to be 1.0 ft (0.3 m) thick, and the walls are assumed to be 0.5 ft (0.2 m) thick.

When the system is operating under steady-state conditions, the fire compartment has a pressure of -0.30 in w.g. (-0.76 cm w.g.) at a temperature of 70°F (21°C). The two inlet ventilators (branches 16 and 17) supply 3679 ft^3/min (1.736 m^3/s) and 290 ft^3/min (0.137 m^3/s) of air to the compartment. The outlet ventilator exhausts 3969 ft^3/min (1.873 m^3/s) of air under steady-state conditions. The fire compartment/overall system steady-state condition was achieved by selecting an initial system pressure distribution and using resistance coefficients. The fire compart-

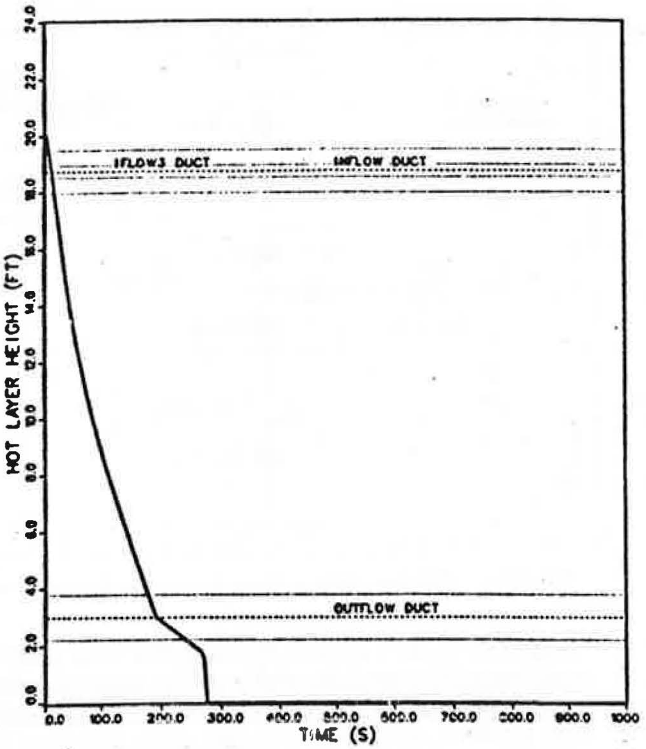

Figure 3: *Hot-layer height vs. time.*

ment exhaust filter (branch 17) is assumed to be 99.95% efficient and has a plugging factor of 20.1/kg. We selected a large filter plugging factor to illustrate the effect of the filter plugging model on the calculated results.

Fire Accident Scenario

This fire sample problem illustrates the use of the FIRIN sequential burning option. Two fuels (kerosene and polystyrene) will be burned sequentially in the calculation. The fire compartment is assumed to contain 3.0 lbm (1.4 kg) of uncontaminated kerosene. The container of kerosene has an exposed surface (burn) area of 5.0 ft^2 (0.5 m^2). In addition to the kerosene, the compartment contains 10.0 lbm (13.6 kg) of contaminated polystyrene. The polystyrene is assumed to have an exposed surface area of 7.0 ft^2 (0.7 m^2) and is contaminated with 0.22 lbm (0.10 kg) of mixed-oxide powder.

TABLE 1
Transient Event Sequence for Sample Problem 2

Event	Time (s)
Kerosene ignites	2
Hot layer descends to center-line elevation of in-flow boundaries	~12
Hot layer descends to center-line elevation of out-flow boundary	~190
Contaminated polystyrene ignites	~265
Transport of radioactive material initiated	~265
Fire compartment exhaust filter begins to plug	~325
Maximum system temperature attained	~806
Fire terminated	~806
End of calculation	1000

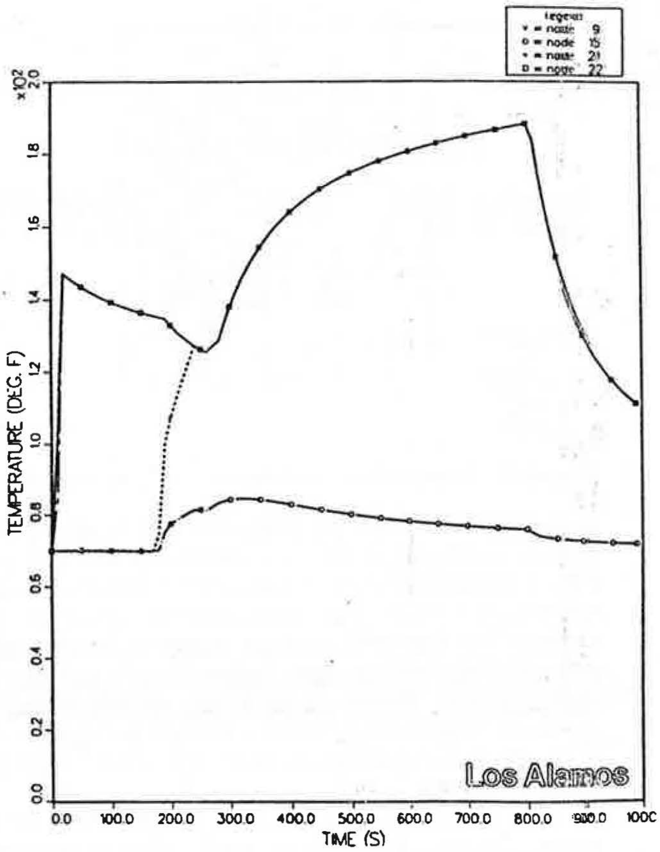

Figure 4: *Temperature response for nodes 9, 15, 21, and 22.*

Because we assumed in the scenario that the two combustibles at risk within the fire compartment will burn sequentially, the maximum number of burning orders is 2. The kerosene was selected to initiate the accident sequence and has a burning order of 1. After all the kerosene has been consumed, the polystyrene will ignite to continue the fire- induced transient.

Example Problem Results

System Response. The sequence of events for the example problem calculation is given in Table 1. The kerosene ignition initiates the accident sequence 2 seconds into the simulation. The fire compartment (represented by nodes 9, 21, and 22 in the system model) rapidly pressurizes from its steady-state operating value of −0.30 in w.g. (0.76 cm w.g.) to approximately 0.5 in w.g. (1.3 cm w.g.) because the fire causes a rapid volumetric expansion of the gases within the compartment. As a result of the pressure increase in the compartment, a reduction in flow at the intakes (branches 16 and 17) and an increase in flow at the compartment exhaust (branch 14) is calculated by FIRAC.

Between 2 and 200 seconds, the hot layer gradually expands and descends toward the out-flow ventilator (Figure 3). As the out-flow ventilator begins to exhaust the hot combustion products/gases composing the hot layer, the fire compartment begins to depressurize. The volumetric and mass flows at the intakes to the compartment are enhanced by the depressurization. The compart-

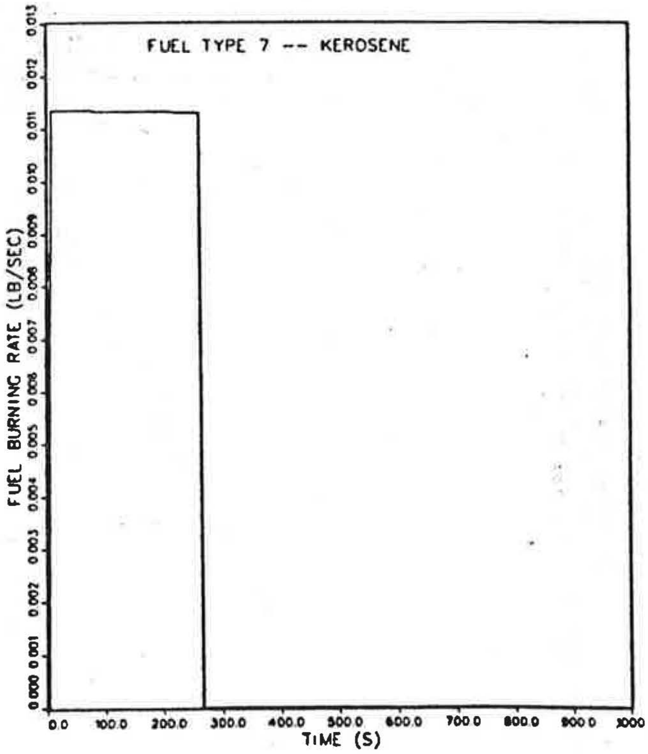

Figure 5: *Kerosene burning rate vs. time.*

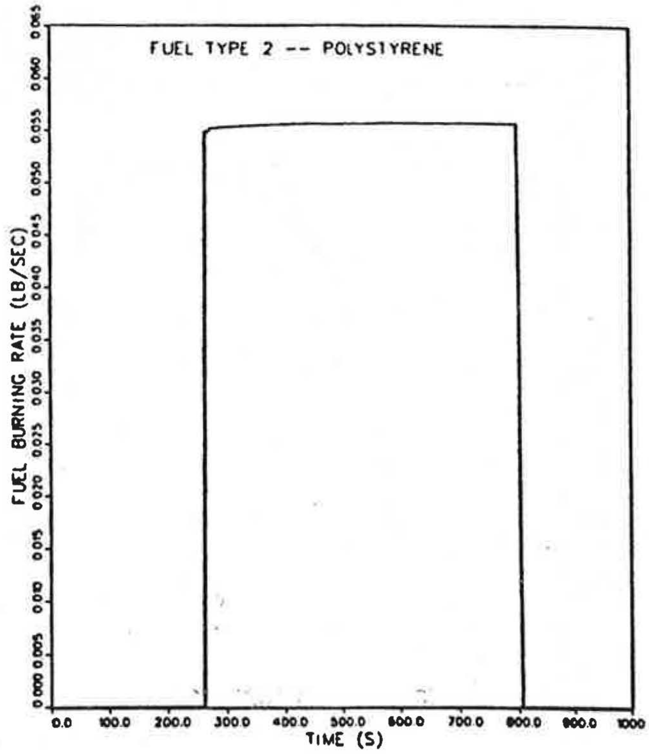

Figure 6: *Polystyrene burning rate vs. time.*

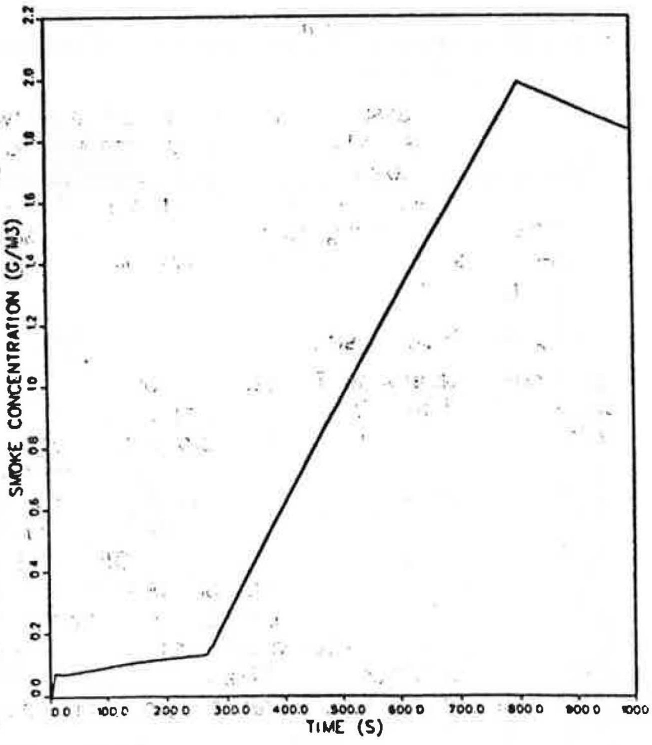

Figure 7: *Fire compartment smoke concentration vs. time.*

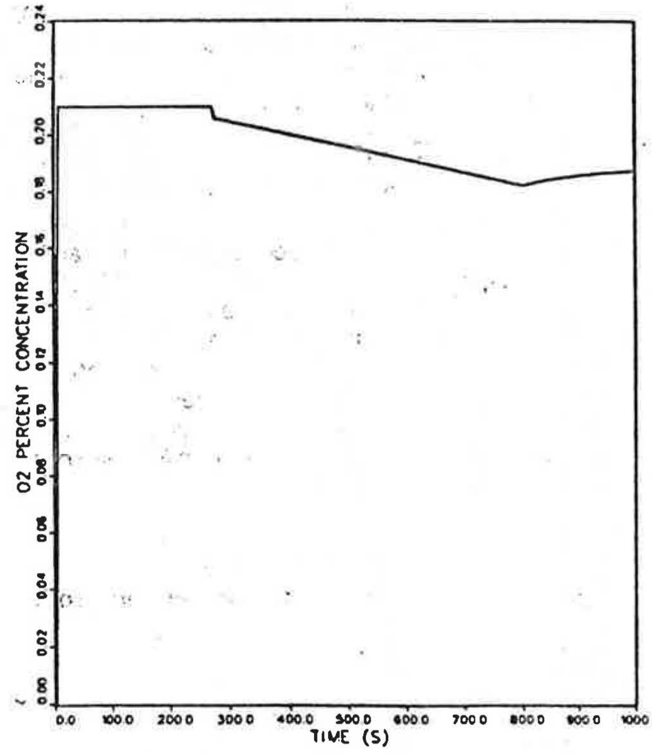

Figure 8: *Fire compartment oxygen concentration vs. time.*

ment exhaust flow rate decreases because of the depressurization and the presence of the hot (less dense) combustion gases at the out-flow ventilator. The temperature history for the fire compartment is shown in Figure 4.

The system is perturbed again as the kerosene fire terminates and the contaminated polystyrene ignites through the sequential burning option. This transition occurs between ~250 and ~275 seconds, as shown in Figures 5 and 6. The ignition of the polystyrene repressurizes the fire

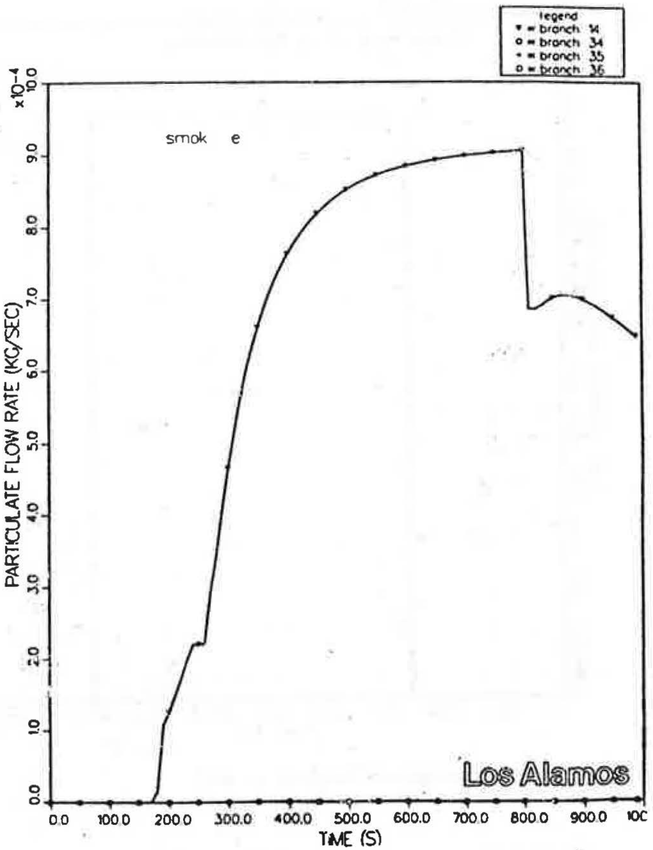

Figure 9: *Smoke particulate mass flow rates for branches 14, 34, 35, and 36.*

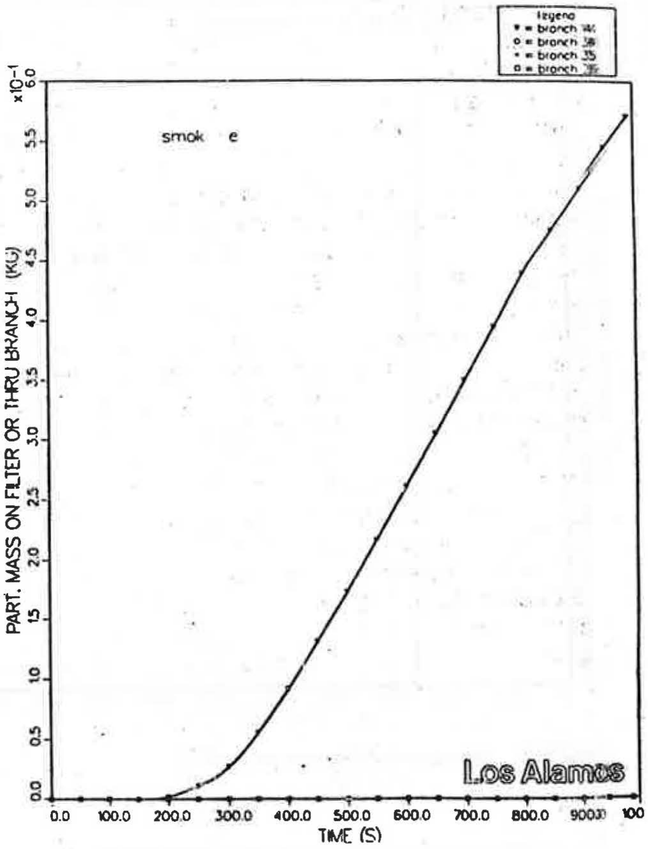

Figure 10: *Accumulated smoke particulate mass for branches 14, 34, 35, and 36.*

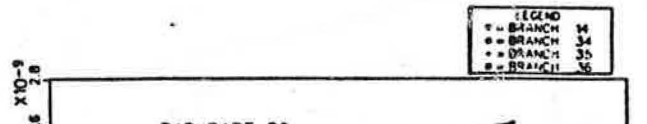

Figure 11: *20-μm radioactive particulate mass flow rates for branches 14, 34, 35, and 36.*

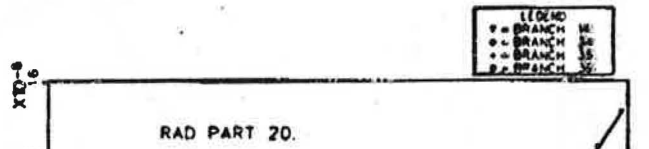

Figure 12: *20-μm radioactive particulate mass for branches 14, 34, 35, and 36.*

compartment to approximately 1.0 in w.g. (2.5 cm w.g.). The flow rates to the compartment are affected by the repressurization: exhaust flow (branch 14) is enhanced, and the flow at the intakes (branches 16 and 17) is reduced. As the polystyrene burns, the compartment remains pressurized at approximately 0.9 in w.g. (2.3 cm w.g.) and becomes more concentrated with smoke particulates. As shown in Figure 7, burning polystyrene releases a significantly larger amount of smoke then does burning kerosene. The introduction of smoke at a faster rate within the compartment begins to deplete the amount of oxygen available to the fire (Figure 8) as a result of filter plugging. The polystyrene continues to burn until ~806 seconds. At this time, all the combustible materials within the fire compartment have been consumed, and the system begins to recover to a new steady-state operating condition.

Material Transport. The combination of the smoke release rate of the burning polystyrene material and a fire compartment exhaust filter plugging factor of 20.1/kg significantly influences the system's response to the fire. The system flow to and from the fire compartment is reduced gradually (after ~300 seconds) as the compartment exhaust filter (branch 14, filter no. 2) plugs with the smoke particulate. As the filter plugs, the polystyrene burns at a constant burning rate, thereby maintaining a constant fire compartment pressure. Even though the intake flows to the compartment are being reduced, a sufficient oxygen concentration level (>15%) is available to sustain a constant fuel burning rate (Figure 8). Figures 9 and 10 show the smoke mass-flow rate and mass accumulation on the compartment exhaust filter and at several locations near the facility exit. The smoke particulate release rates indicate an increasing accumulation rate in branch 14. After ~300 seconds, the flow rate in branch 14 decreases with time (Figure 10); however, the smoke concentration in the hot layer (Figure 7) steadily increases. The net result is the mass-flow rate profile in Figure 9.

The release mechanism for radioactive material is the burning of a contaminated combustible solid (polystyrene). Because the burning order for the polystyrene is 2 and the kerosene was assumed to be uncontaminated, radioactive material is not transported through the system until the polystyrene has been ignited. The radioactive particulate mass-flow rate and mass accumulations for the 20-mm particle size distribution are shown in Figures 11 and 12. The radioactive particulate results are similar to the smoke particulate results and can be explained similarly.

After the fire is terminated (~806 seconds), the smoke and radioactive particulate flow rates begin to decrease as the particulate concentrations in the hot layer decrease and as the compartment exhaust flow decreases. The system gradually will establish new steady-state operating conditions based on the consequences of the fire. By ~1000 seconds, more than 1.21 lbm (0.55 kg) of smoke particulate has been deposited on the fire compartment exhaust filter. To the system, the particulate mass on the filter represents an increase in resistance for branch 14. The system will readjust and establish new steady-state conditions based on the increase in flow path resistance for branch 14.

SUMMARY

We have described a computer code called FIRAC that can be used to model smoke generation and movement throughout a nuclear facility. The material transport theory used in the code was described in detail, and the code was applied to an example problem to illustrate its modeling capability. The facility contained multiple blowers, compartments, dampers, and filter systems, and the fire scenario involved two materials (kerosene and polystyrene), with the polystyrene contaminated with a radioactive mixedoxide powder. The example problem illustrated sequential burning of material, filter plugging, and movement of 11 radioactive particle sizes and smoke particulate. Graphical output has been used to help interpret the results of this calculation.

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