HTAS2: A Three-Dimensional Transient Shipping Cask Analysis Tool

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INTRODUCTION

Predicting specific thermal behavior of spent fuel assemblies involved in an accident during shipping is difficult because of the geometric complexity typical of the shipping casks. Models range from a simple expression like the Wooton-Epstein correlation (described by Bucholz 1983) to detailed finite difference or finite element calculations. Certainly, with enough computer resources and manpower, any given cask arrangement can be accurately analyzed for laminar conditions. However, the cost of such an effort would be prohibitive. Developing an analytical tool thus entails reaching a compromise between accuracy and speed and economy.

The Heat Transfer Analysis Sequence 2 (HTAS2) program is being developed for the United States Nuclear Regulatory Commission for the standard safety analysis of nuclear fuel shipping containers (casks) during transport. HTAS2 is intended for use as a driver module in the Standardized Computer Analyses for Licensing Evaluation (SCALE) system (U.S. NRC 1984). As a part of the HTAS2 analysis, an additional SCALE module WHOCAM (WHOle CAsk Model) is also being developed.

HTAS2 involves a three-dimensional model of the cask and its internals that accounts for radiation and conduction within the enclosed fuel assemblies and partitioning basket. It is an extension of its two-dimensional predecessor, HTAS1 (Turner and Cobb 1983).

The HTAS2 analysis has been divided into three parts because of the complexity of the geometry and the disparity in length scales. The first part is a three-dimensional global cask calculation performed by WHOCAM, containing a coarse representation of the shipping cask and contained fuel assemblies. It is assumed that the detailed calculation of temperatures within the fuel assemblies is not necessary to accurately predict the temperature distribution in the cask and basket.

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The WHOCAM results can then be used as boundary conditions for the second part of the analysis, a detailed calculation of temperatures in an isolated fuel assembly. To predict the maximum fuel pin temperature, only the one assembly, determined by a coarsely discretized model to be the hottest, is analyzed in detail. The third part of the analysis is the calculation of gray, diffuse radiation factors. This part needs to be done only once for a given fuel assembly. HTAS2 requires the user to supply only the major geometric and thermophysical parameters in a keyword-oriented free-form input. The form of the input closely resembles that of HTAS1.

GLOBAL CASK ANALYSIS

The coarsely discretized representation of the shipping cask and contained fuel assemblies is analyzed by the SCALE module WHOCAM. The WHOCAM model is a three-dimensional lumped-parameter representation of the cask that supplies the necessary boundary conditions to the single assembly analysis.

Although the cask geometry generally lends itself to a cylindrical discretization, the fuel assemblies contained within do not. Thus, the model is divided into two differently discretized radial regions. The grid is identical on each axial plane. A sample discretization is shown in Figs. 1 and 2. The basket is assumed to be a square grid with each wall extending across the cavity. A fuel assembly occupies each full cell in the grid. No offsets are allowed.

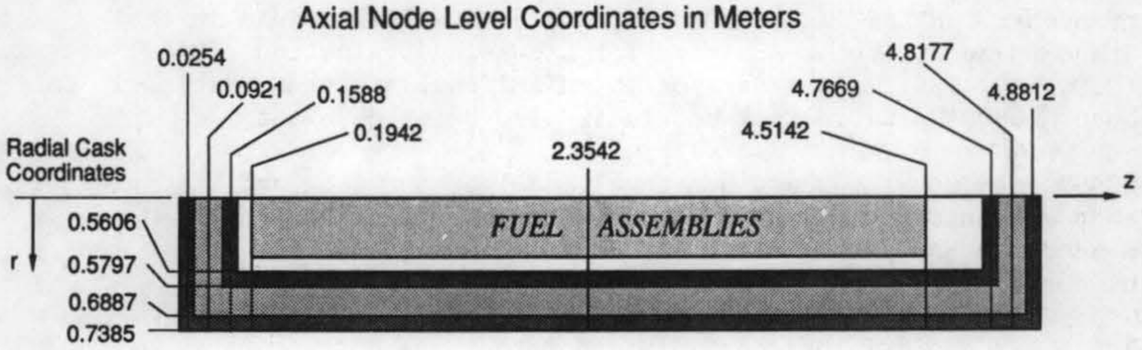

Figure 1. Axial node levels for sample cask discretization.

All radiation and conduction connections between fuel assembly nodes and basket wall nodes are represented by two constants that can be determined from preliminary single assembly analyses. Radiation between the outermost basket walls and the cask outer body is modeled in two dimensions assuming gray, diffuse surfaces. At the top end of the cask, a one-dimensional radiation connection is made between the fuel assemblies and the inner cask wall. At the lower end, a contact resistance is assumed. Conduction is allowed in the assemblies and basket walls both axially and transversely. Natural convection and radiation are modeled between the cask exterior and the environment.

The transient portions of the global cask analysis are solved using the classical explicit procedure. A relaxation technique for steady-state solution similar to the technique used in HEATING (Elrod, Giles, and Turner 1983) was implemented into WHOCAM. The HEATING document for Version 6.1 that is used by HTAS2 has not yet been published.

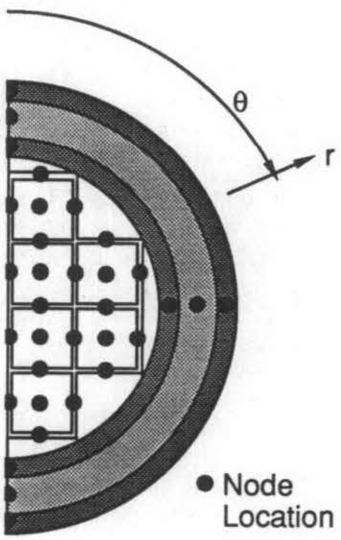

Figure 2. Typical discretization on an axial node level.

SINGLE ASSEMBLY ANALYSIS

Radiation, conduction, and convection in the single assembly with fuel pins in a square lattice may all be represented by HTAS2 using the HEATING module. To represent the geometry with a Cartesian grid the circular fuel pin cross-section is modeled as square. A fuel pin region is delineated by four nodes, each associated with a one-quarter segment of the pin surface. The four surrounding basket wall surfaces are discretized into a related number of surface segments. Such a discretization is shown in Fig. 3. The words "node" and "surface" will be used interchangeably. Conductance through the interstitial fluid is approximated by adjusting the pitch in the square model to a value different from the true cylindrical rod pitch. The true pitch is used for view factor calculations.

Natural convection is approximated by advection of energy along preassigned flow paths (Fig. 3). This attempt to account for redistribution of heat in the assembly due to convection of energy at low speeds is reasonable for cases where convection is small. Similar analysis is published by Fry et al. (1983).

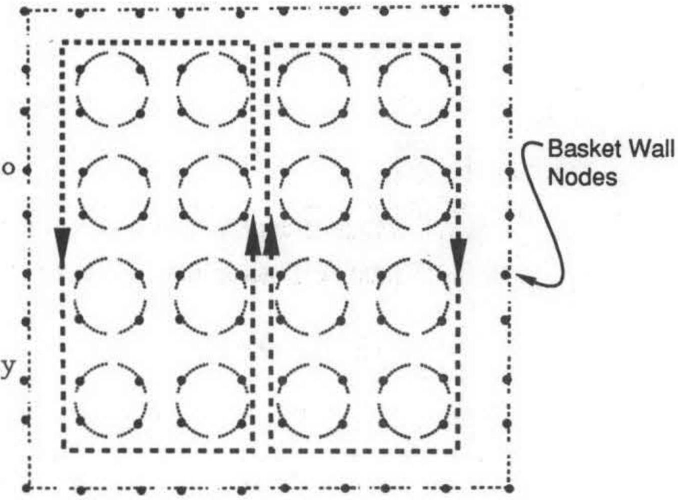

Figure 3. Sample discretization of a fuel assembly.

The parameters of this model should be based on appropriate data. Only by selection and verification of these parameters can this model be confidently used. As the fuel residual heat is increased, the importance of natural convection also increases. At some point this scheme will become inappropriate.

Since available experiments (e.g., Fry 1983) with typical spent fuel assemblies have indicated radiation as the most significant heat transfer mechanism, the single assembly radiation model is quite detailed. HTAS2 automatically calculates the two-dimensional radiation factors (RFs) for fuel pin array within a relatively small CPU time. An RF is defined as the fraction of energy emitted from a source surface (assumed black) that is ultimately absorbed at another surface, including all intermediate diffuse reflections.

RFs are calculated by tracking diffusely reflected energy emitted from the source through the assembly. Succeeding reflections are tracked by monitoring which surfaces receive incident energy and how much is absorbed and reflected at each surface. After enough reflections, almost all of the energy has been absorbed into the fuel pin or wall surfaces. The fraction of originally emitted energy that is absorbed at a receiving surface in the assembly times the emissivity of the source surface is equal to the RF between the source surface and that receiving surface. Each node is in turn treated as the source to generate the entire RF matrix. To ensure a symmetric RF-area matrix using the reflection tracking method, the entire matrix is calculated and elements that should be equal are averaged. The required view factors were generated in a manner similar to that described by Childs and Bryan (1986).

Using reflection tracking, the user can opt to perform an inexpensive, less accurate calculation. This is done by tracking a small number of reflections or by neglecting connectors smaller than an assigned cutoff. Also, only half of the RF matrix needs to be stored in computer memory, allowing significant savings for large fuel assemblies.

ASSESSMENT OF SINGLE ASSEMBLY MODEL

The international benchmark problem UK1 (Glass 1988) has served as a verification case since computational and experimental results are available for comparison. UK1 simulates steady-state heat transfer in a typical assembly.

Comparisons for the UK1 problem are shown in Fig. 4. It was confirmed that differences between the current results and those of Childs and Bryan are due to differences in the view factors. HTAS2 calculates the view factor patterns exactly, whereas Childs and Bryan used a graphical method. HTAS2 more accurately predicted the shape of the temperature distribution, while the Childs and Bryan results fortuitously are closer to the data. The most likely cause of the discrepancies in the comparison with the experiment is uncertainty in the value for the emissivity of the fuel pin cladding. Other factors include experimental measurement and control errors.

Additional calculations (Fig. 5) were compared to data published by Fry et al. (1983). It was possible to reproduce experimental data with the simple flow pattern by adjusting the strength of the circulation. Fry indicated that the measured values for emissivity of the fuel pin cladding ranged from 0.42 to 0.93.

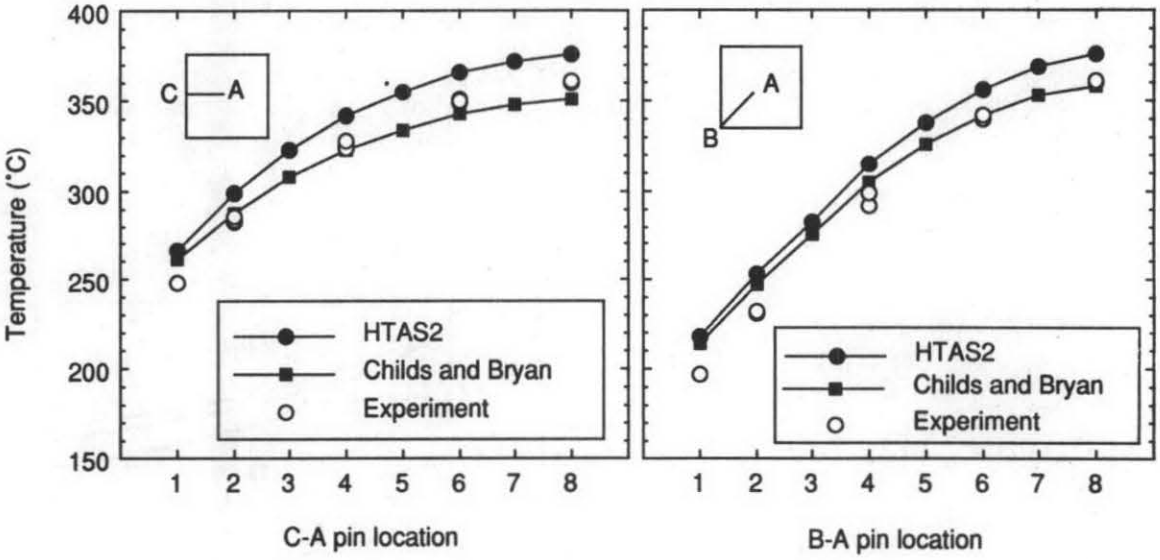

Figure 4. Temperature comparison for a single UK1 fuel assembly.

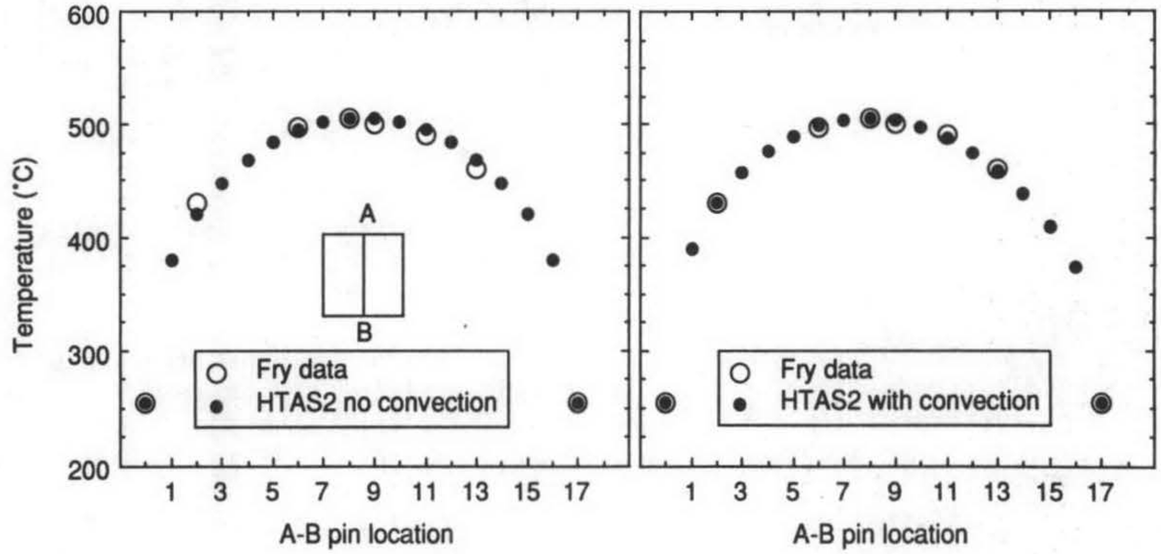

Figure 5. Comparison with Fry experimental data for a single fuel assembly.

ASSESSMENT OF THE WHOLE CASK MODEL

Insufficient experimental data are available to validate the HTAS2 models. Alternatively, a 12-assembly hypothetical cask was designed (Fig. 1), and HTAS2 results were compared with HTAS1 results and the

Wooton-Epstein correlation. The hypothetical analysis sequence consists of a prefire steady-state, a 30-min. fire transient, and a 180-min. postfire transient.

HTAS1 Comparison

Because of the limitations in HTAS1, only the calculated temperatures in the cask outer body could be compared. A comparison of the maximum and minimum temperatures on the inner and outer surfaces of the shipping cask throughout the analysis is presented in Fig. 6. HTAS1 imposes the fuel heat load uniformly across the inside wall of the cask, while HTAS2 includes a model for the cask internals allowing uneven distribution of that heat as it passes into the cask outer body.

For the initial prefire steady-state, the HTAS1 cask temperatures all lie within the range of HTAS2 cask temperatures. This must be the case since the same amount of heat is being generated within the cask and hence lost out the boundaries to the environment.

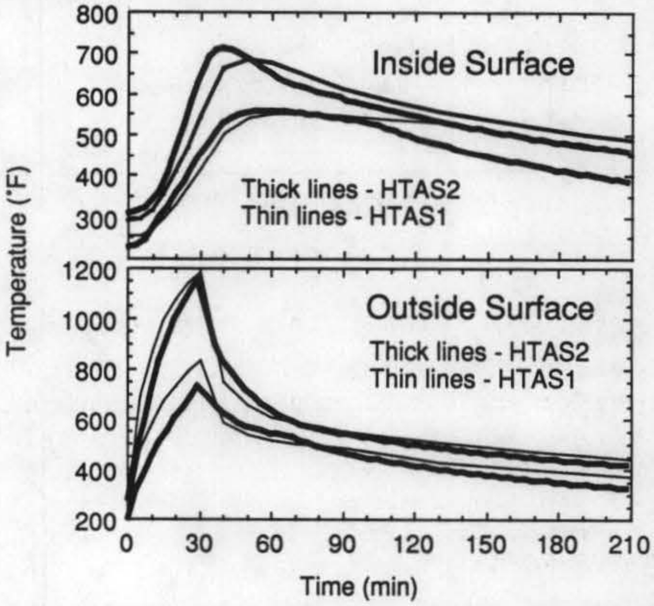

Figure 6. Comparison of HTAS1 and HTAS2 cask temperatures for hypothetical cask problem.

Wooton-Epstein Comparisons

An HTAS2 single assembly analysis was run using the results from the global cask analysis of the hypothetical shipping cask, and the resulting maximum fuel pin temperature was compared with the Wooton-Epstein correlation. R. O. Wooton and H. M. Epstein performed experiments and developed a steady-state correlation for determining the maximum cladding temperature in a shipping cask. Their unpublished work has been reproduced in a condensed form by J. M. Bucholz (1983). The Wooton-Epstein correlation is conservative due to exclusion of transient effects. Additional conservatism was intentionally included by Wooton-Epstein. Comparisons with this correlation have been made (Fig. 7) for two cases: (1) considering all the fuel pins contained in the cask and using the maximum inner cask temperature as the boundary condition (curve 1) and (2) considering only the fuel pins in one assembly with the maximum basket wall temperature as the boundary condition (curve 2). Using the maximum inner cask temperature calculated by HTAS2 (curve 3), the correlation predicts a maximum cladding temperature 750°F higher than that calculated by HTAS2. This may be partially due to conduction through the basket which did not exist in the experiments.

Although it is expected that HTAS2 is indeed underpredicting the degree of thermal contact between the fuel and the cask outer body, it is not likely that even the simple model included would miss by so wide a margin. This indicates that including a model of the cask internals in the analysis tool provides much more realistic results than a cask-only analysis (such as HTAS1) could produce.

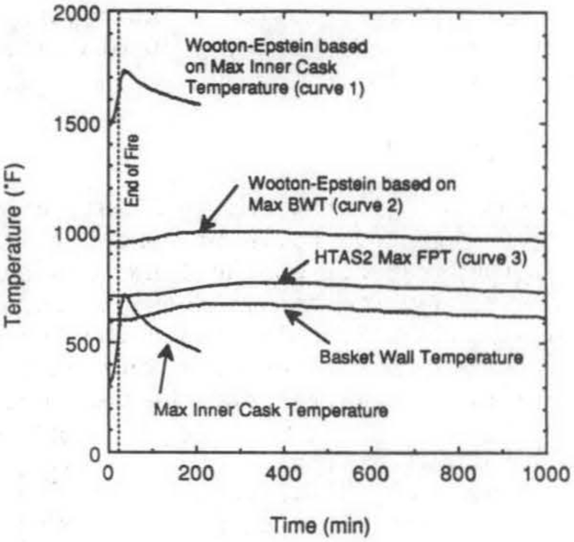

Figure 7. Maximum fuel pin temperature comparisons for hypothetical cask problem.

Although the Wooton-Epstein correlation should be applicable for the UK1 assembly, basing the correlation on the maximum basket wall temperature predicted by HTAS2 shows more than a 200°F temperature difference. At the power level of the UK1 assembly, the correlation overpredicts the experimental data by approximately 100°F. Additionally, Wooton-Epstein is based on measurements taken in a square assembly surrounded by a circular enclosure, rather than a square enclosure as in the single assembly analysis. This means that an additional volume of air separated the fuel from the enclosure, which should result in higher fuel pin temperatures in the experiment.

FUTURE WORK

To accurately predict the effect of natural convection in a cask analysis using the current approach requires that additional experimental data be assimilated and the appropriate correlations be formulated. Alternatively, it should be possible to incorporate a detailed natural convection model for single assembly analyses.

The irregular discretization in the cask ends could present some problems. Additional verification is needed to determine the adequacy of this discretization. An alternative discretization may be required. Also, to increase its capabilities, HTAS2 should be modified to allow voids and offsets in the arrangement of the fuel assemblies contained within the cask.

CONCLUSIONS

The HTAS2 program is still being developed and has undergone very limited validation. The program achieves a reasonable level of detail (calculating the maximum fuel pin temperature) without an excessive degree of computational effort. This is accomplished by a two-module approach, where results from a coarse three-dimensional model are used to determine the boundary conditions for a detailed two-dimensional single assembly calculation. The most important mode of heat transfer in typical fuel assemblies is radiation. HTAS2 contains a generalized, detailed two-dimensional radiation model which produces results that compare favorably with other experimental and computed data. Although the Wooton-Epstein correlation predicted significantly higher temperatures than the single assembly analysis in HTAS2, the differences were not unreasonable in light of the uncertainties in the Wooton-Epstein experiments and differences between the enclosure geometries.

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