Investigation of Thermal Response of Radioactive Material Transportation Casks to Open Pool Fire Test Simulations

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Abstract

Hazards in the transportation industry from truck and rail shipments can result in accidents involving fire. Fire is a concern in the transportation of radioactive material, specifically, that transportation accidents can cause ignition of flammable materials that could fully engulf a transportation package, increasing the potential for release of radioactive material. Title 10 of the Code of Federal Regulations Part 71 section 73(c)(4), (10 CFR 71.73(c)(4)) delineates that transportation packages designed to ship radioactive material and that are subject to accident conditions must be designed to resist a consuming fire of a duration of 30 minutes in order to protect the contents of the package and prevent release of radioactive material to the environment. Testing and analysis of the performance of a transportation package design is therefore essential to ensuring that a package can survive a fire accident and will not exceed radioactivity release limits established by the NRC. Staff of the NRC Spent Fuel Project Office visited Sandia National Labs in Albuquerque, New Mexico, to observe an open pool fire test of a large steel calorimeter, similar in size to a typical transportation cask for a single assembly of spent nuclear fuel. The test was conducted to verify the Cask Analysis Fire Environment (CAFE) computer code being developed by Sandia for the analysis of radioactive material transportation package thermal performance. The Sandia test was conducted in accordance with the thermal requirements outlined in 10 CFR 71.73. This paper will discuss the staff's plans to use the CAFE code, in conjunction with the finite element analysis program ANSYS, to conduct several investigations of the thermal response of shipping cask designs to open pool fire testing. Several variables for testing of casks will be investigated in the staff's efforts.

Introduction

Hazards in the transportation industry from truck and rail shipments can result in accidents involving fire. Fire is a specific concern in the transportation of radioactive material, as an accident could cause ignition of flammable materials that could fully engulf a transportation container, possibly increasing the potential for a release of radioactive material.

The staff of the Spent Fuel Project Office (SFPO), in the Office of Nuclear Material Safety and Safeguards (NMSS) plans to model a generic transportation cask engulfed in a fire under several different orientations in support of ongoing risk assessments and risk informing initiatives. Transportation containers (or casks) are commonly fire tested in either a horizontal or vertical orientation, depending on container size. The staff believes that further investigation of transportation container orientation in open pool fires, using the latest analytical techniques, could either bolster or negate existing test practices. For example, during a fire test, the most vulnerable portion of a container using a bolted lid closure mechanism is often the lid seal region. Changing the orientation of the container, as required by realistic risk studies, may lead to different temperature responses . The staff will investigate this issue using a coupled analytical approach including the Cask Analysis Fire Environment (CAFE) code and the ANSYS finite element analysis (FEA) program as analytic tools. The long term benefits of this study may include shorter review time for the technical reviewer, risk-informed regulatory decisions, and a significant cost savings for cask vendors who elect to use similar analytical techniques over conventional full scale fire tests.

Background

The U.S. Nuclear Regulatory Commission (NRC) reviews and certifies designs for radioactive material transportation containers. The reviews conducted by the NRC includes an analysis of the performance of a container when subject to a "regulatory" fire, as defined in Title 10 of the *Code of Federal Regulations* Part 71 section 73(c)(4), (10 CFR 71.73(c)(4)) and in International Atomic Energy Agency (IAEA) Safety Series No.6 (SS-6). Federal and international regulations require that transportation packages designed to ship Type "B" quantities of radioactive material (defined in 10 CFR 71.4) be designed to resist a consuming fire accident in order to protect the contents of the package, maintain subcriticality and shielding, and prevent a release of radioactive material to the environment.

The staff reviews thermal analyses conducted by companies applying for Certificates of Compliance (CoCs) for their package designs. Applicants for CoCs often utilize FEA or other analytic methods to demonstrate that their designs will meet NRC regulations. FEA is one of the most cost effective analytic methods, however; in order to utilize realistic FEA modeling techniques with confidence, the analysis software used must be validated against data gathered from experiments, such as fire tests.

Physical fire testing of full scale design prototypes of spent fuel transportation casks and other large Type B radioactive materials transportation containers is generally not done, as testing is difficult and costly, however; physical testing can conclusively demonstrate that a container has met the regulations, as well as provide valuable information towards validation of analytical methods.

Analytical techniques, such as CFD and FEA, have matured to a point where a high degree of confidence can be afforded to results gained by these techniques, if they are applied properly. Analysis codes are now more capable than ever in their ability to capture the turbulent nature of the fire environment and can effectively model the different modes of heat transfer encountered in that environment.

New Tools in Fire Accident Analysis

Evaluating the thermal performance of a transportation package design is essential to ensuring that a package can survive a fire accident and will not release radioactive material in excess of the release limits established by the NRC. One of the tools recently developed by the Sandia National Laboratories (SNL) for predicting the response of transportation packages to open pool fire environments is the CAFE computer code.

The CAFE code is a computational fluid dynamics (CFD) code that simulates the environment of a pool fire by modeling the physics of the combustion of JP-4 or JP-8 jet fuel. When coupled to an FEA code, CAFE can be used to analyze the thermal response of specific transportation container designs to a fully engulfing fire environment.

How CAFE Works

The governing equations in the CAFE code are as follows: an energy equation is used for predicting the heat transfer and temperature field, momentum equations are used in order to predict the velocity field, and three scalar transport equations are utilized to track the flow of oxygen, fuel vapor, and turbulent kinetic energy.

CAFE uses a staggered, finite-difference grid for discretization of the above governing equations. Vector quantities, such as heat flux and momentum, are defined at grid or element interfaces, and scalar quantities, such as temperature and pressure, are defined at the element centers.

The CFD model developed in CAFE is coupled to an FEA code, via user developed subroutines, in order to apply thermal boundary conditions. Several steps are involved in the exchange of information between CAFE and the selected FEA code. First, surface temperature information at the start of the fire transient is provided from the finite element model (FEM) to CAFE, via a subroutine. CAFE then uses the temperature information to determine a heat-flux that is position dependent. As the fire transient progresses, the position dependent heat-flux generated by CAFE is then passed back to the FEM which uses the calculated position dependent heat-flux as a local boundary condition to predict the cask's internal thermal response.

The FEM then has time and position-dependent fire boundary conditions that vary given the physics of the particular fire environment. The heat-flux and temperature data passing between the CFD and FEA codes are user controlled. The user will set the criteria for how often the CAFE code updates the heat flux profile of the model. A detailed description of the CAFE/FEA interface can be found in Suo-Antilla *et al.*,1999.

Verification of the CAFE Code

The SFPO staff visited SNL in Albuquerque, New Mexico, to observe an open pool fire test of a large steel calorimeter, similar in size to a typical transportation cask for spent nuclear fuel. The 3800kg (8400lb) cylindrical carbon steel calorimeter was positioned above a large pool of JP-8 jet fuel floated over a water table. The calorimeter was located in accordance with the regulatory requirements described in 10CFR71, which require that the test specimen be 1 meter above the surface of the fuel pool and that the fuel pool extend 1 to 3 meters beyond the edge of the specimen. A quantity of fuel sufficient to maintain at least a 30 minute burn was pumped into the test pool. Time for fuel ignition was also considered when determining the required fuel inventory. The test area was surrounded by wind fences to minimize the effects of wind on the fire test.

The calorimeter was fitted with an internal array of thermocouples. Data from the thermocouples could then be used to back calculate the heat flux to the outer surface of the calorimeter using the Sandia One-Dimensional Direct and Inverse Thermal (SODDIT) code. The SODDIT code has been used effectively to solve inverse conduction problems in other heat transfer measurement experiments and uses temperature vs time data, material properties, and the dimensions of the conduction domain as input variables. The results from the SODDIT analysis are used to validate the heat flux predictions determined by the CAFE code.

Open Pool Fire Testing of Transportation Containers

Fire testing of transportation containers is traditionally conducted with the container in the fully horizontal or fully vertical (upright) position. Orientation is often based on the size of the container. The staff has not been able to find any data on fire testing of containers in orientations other than those mentioned above. Many current container designs have bolted lids and metallic or elastomeric O-ring seals. The seals are part of the containment boundary that prevent the release of radioactive materials and gasses from the interior of the container (a release assumes a container has failed, which is unlikely for welded containers). The seal areas can be critical to the containment integrity of transportation containers.

In a probabilistic risk analysis (PRA), the analyst may need to evaluate container performance for various container orientations. In addition, a container that has been damaged from a drop test sequence could also warrant a different orientation based on the location of the worst damage. A "worst-case" orientation for a given event could be other than the vertical or horizontal orientations.

Given the time and expense involved in fire testing transportation containers, the CAFE code would be a useful tool to investigate the performance of transportation containers in open pool fires, for various orientations, through analysis.

Recent and Proposed Uses of the CAFE Code

Recently the CAFE code has been coupled with the commercial finite-element code PATRAN/P-Thermal to investigate 2-dimensional temperature distributions on a large object engulfed in a open pool fire (Koski, *et. al.*, 2000). The CAFE code is currently undergoing optimization and a 3-dimensional version is being developed. The staff plans to use the 3-dimensional version of the CAFE code, along with the FEA code ANSYS, to support risk studies by performing realistic evaluations of transportation casks at various orientations in open pool fires.

The staff will couple the CAFE code to ANSYS by writing the necessary subroutines. The staff then plans to model a transportation cask in several different orientations consistent with the analyzed event. The benefit of using the CAFE code for this type of investigation is a significant cost savings over running actual open pool fire tests. The staff intends to use the results of this investigation to risk inform parts of 10 CFR Part 71, as well as to reduce the uncertainties in existing and ongoing risk studies

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