Fire Models for Assessment of Nuclear Power Plant Fires*

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Abstract

This paper reviews the state-of-the-art in available fire models for the assessment of nuclear power plant fires. The advantages and disadvantages of three basic types of fire models (zone, field, and control volume) and Sandia's experience with these models will be discussed. It is shown that the type of fire model selected to solve a particular problem should be based on the information that is required. Areas of concern which relate to all nuclear power plant fire models are identified.

Introduction

Fires in nuclear power plants can initiate accidents and threaten plant safety systems. The risk which fires pose to nuclear power plants can be assessed using a fire model. Fire models are used to simulate the adverse environments associated with a fire and the effects of these environments on plant components. When coupled with information on the environmental thresholds at which components are damaged or fail, fire models can be used to predict whether or not a safety-related component will be rendered inoperative by a fire, and the length of time and the size and location of the fire which are necessary to do so. These results can then be used to assess the vulnerability of plant safety systems to postulated fire events.

Types of Fire Models

There are a variety of fire models in existence with a broad range of complexity and applicability. The three basic types of fire models, in increasing order of complexity are: zone models, control volume models, and field models.

The simplest fire models are zone models that divide the fire environment into four regions: flame, plume, hot gas layer, and ambient (Figure 1). Empirical correlations and simple heat transfer models are employed to determine the thermal environment in each zone and interaction between the zones. The response of an object (e.g., a cable tray) to the environment in a

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particular zone can then be determined. Examples of zone models which have been used to simulate fires in nuclear power plants include COMPBRN (UCLA) [1] The Harvard Fire Code (Harvard University) [2], and MAGIC (Electricite de France, France) [3].

Because of their simple nature, zone models typically run quickly on a computer (even on a personal computer) and require comparatively little computer memory. Thus, they are usually inexpensive to use. For this reason they are typically employed in nuclear power plant fire risk analyses where a large number of different scenarios (on the order of hundreds) must be investigated.

There are several disadvantages to using a zone model. First, they are based on empirical correlations that have a limited range of validity. Because of this, they have difficulty handling a wide variety of possible fire scenarios and in some cases will yield erroneous results or they will not run at all. For example, hot gas layer temperature is a function of many parameters, including room height, ceiling area, heat release rate, doorway height, and forced ventilation rate. Correlations that adequately predict hot gas layer temperature over the wide range of these parameters commonly encountered in a nuclear power plant are currently not available.

A second disadvantage of a zone model is that it typically does not provide local information within a zone such as the temperature stratification within the hot gas layer. This local information can be critical for some problems, such as determining the length of time before a fusible link melts in a ceiling-mounted fire suppression sprinkler head. For this particular problem, failure to account for temperature stratification within the hot gas layer will lead to lower hot gas layer temperatures (due to averaging) and a prediction of longer time to melt the link. A final disadvantage to fire zone models is the large number of input parameters which the user must prescribe to model even a simple fire scenario. These result from the many correlations in the zone model. The choice of some critical parameters requires considerable engineering judgement and can lead to erroneous results if not properly selected. Thus, the user's experience in modeling fires can be a significant factor in the results obtained.

Field models are at the opposite end of the spectrum in complexity from zone models. These models solve a discretized form of the governing differential equations of mass, heat, and momentum transfer at a number of points throughout the entire room or enclosure (Figure 2). Thus, they provide detailed information about the fire environment such as the temperature stratification and velocity profile within the hot gas layer. Since field models solve the governing physical equations, very few empirical correlations are necessary. They can be used to accurately predict fire environments over a much broader range of scenarios than possible with a typical zone model. For example, the influence of room height, ceiling area, heat release rate, doorway height, and forced ventilation rate on the local hot gas layer temperature are all inherent in the equations (and boundary conditions) which the field model solves. Examples of field models which have been used to

simulate fires in nuclear power plants include SAFFIRE (CHAM of North America) [4], HMS (Los Alamos National Laboratory) [5], and the Notre Dame Fire Code (University of Notre Dame) [6].

There are two main disadvantages usually associated with a fire field model. First, solution of the governing equations at a large number of points typically requires a large amount of computer time and memory, even on the fastest computers. For example, several hours of computer time on a CRAY XMP computer would not be uncommon. Therefore, the use of a fire field model to assess all the different scenarios which must be considered in a fire risk analysis would be prohibitively expensive.

The second disadvantage of a field model is that computer input requirements are typically more complex than for a zone model, and the model requires generation of a finite difference grid along with appropriate boundary conditions. Frequently, the user must be familiar with numerical methods to make sure the computer code is used correctly. However, the state-of-the-art is progressing to the point where the detailed model construction is often transparent to the user, and relatively few input parameters are required. Thus, in some instances, state-of-the-art fire field models may actually require less user knowledge than zone models.

The fire zone models and field models available to date are typically limited to prediction of the fire environment in a single room. In the case of fire zone models, the difficulty associated with development of correlations for room-to-room transport of mass, heat, and momentum that are valid over a broad range of possible scenarios effectively limits their application to a single room. On the other hand, fire field models can theoretically simulate room-to-room transport. In practice, however, the large number of grid points and associated computer time and memory necessary for an accurate calculation makes the application of field models to more than one room impractical for most situations. There is, however, a third type of fire model which is capable (in a practical sense) of modeling more than one room at a time: the control volume model. Control volume models (or lumped parameter models) are intermediate in complexity between zone and field models. Here, the region of interest is divided into discrete volumes which are typically smaller than the zones of a fire zone model but larger than the grid spacing employed in a fire field model (Figure 3). Mass, heat, and momentum transfer occur between different control volumes through a series of pipelines or pathways for transport. The governing differential equations are integrated over each control volume, and additional models are required to accommodate the transport between control volumes. Because the control volumes can be made relatively large in theory (e.g., 5 to 10 control volumes in a single room), many interconnected rooms can be modeled. Thus, the transport of heat and smoke through an entire industrial-sized building (e.g., a turbine building or containment building) can be addressed. An additional advantage is that engineered safety features models (e.g., fire suppression sprinklers) can be incorporated into a control volume model. Examples of control volume models which have been used to simulate fires in nuclear power plants include RALOC (GRS, Germany) [7] and HECTR (Sandia National Laboratories) [8].

Because a control volume model is intermediate between a zone and field model, it shares some of the disadvantages of both. As with a zone model, there are many input parameters requiring engineering judgement. One of the most critical is the choice of control volume size. For example, if an insufficient number of control volumes is selected to model a narrow passageway, a control volume model can predict a flow field which is completely erroneous. Conversely, as the number of control volumes is increased to improve accuracy and provide additional local detail, the required computational time and storage begin to approach that of a field model calculation.

Sandia Experience

Sandia's experience with the application of the three types of fire models to the simulation of nuclear power plant fires will now be discussed. Two different zone models have been used at Sandia: the Harvard Fire Code and COMPBRN.

The Harvard Fire Code was originally developed to model fires in homes and offices as opposed to fires in large industrial buildings. It is typically regarded as incorporating good physical models with a stable numerical method, but its application to large-scale enclosures representative of nuclear power plant buildings and rooms has been questioned.

Sandia has used the Harvard Fire Code zone model to assess the 20-foot separation criterion for redundant safety systems in nuclear power plants [9] as prescribed in the Code of Federal Regulations. In these calculations, a fire in a 7.6 m x 4.3 m x 3 m enclosure with an open doorway and no forced ventilation was simulated. Of particular interest in the calculations was the predicted hot gas layer temperature, as this parameter was directly related to failure of redundant trains of electrical cable. Reasonable agreement with experiment was obtained (Figure 4), but only after some input parameters had been set to values outside the normally accepted range. For example, it was necessary to increase the heat of combustion of the heptane fuel source by 50% over its normally accepted value to obtain agreement. In general, the code was found to be inadequate to calculate the effects of room geometry, fuel load, fuel location, and ventilation conditions on the thermal environment for the test conditions which were simulated.

The COMPBRN III Code is a zone model which has been developed specifically for simulation of nuclear power plant fires. It incorporates correlations and models for large scale fires and enclosures along with a relatively simple numerical method which is sometimes prone to instabilities.

Initial attempts to use COMPBRN III at Sandia for nuclear power plant fire risk assessment resulted in the observation of several errors and inconsistencies in the code [10]. In order to obtain physically meaningful results, several modifications had to be made to COMPBRN III [11]. These included changes to the forced ventilation hot gas layer temperature

algorithm, flame heat transfer model, thermal feedback model, and thermal radiation viewfactor model (Figure 5). This modified version of COMPBRN III has since been used in several probabilistic risk assessments [12, 13, 14]. The modifications made to the code have been shown to impact the assessment of fire risk by a factor of up to twenty.

Sandia's experience with publically available, non-proprietary fire field models has been with the University of Notre Dame fire code. This code uses a three-dimensional finite difference model to solve for the local flow and temperature field induced by a fire. An empirical turbulence model and wall response models are included in the code. Surface and gas radiation effects can also be included, as well as forced ventilation effects. This code is not user oriented and it requires detailed input that is best handled by the code developers.

The University of Notre Dame fire code has been used at Sandia to simulate fires in a nuclear power plant control room with forced ventilation and thermal radiation effects. Complex three-dimensional temperature and flow fields involving the interaction of forced and natural convective effects and surface radiation were calculated (Figure 6). The modeling of the thermal response of the enclosure walls was found to be an important factor, as the walls can absorb 80-90% of the energy released by the fire. Thus, the convective heat transfer coefficient or wall turbulence model is critical to proper modeling of the fire environment. Of the 80-90% of the fire energy deposited in the walls, approximately 30% was deposited via thermal radiation, indicating that thermal radiation cannot be neglected in the simulation of large-scale enclosure fires. While this code has been useful in yielding insights into the physics of fires in large, complex enclosures, it is not readily useable by the fire community at large and remains in a developmental stage.

Sandia's only experience with control volume fire models is limited to the HECTR code. HECTR was developed to model hydrogen transport and combustion in a reactor containment building. Many input parameters which require engineering judgement are necessary for proper use of this code. There can also be significant sensitivity to the size of the control volumes selected as well as to their placement throughout the building [15]. HECTR has only been used to model hydrogen combustion in containment buildings, and it is, therefore, not known how well it would model non-hydrogen fires.

Areas of Common Concern

There are three areas of concern which apply to all fire codes used to simulate fires in nuclear power plants. First, all codes either predict or rely on the user to input the fire source strength (energy release rate versus time). This can be a complex function of the fuel type and geometry as well as the local thermal environment. For nuclear power plants, the most common fuel source is electrical cable insulation. Electrical cable insulation fires are not well understood and the existing database is quite limited. Thus,

there is significant uncertainty associated with the fire source strength characterization which drives the problem. A fire model should be used with this point in mind.

A second concern surrounds the lack of data on damage and failure thresholds for critical components. Any appropriate fire model requires accurate damage and failure thresholds for the components of concern. Electrical cables are often the components of interest because cables from physically separated redundant equipment have a tendency to be routed together at several locations in the plant (e.g., control room and cable spreading room). The database on cable damage and failure thresholds is severely limited and some of the available data has been misinterpreted [16]. More work is necessary to provide appropriate criteria for assessing the damage and failure thresholds of electrical cables. Additionally, only thermal damage mechanisms (and these to a quite limited extent) have been investigated to date.

Finally, fire modeling of nuclear power plant fires is hampered by a lack of experimental data for validation purposes. The available data is quite limited, and most of it is not representative of the large enclosures, cable fuel sources, and high forced ventilation conditions typically found in nuclear power plants. Of note is a series of tests conducted by Sandia [17] (under sponsorship by the United States Nuclear Regulatory Commission) specifically for use in the benchmarking of nuclear power plant fire models. The series of 25 tests was conducted in a large (18.3 m x 12.2 m x 6.1 m) enclosure under typical nuclear power plant forced ventilation conditions (1-12 room air changes per hour) with simple fuel sources as well as cable-loaded electrical panels. While extensive data were recorded, very little of it has been processed to date due to the cutting off of funds for the project. Reduction of these data would greatly aid in the validation of a fuel model for assessment of nuclear power plant fires.

Summary

In summary, the type of fire model selected to solve a particular problem should be based on the information that is required. If detailed fire environment information is required, a fire field model is necessary. If a very large number of simulated fire scenarios must be assessed for a fire risk assessment, then a fire zone model is appropriate. Finally, if multi-room transport of combustion products is of interest, a control volume model is the only practical approach. Sandia's experience with application of each of the different types of fire models to nuclear power plant fires indicates that each type of model has advantages and disadvantages. All of the models show room for improvement, as a significant amount of engineering judgement is necessary to obtain acceptable results. A common concern in the application of any fire model is the lack of experimental data for model inputs such as fire source strength characterization and component damage and failure thresholds. Also, the lack of experimental fire data appropriate for nuclear power plant hampers fire code validation efforts.

References

1. V. Ho, N. O. Siu, and G. Apostolakis, COMPBRN III -- A Computer Code for Modeling Compartment Fires, University of California, UCLA-ENG-8524, November 1985.
2. H. E. Miller and H. W. Emmons, Documentation for CFC V, The Fifth Harvard Computer Fire Code, Home Fire Project Technical Report No. 45, Harvard University, Division of Applied Sciences, October 1981.
3. M. Mosse and F. X. Rongere, "Use of Computer Code for Layed Cable Fire Test Analysis," Proceedings on Operability of Nuclear Power Systems in Normal and Adverse Environments, p. 572, Albuquerque, NM, September 29, 1986.
4. J. Usher, J. Boccio, A. Singhal, and L. Tam, "Fire Environment Determination in the La Salle NPP Control Room" Proceedings on Operability of Nuclear Power Plants in Normal and Adverse Environments, p. 556, Albuquerque, NM, September 28, 1986.
5. J. R. Travis, BWR Standard Problem -- Mark III Hydrogen Burn Base Case B, C, and 3, Los Alamos National Laboratory, Los Alamos, NM, LA-UR-84-1305, 1984.
6. V. K. Liu and K. T. Yang, UNSAFE -- II: A Computer Code for Buoyant Turbulent Flow in an Enclosure with Thermal Radiation, University of Notre Dame, Notre Dame, IN, TR-79002-78-3, July 15, 1978.
7. H. W. Brenig and B. Schwinges, "The Calculation of Fire Effects in the Containment of Nuclear Power Plants," Proceedings on Operability of Nuclear Power Plants in Normal and Adverse Environments, p. 564, Albuquerque, NM, September 29, 1986.
8. S. E. Dingman, A. L. Camp, C. C. Wong, D. B. King, and R. D. Gasser, HECTR Version 1.5 User's Manual, Sandia National Laboratories, SAND86-0101, NUREG/CR-4507, April 1986.
9. D. D. Cline, W. A. von Riesemann, and J. M. Chavez, Investigation of Twenty-Foot Separation Distance as a Fire Protection Method as Specified in 10 CFR 50, Appendix R, Sandia National Laboratories, Albuquerque, NM, SAND83-0306, NUREG/CR-3192, October 1983.
10. J. A. Lambright, S. P. Nowlen, V. F. Nicolette, and M. P. Bohn, Fire Risk Scoping Study: Investigation of Nuclear Power Plant Fire Risk, Including Previously Unaddressed Issues, Sandia National Laboratories, Albuquerque, NM, SAND88-0177, NUREG/CR-5088, January 1989.
11. V. F. Nicolette, S. P. Nowlen, and J. A. Lambright, "'Observations Concerning the COMPBRN III Fire Growth Code,'" Proceedings of International Topical Meeting on Probability, Reliability, and Safety Assessment: PSA '89, Volume 2, p. 1279, Pittsburgh, PA, April 2-7, 1989.

12. J. A. Lambright and M. P. Bohn, Analysis of Core Damage Frequency: Peach Bottom Unit II External Events, NUREG/CR-4550, Vol. 4, Part 4, draft under review by U.S.N.R.C., January 1989.
13. J. A. Lambright and M. P. Bohn, Analysis of Core Damage Frequency Due to External Events at the DOE N-Reactor, Sandia National Laboratories, Albuquerque, NM, SAND89-1147, March 1989.
14. J. A. Lambright, D. A. Brosseau, M. P. Bohn, and S. L. Daniel, Analysis of Core Damage Frequency Due to Fire at the Savannah River K-Reactor, Sandia National Laboratories, Albuquerque, NM, SAND89-1786, July 1989.
15. D. B. King, V. F. Nicolette, V. J. Dandini, and B. L. Spletzer, Safety-Related Equipment Survival in Hydrogen Burns in Large Dry PWR Containment Buildings, Sandia National Laboratories, Albuquerque, NM, SAND86-2280, NUREG/CR-4763, March 1988.
16. V. F. Nicolette and S. P. Nowlen, "A Critical Look at Nuclear Qualified Electrical Cable Insulation Ignition and Damage Thresholds," to be presented at the International Conference on Operability of Nuclear Systems in Normal and Adverse Environments (OPERA '89), Lyon, France, September 18-22, 1989.
17. S. P. Nowlen, Enclosure Environment Characterization Testing for the Base Line Validation of Computer Fire Simulation Codes, Sandia National Laboratories, Albuquerque, NM, SAND86-1296, NUREG/CR-4681, March 1987.

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Figure Captions

- Figure 1. Zone Model Approach
- Figure 2. Field Model Approach
- Figure 3. Control Volume Approach
- Figure 4. Harvard Fire Code Hot Gas Layer Temperature [9].
- Figure 5. Effect of Thermal Radiation Modifications to COMPBRN III on Cable Tray Temperatures [11].
- Figure 6. Isotherms Calculated Using the Notre Dame Fire Code to Simulate a Control Room Fire.

Figure 1.

Figure 2.

Figure 3.

Figure 4.

Figure 5.

a) time = 2 min

b) time = 4 min

c) time = 6 min

d) time = 8 min

Figure 6.

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