Thermal-Hydraulic Analyses of the TN-24P Cask Loaded With Consolidated and Unconsolidated Spent Nuclear Fuel

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INTRODUCTION

This paper presents the results of comparisons of COBRA-SFS (spent fuel storage) temperature predictions with experimental data from the TN-24P (Transnuclear) spent fuel storage cask loaded with unconsolidated and consolidated spent PWR fuel. Peak cladding temperature predictions using the COBRA-SFS code are compared with test data and predicted axial and radial temperature distributions are compared with measured temperature profiles. The pre-test accuracy of the COBRA-SFS code in predicting temperature distributions (before the experimental data were obtained) is discussed, along with the effect of post-test model improvements on temperature predictions. This paper also briefly describes the COBRA-SFS code, which is designed to accurately predict flow and temperature distributions in spent nuclear fuel storage and transportation systems.

CODE DESCRIPTION

The COBRA-SFS code (Rector et al. 1986; Rector et al. 1986; Lombardo et al. 1986; Rector and Michener 1988) is a lumped-parameter, finite-difference computer code that predicts flow and temperature distributions in spent fuel storage and transportation systems and fuel assemblies under mixed and/or natural convection conditions. The code provides finite-difference solutions to the equations governing conservation of mass, momentum, and energy for incompressible flows. Analyses are conducted using a subchannel approach in which the flow areas of assemblies or storage systems are divided transversely and axially into discrete control volumes. These conservation equations are then solved using an iterative implicit method. The energy equations for the coolant, rod cladding, fuel, and structural members are solved implicitly by iteration, simultaneously in a plane. Axial conduction in the structural members is considered. A nonparticipating media, gray body radiation heat transfer model allows two-dimensional radiant heat exchange among all solid members (including rod-rod) in a given enclosure and is iteratively coupled to the rod and wall energy equations.

TN-24P SPENT FUEL STORAGE CASK

The TN-24P spent fuel storage cask has a forged steel body for structural integrity and gamma shielding, and an enclosed solid neutron shield (Figure 1). The cask basket consists of stacked interlocking borated aluminum plates that form 24 fuel storage locations and provide structural support and criticality control. The cask accommodates unconsolidated PWR assemblies or consolidation canisters (rods from two assemblies to a consolidation canister) (Figure 2). Temperature instrumentation was located in selected fuel assembly/canister guide tubes and was attached to the cask basket, inner wall, and exterior surface. Detailed discussions of the cask design and instrumentation placements are provided in Creer et al. (1987) and McKinnon et al. (1989).

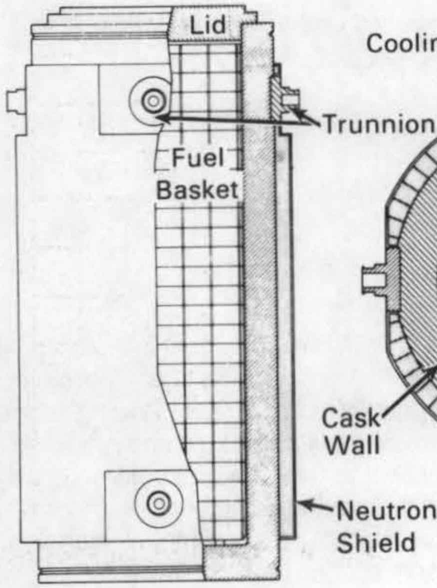

Figure 1. TN-24P Spent Fuel Storage Cask

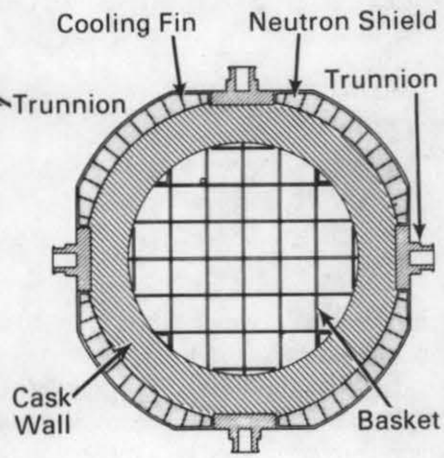

Figure 2. TN-24P Cask Cross Section

UNCONSOLIDATED FUEL MODEL AND ANALYSES

The TN-24P cask loaded with unconsolidated spent fuel was analyzed using two different three-dimensional models. A one-eighth section model was used for the analyses in the vertical orientation, and a one-half section model was used for the analyses in the horizontal orientation (Figures 3 and 4). The one-eighth section model represented the smallest symmetric slice of the cask, while the larger model was necessary to account for the basket and fuel assemblies shifting when the cask was placed in a horizontal position. In both the unconsolidated fuel and the consolidated fuel analyses, the basic cask body model remained the same, only the fuel assembly/canister models differed.

One-Eighth Section Cask Model - Unconsolidated Fuel

The COBRA-SFS one-eighth section model used for the analyses in the vertical orientation consisted of 18 uniform axial levels, with each level modeled with 51 wall nodes, 386 fluid subchannels, and 450 rod surface nodes (Figure 3). As shown in Figure 5, the "lumping" capability of COBRA-SFS was employed for the full size assemblies, which allows the modeler to represent multiple rod surfaces as a single rod surface node. This is an effective way to reduce the computational requirements when multiple rods are believed to be at or near the same temperature. Each full assembly was modeled with 105 lumped rod nodes and 57 subchannels.

In the two COBRA-SFS half fuel assemblies resulting from symmetry (Figure 3), each spent fuel rod was modeled as a single rod node, for a total of 120 rod nodes and 136 subchannels (Figure 6).

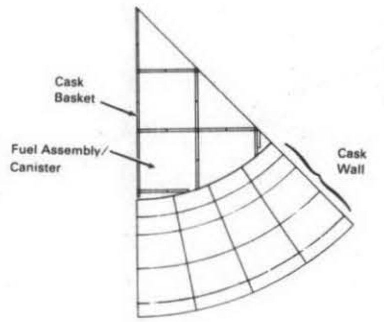

Figure 3. One-Eighth Section Cask Model

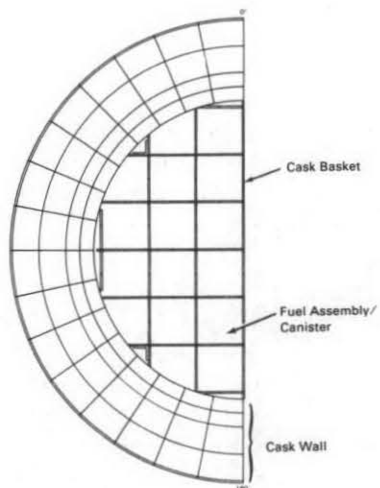

Figure 4. One-Half Section Cask Model

One-Half Section Cask Model - Unconsolidated Fuel

The one-half section model used for the analyses in the horizontal orientation is presented in Figure 4. In this model, 191 wall, 694 subchannel, and 1260 rod surface nodes were used. The same fuel assembly lumping depicted in Figure 5 for the one-eighth section full assembly model was used for all fuel assemblies in the one-half section model.

Pretest Vertical Orientation Predictions - Unconsolidated Fuel

In all cases, pretest predictions were completed before the experimental data had been obtained. The predicted axial temperature profiles and experimental data along the guide tube with the peak temperature for the vertical orientation and three fill gases are compared in Figure 7. The predicted peak guide tube temperature in helium is in good agreement with the measured value; however, overpredictions of temperatures up to 30°C exist in the lower region of the cask. This result is attributed to under-estimated heat transfer to the lower plenum (space between lower end of spent fuel rods and cask bottom). For the nitrogen run, the effect of the underpredicted heat transfer to the lower plenum is also apparent. In this case, the model overpredicted the measured peak temperature by 20°C. The vacuum run was in good overall agreement with data (25°C). Although the peak temperature was within 1°C, in vacuum, the upper and lower sections of the profile are not rounded like the data profile. This is a result of not having considered axial conduction in the basket in the pretest model.

Comparisons of the vacuum and nitrogen test runs show that convection within the cask results in a 44°C lower peak temperature in the nitrogen backfill case. Both cases used nitrogen properties in the fluid conduction model; however, the vacuum case had a negligible flow field. The presence of convection in the helium test run is indicated by the shape of the axial temperature profile, which is skewed slightly toward the upper end of the cask. All horizontal orientation pretest predictions were in similar agreement with test data.

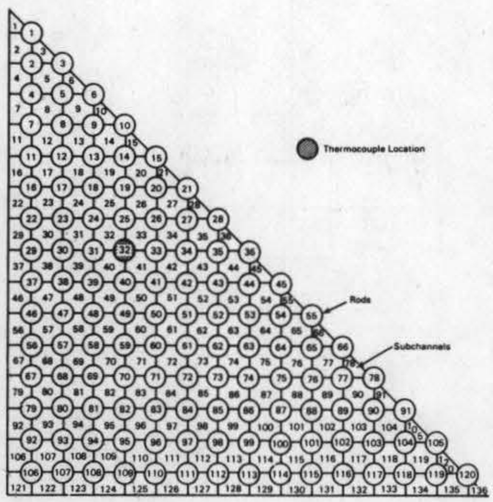

Figure 5. Full Assembly Rod and Subchannel Lumped Model, One-Eighth Section

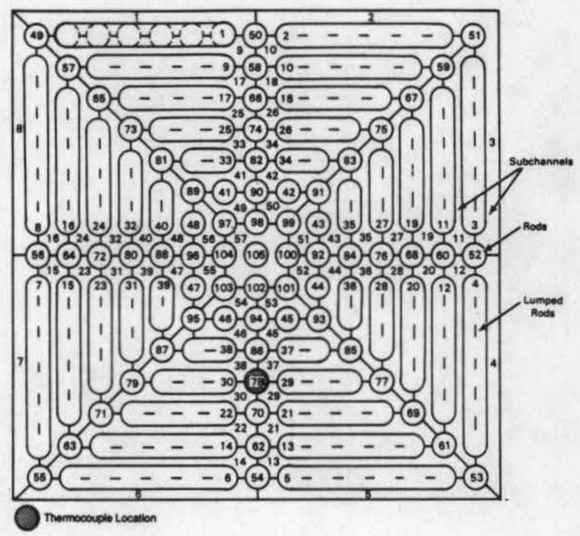

Figure 6. Half Assembly Rod and Subchannel Model, One-Eighth Section

Post-Test Model Changes - Unconsolidated Fuel

The following changes were incorporated into the post-test unconsolidated fuel analyses based on observations from comparisons of pretest predictions with test data:

- axial conduction in the aluminum basket was added
- a cooling fin model was added to better represent the heat transfer from the bottom of the cask to a railcar on which the cask was placed during testing
- a thermal connection between the basket and the lower plenum was added to the post-test model
- the cask surface-to-ambient heat transfer was overpredicted. A modified correlation was used in the post-test analyses.

Post-Test Vertical Orientation Predictions - Unconsolidated Fuel

The post-test axial temperature comparisons for the vertical orientation cases are shown in Figure 8 for the three backfill gases. The helium case shows the expected improvement in the temperature profile shape, because of the inclusion of axial conduction in the basket and heat transfer in the lower portion of the cask. The nitrogen case shows a clear improvement in the shape of the temperature profile, with a COBRA-SFS over-prediction of the peak guide tube temperature of 15°C. The post-test vacuum vertical orientation temperature predictions are in excellent agreement with test data. The model underpredicted this case by 2°C, with good agreement with axial temperature profiles. Post-test axial profile predictions for all horizontal orientation test runs compared with test data in a similar manner.

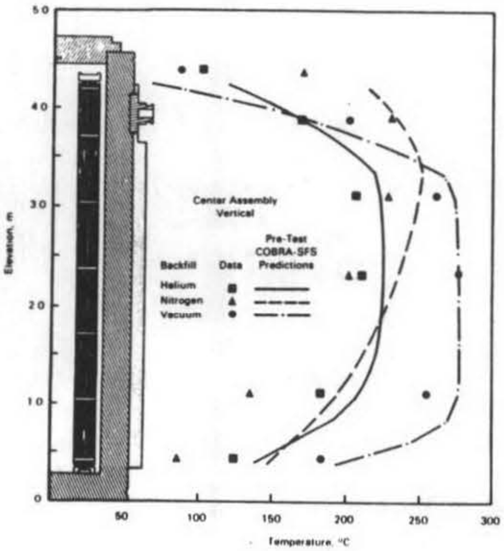

Figure 7. Pretest Unconsolidated Fuel Axial Temperatue Predictions

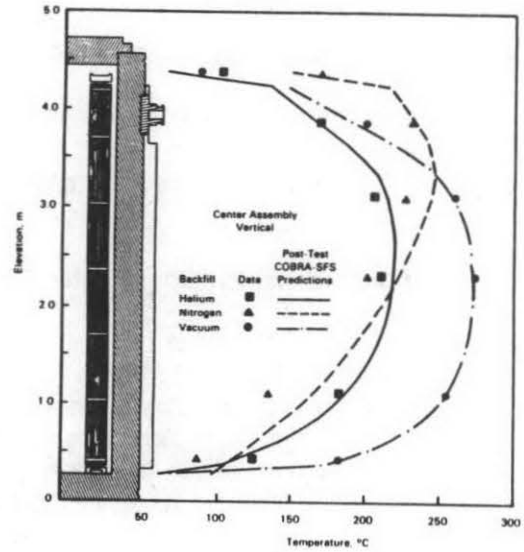

Figure 8. Post-Test Unconsolidated Fuel Axial Temperature Predictions

Post-Test Prediction Summary - Unconsolidated Fuel

Comparisons of the peak-to-ambient pretest and post-test temperature predictions with data for all six test runs are shown in Figure 9. All stated temperature differences are based on

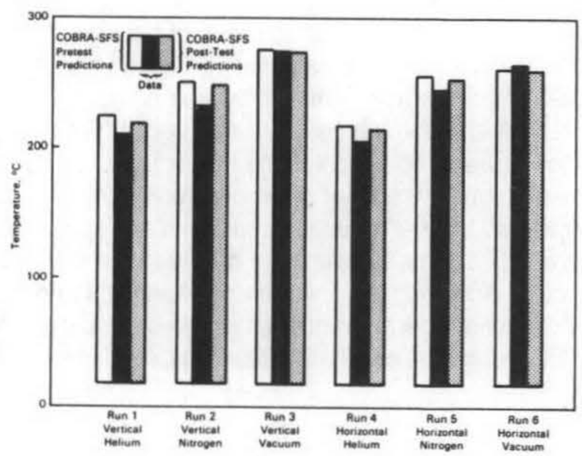

Figure 9. Pre- and Post-Test Unconsolidated Fuel Peak-to-Ambient Temperature Predictions for all Test Runs.

the ambient-to-peak temperature differences. The post-test changes did little to change the peak temperature predictions, because the changes mainly influenced the shape of the axial temperature profiles. Again, as in the pretest comparisons, the greatest discrepancy occurred for the vertical nitrogen case, where a 7.4% (6°C) overprediction existed. The mean temperature difference between data and post-test predictions for the six runs was 2.9% (6°C), with a standard deviation of 3.4% (7°C).

CONSOLIDATED FUEL MODEL AND ANALYSES

A one-half section model of the TN-24P cask was used to investigate the cask thermal response when loaded with consolidated spent fuel, for both vertical and horizontal orientations. The asymmetries of the decay heat loading pattern made the one-eighth section cask model insufficient.

One-Half Section Cask Model - Consolidated Fuel

The COBRA-SFS consolidated fuel one-half section cask model differed slightly from the unconsolidated fuel model. An additional 48 wall nodes were used at each axial level to model the fuel canisters containing rods from two spent fuel assemblies. All other features of the cask model noding geometry remained the same. The flexibility of the COBRA-SFS rod and subchannel modeling was used to selectively lump rods and subchannels together to reduce the size of the computational model inside the fuel canisters. The 408 rods within each canister were represented by 5 lumped rods and the flow subchannels were represented by 9 lumped subchannels, as displayed in Figure 10, compared with the 105 lumped rods and 57 lumped subchannels used to model an unconsolidated assembly. With the exception of the fuel canister model, the modeling of the gap formed between the canister and the basket wall, and the rod and subchannel models, all other COBRA-SFS modeling parameters used in the post-test unconsolidated fuel analyses remained the same for the consolidated model.

Pretest Vertical Orientation Predictions - Consolidated Fuel

In all cases, pretest predictions were completed before the experimental data had been obtained. The peak guide tube axial temperature comparisons are presented for the vertical orientation and three fill gases in Figure 11. The predictions of peak guide tube temperatures for a helium backfill are in good agreement with data, with a maximum difference of 7.6°C. The shape of the profile is also in good agreement with the experimental data. For nitrogen fill gas, the comparison of peak guide tube temperature was within 25°C, with COBRA-SFS underpredicting the test temperatures. The predictions reflect a lack of convection within the COBRA-SFS model, whereas the test data axial temperature profile indicates significant convection heat transfer. In Figure 11, the vertical vacuum test run comparison shows a COBRA-SFS underprediction of 34°C. The temperature profiles from this run accurately reflect the assumed axial power profile. Although the peak temperature was underpredicted, fairly good agreement between the axial temperature profiles is noted. The peak guide tube axial temperature predictions for the horizontal orientation test runs were in similar agreement with test data for all three backfills.

Post-Test Consolidated Fuel Model Changes

The following change was incorporated into the post-test consolidated fuel analyses:

- The pretest assembly rod model that consisted of 5 lumped rod nodes was replaced with a concentric "ring" pattern incorporating 13 lumped rod nodes, as shown in Figure 12. All six post-test simulations were made using the 13-ring lumping scheme.

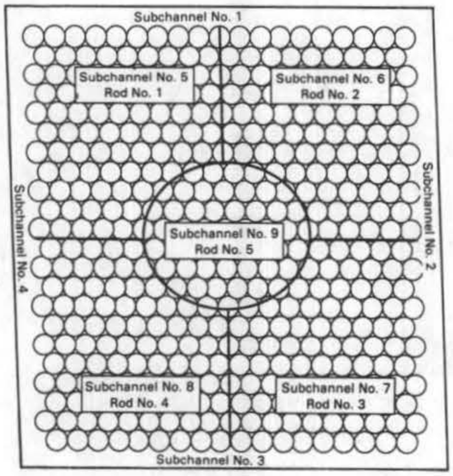

Figure 10. Pretest Consolidated Fuel Lumped Rod and Subchannel Model.

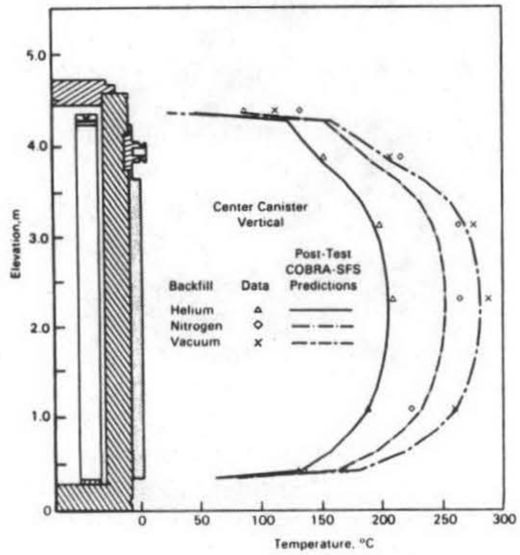

Figure 11. Pretest Consolidated Fuel Axial Temperature Predictions

Post-Test Vertical Orientation Predictions - Consolidated Fuel

The axial guide tube temperature profile predictions for the three fill gases, along with the test data, are presented in Figure 13. Significant improvements were achieved for all three fill gases, with all predictions within 13°C. An improvement in predicted peak guide tube temperature magnitudes for the helium fill gas test run is seen in Figure 13, with the peak measured temperature underpredicted by 4°C. The prediction of peak guide tube temperature for the nitrogen fill gas case was also improved. COBRA-SFS underpredicted the peak guide tube temperature in this case by 13°C. The post-test vertical vacuum simulation compared closely with test data, with the peak temperature underpredicted by 8°C. This result indicates that the conduction and radiation heat transfer models are accurate, as the convection in this case is negligible. The peak guide tube axial temperature comparisons for the horizontal orientation were again in similar agreement with test data.

Post-Test Prediction Summary - Consolidated Fuel

Comparisons of the peak-to-ambient temperature predictions for the six cases are displayed in Figure 14. All stated temperature differences are based on ambient-to-peak temperature differences. The post-test model change improved the COBRA-SFS predictions for all six cases. The mean temperature difference between the test data and the post-test predictions for the six test cases was 3% (6°C), with a standard deviation of 2% (5°C).

CONCLUSIONS

The results of the COBRA-SFS analyses permit the following conclusions:

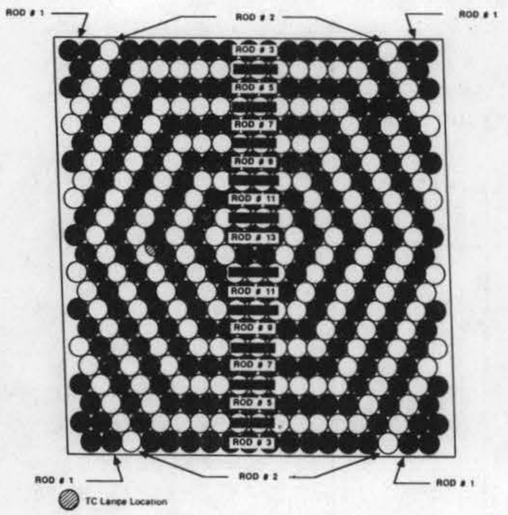

Figure 12. Post-Test Consolidated Fuel Rod Lumping Model.

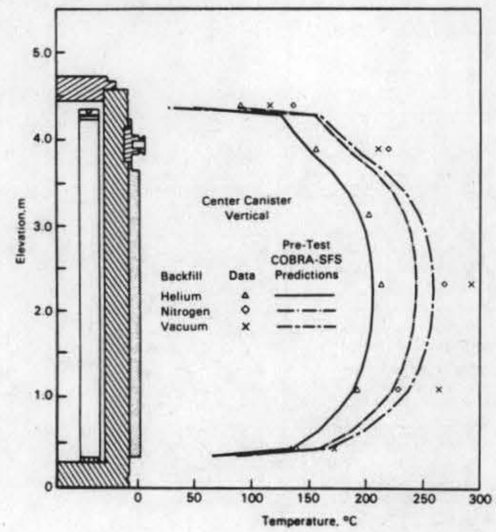

Figure 13. Post-Test Consolidated Fuel Axial Temperature Predictions.

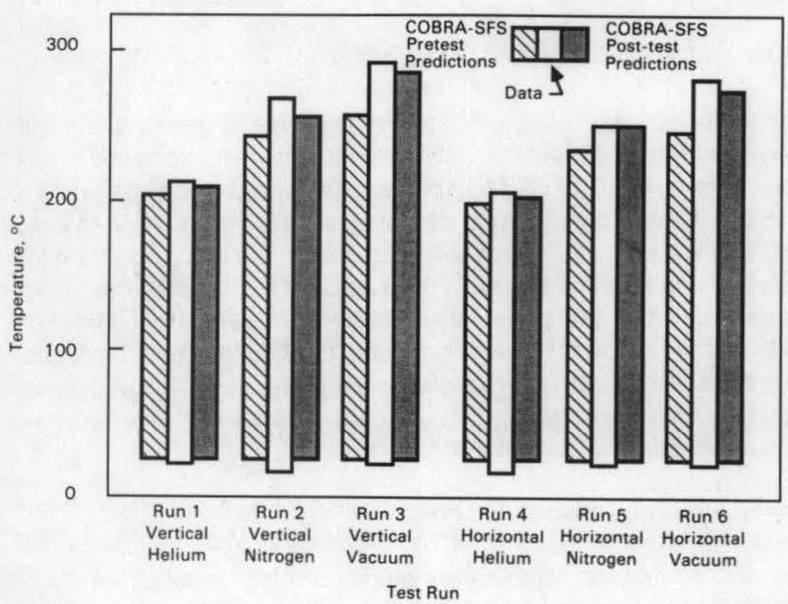

Figure 14. Pre- and Post-Test Consolidated Fuel Peak-to-Ambient Temperature Predictions for all Test Runs.

COBRA-SFS Unconsolidated Spent Fuel Analyses

- Comparisons of pretest predictions of peak temperatures with test data showed very good agreement. The maximum disagreement was less than 20°C and occurred for the vertical nitrogen test case.
- Comparisons of pretest predictions with test data showed the need to model axial conduction in the aluminum basket and to model the railcar as a fin attached to the bottom of the cask during the vertical runs.
- Post-test predictions of peak temperatures were in excellent agreement with test data. The mean temperature difference between predicted peak temperatures and measured values was 6°C, with a standard deviation of 7°C. The greatest temperature difference (16°C) was for the vertical nitrogen test case.

COBRA-SFS Consolidated Spent Fuel Analyses

- Comparisons of pretest predictions of peak temperatures with test data showed good agreement. The maximum disagreement was less than 35°C, which occurred for the vertical vacuum run.
- Comparisons of pretest predictions with test data showed the need to increase detail in the fuel canister model so it would be similar to that used for unconsolidated fuel assemblies.
- Post-test predictions of peak temperatures were in excellent agreement with test data. The mean temperature difference between predicted peak temperatures and measured values was 6°C, with a standard deviation of 7°C. The greatest difference (13°C) was found for the vertical nitrogen run.

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