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MODELING REQUIREMENTS FOR FULL-SCOPE REACTOR SIMULATORS OF FISSION-PRODUCT TRANSPORT DURING SEVERE ACCIDENTS (U)

by

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DISCLAIMER

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ABSTRACT

This paper describes the needs and requirements to properly and efficiently model fission product transport on full scope reactor simulators. Current LWR simulators can be easily adapted to model severe accident phenomena and the transport of radionuclides. Once adapted these simulators can be used as a training tool during operator training exercises for training on severe accident guidelines, for training on containment venting procedures, or as a training tool during site wide emergency training exercises.

INTRODUCTION

Severe Accident Guidelines are being developed in the nuclear industry as part of an overall accident management system to mitigate beyond design basis accidents. An essential ingredient of an accident management team is the development and use of these guidelines with due consideration a.) for man-machine interfaces, b.) for technical basis of the guidelines, c.) and for the use of simulators to train in the concepts of the severe accident guidelines.

Currently, full scope reactor simulators are available in Europe to train operations staff on beyond design basis severe accident phenomena and to develop more refined severe accident guidelines. Currently, these simulators lack the ability to track the release and transport of radioactive materials.

Radioactive materials can be released during some postulated severe accidents. These radioactive materials are deposited throughout the primary system and containment of the reactor. To reduce the radiation dose to the general public and to the operations staff from airborne materials during these postulated accidents, filtered containment vents are being added to some European nuclear reactors and hardened wetwell vent lines to some US BWR plants.

The addition of filtered vented containment systems to European nuclear reactors and the hardened vent systems that are being backfitted to some BWR plants requires the development of venting procedures. Proper operations training on these procedures is required to guarantee the effectiveness of these venting backfits. Full scope simulation training on the behavior of radionuclide transport during beyond design basis accidents is required to minimize offsite doses during containment venting procedures. Emergency operations staff need to be aware of severe accident phenomena to reduce off site doses during venting.

Severe accident modeling and analysis has achieved a state of maturity in the commercial nuclear sector. Several commercial, national and international government funded programs have led to an overall understanding of the important phenomena, and an ability to model severe accident progression during some postulated initial failures of reactor components. The cause and effect assessment and the interaction of important phenomena are better understood as a result of these programs. Currently information gained as a result of these programs is being transferred to operations staff through the individual plant evaluations being performed in the US and by the operations training staff at some European reactors. Severe Accident Guidelines to manage beyond design basis severe accidents are being formulated and reviewed to terminate and/or reduce the radioactive source term to the environment.

There still exists uncertainty over the accident progression paths in these types of beyond design basis accidents. The initiating conditions and the progression of the accident are being debated. Severe accident guidelines then must rely on understanding of the severe accident phenomena and relating the phenomena to existing instrumentation in the reactor's control room. Severe accident guidelines will be based on understanding the phenomena control room instrumentation relationship and how the various engineered safeguards can be used to terminate the accident or reduce the magnitude of the source term. The source term reduction is accomplished by causing more radioactive materials to be deposited in the reactor's containment structures. Severe accident guidelines should then be only used by knowledgeable staff who have a basic understanding of the severe accident phenomena and are qualified on the reactor control room instrumentation. In the opinion of the authors the normal operations staff do not need to understand these guidelines. The normal operations staff must only be able to work closely with and have confidence in a qualified staff member. This qualified individual or individuals must be able to interpret the control room instrumentation in terms of severe accident phenomena and must be able to supply the necessary control inputs to terminate the accident or reduce the source term to the environment.

Human factor requirements along with the need to understand and interpret control room instrumentation during a crisis situation requires that appropriate staff be trained on severe accident guidelines and phenomena. This training can be supplied in part by upgrading the reactor simulator to model the severe accident phenomena as has been done in Sweden. Similar severe accident simulator upgrades are currently being assessed for their feasibility in the commercial and noncommercial US nuclear sectors.

The severe accident simulator upgrades require the addition of simple simulation models of the phenomena that control the release and transport of radioactive materials to the simulator software. The severe accident and fission product release and transport modeling additions are simple modifications to the current simulator's software. The present day simulator thermohydraulic software models are currently better than those used in some of the state of the art severe accident software. The upgrades that are needed to the simulator software are in the areas of release and transport of radioactive fission products and structural materials from fuel and during molten core concrete attack. Additions also include the need to model pool scrubbing of fission products, filtered vented systems, the effects of dose reduction from engineered safeguards, along with the deposition and revaporization of fission product materials. The specific needs of these models are based on understanding effects only. Detailed mechanistic models are not required, only cause and effect modeling is necessary.

Models and Modeling Requirements

Transport

A severe accident in current generation nuclear facilities is the result of a low probability sequence of events. Severe accidents are not expected to occur in the lifetime of a particular facility. Severe accidents have certain characteristic signatures which can be identified and used to mitigate the offsite releases of radioactive materials to the environment.

Some of the the severe accident signatures can be introduced by first considering a generic type of severe accident. A severe accident occurs from the loss of cooling to the reactor's fuel. The fuel overheats and melts releasing volatile fission products to the primary coolant system. Typical species are cesium, iodine, tellurium. noble gases and structural inerts. These vaporized materials are transported as aerosols or as gases. A majority of the substances are deposited in the primary coolant system of the reactor. The decay heat associated with these deposited fission products eventually heats the primary coolant systems structures to a temperature that allows some of the deposited materials to revaporize. These materials are then available to be transported from the primary coolant system to the containment structures of the reactor.

The molten fuel material in the reactor vessel eventually fails the vessel. This allows molten material to be ejected to the below grade areas of the containment building. The high temperature molten fuel will attack and erode the concrete of the reactor's building's containment. During this process of core-concrete attack, nonvolatile fission products such as lanthanum and other rare earths are released as aerosols to the containment building. The pressure of the containment building increases during this time period as a result of noncondensible gas generation and steam production. The containment building wall's may crack and as a result the containment begins to vent steam and noncondensible gases to the environment. Any fission products in the containment's atmosphere are available at this time to be swept with the leaking gas to the environment.

As is seen from the above brief description, a major portion of the radioactive mass is transported as an aerosol in severe accidents. Thus, accurate modeling of fission product aerosol behavior is an important aspect in predicting the consequences of a core melting accident. The modeling of fission product transport as an aerosol has evolved along two separate paths. Detailed separate effects computer calculations which directly solve the integro-differential equation of aerosol agglomeration and deposition have been developed. These models are typically very computer time intensive and require large amounts of memory. Some of these models have been utilized in detailed semi-mechanistic severe accident software. The second approach that has been taken is that of developing a set of aerosol deposition correlations that are based on asymptotic solutions of the aerosol agglomeration and deposition equations. This approach has been used extensively and has been widely accepted as a alternative to detailed mechanistic modeling of aerosol growth and deposition. The approach is novel and is easily adapted to the reactor simulator environment.

The aerosol correlation approach was developed from a review of the available data on aerosol coagulation and decay. These experiments have been carried out in large and small vessels with different materials and initial aerosol cloud densities. The majority of the experiments have been conducted with dry aerosols, as opposed to hygroscopic aerosols in a wet environment and considerable data has been accumulated under conditions where the principle means of removal is sedimentation with agglomeration due to Brownian and gravational movement.

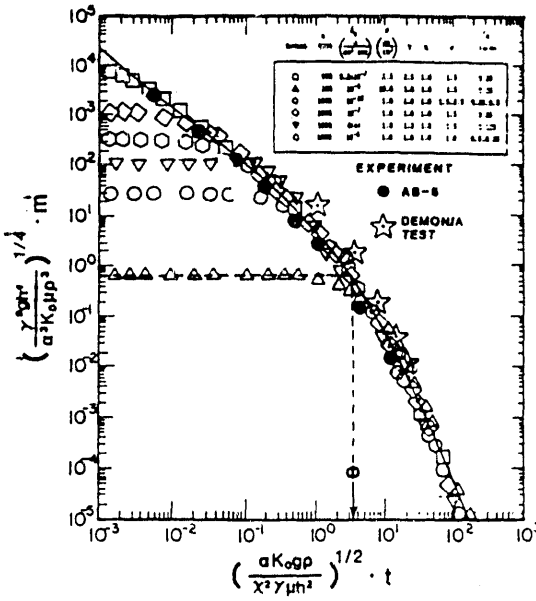

Fig. 1 Aerosol Similitude (Epstein 1986)

From figure 1, it is seen that the decay of the aerosol is well represented by a single asymptotic curve that is independent of the initial conditions of the aerosols. This asymptotic condition of aerosol similitude is achieved because sufficient particle coagulation takes place so that the distributions become independent of the initial distributions of particle sizes. As a consequence of this asymptotic behavior, the significant dimensionless variables that characterize aerosol behavior have been identified by reference to the basic integro-differential equation of aerosol coagulation. These nondimensional parameters can be used to model the transport and deposition of radioactive materials in a simulator training environment.

The movement of the aerosols and radioactive gases between volumes in the simulator can rely on the thermohydraulic models of the simulator. The technology available in todays simulators is superior to some of the themohydraulic models used in some of the best estimate severe accident codes. This greatly simplifies modeling requirements and changes to the simulators software.

Fission Product Release

Fission product release from the fuel occurs in two locations. These locations are in vessel during the time the fuel is heating up to melting and the second location is from core concrete attack. Release during the in-vessel phase of the accident can be modeled in the same way as it is being modeled in the detailed severe accident models. These codes use a correlation of experimental data that is a function of the inventory of the species and the temperature of the fuel. For some elements, like tellurium, the release may be coupled to the amount of cladding oxidation of the fuel. The models used are very simple and almost always consists of only one line of FORTRAN to determine the release rate.

Modeling of fission product release from core-concrete attack is an area where some effort must be expended to develop a fast running simulation model that properly models the release rate of the rare earths and the nonradioactive concrete species. The modeling approach may be one of choosing one species to represent the rare earths' contribution to the source term, with an inert material to model the concrete species. It is extremely important to model the inert materials in concrete since they serve to reduce the source term to the environment by increasing the fallout rate of the radioactive materials suspended in the containment's atmosphere.

Radioactive Material Deposition

The deposition of radioactive materials occurs by both natural phenomena, and by engineered safeguards. Natural phenomena cause aerosolized materials to be deposited by gravational sedimentation, thermophoresis, inertial impaction and by Stefan flows. These mechanisms can be modeled on the simulator in much the same way as is done in the available severe accident codes. Aerosolized materials can make use of the aerosol correlations. The deposition of aerosols by Stefan flows can be modeled by the use of the steam condensation rates from the thermohydraulic models of the simulator software.

The deposition of condensable radioactive gases occurs either on, surfaces of the primary system, containment or aerosolized materials. The mass transfer correlations available to model these effects are well known and supported by experimental data. The deposition of condensable gases is then easily modeled with only the uncertainty in the correlations to be of concern.

Engineered safeguards are very important in reducing the source term to the environment. The effects of sprays and flooding on decontaminating fission products from gases is also well known and understood. There exists several simple models that can be used in a simulator environment to model the effects of containment sprays that are supported by data. The decontamination of aerosols and vapors by water pools has been modeled well by several approaches. These approaches appear at this point to be too complicated and CPU extensive to use on a real time training simulator. Recent developments have shown that it is possible to construct efficient and accurate pool scrubbing models. Model developments based on this approach would be required to produce a software package that would function in a real time environment on a training simulator. Other engineered safeguards can also be adequately modeled on a real time bases. These other engineered safeguards are such items as fan coolers, filters, and filtered containment vents.

Fission Product Species

The modeling of the environmental releases from the plant requires that several radioactive species be tracked from the point they are released from the fuel to when they are deposited. The number of materials should be kept to as few as possible to reduce running time of the software. The minimum species to be considered are: Iodine, cesium, tellurium, a rare earth and the noble gases. Due to the strong effect of source term reduction from the structural materials in the fuels cladding and from the concrete an inert aerosol material also needs to be considered.

Benchmarking & Validation

The simulator software, as modified to handle severe accident considerations, must be validated to guarantee that the modeling additions have not altered both the design basis event modeling or severe accident effects. Integral software validation can be accomplished by comparison to other severe accident software. Development of new simulator models, as might be required for pool scrubbing and fission product release from core concrete attack, would also require validation of the model to the experimental data base and comparison of the model to separate effects computer software designed to model these phenomena.

Summary & Conclusions

Severe Accident Guidelines are being developed in the nuclear industry as part of an overall accident management system to mitigate beyond design basis severe accidents. An essential ingredient of an accident management team is the development and use of these guidelines with due consideration for:

a.) man-machine interfaces,
b.) technical basis of the guidelines,
c.) the use of simulators to train in the concepts of the severe accident guidelines.

This paper has described the needs and requirements to properly and efficiently model fission product transport on full scope reactor simulators. It is believed that current LWR simulators can be easily adapted to model severe accident phenomena, including the modeling of the transport of radionuclides in a real time training environment. Once adapted, these simulators can be used as a training tool during operator training exercises on venting procedures, for training on severe accident guidelines, or as a training tool during site wide emergency training exercises.

Two areas of simulation software model development may be required to efficiently model fission product transport on full scope simulators. These two developmental areas are:

a.) a fast running model for fission product release from core concrete attack
b.) a fast running simulation of the deposition of aerosols and condensable gases in water pools.

Neither of the two above items are an impediment to the development of a real time severe accident training simulator.

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