A SIMPLIFIED MODELING TECHNIQUE FOR THE THERMAL ANALYSIS OF SPENT NUCLEAR ASSEMBLIES*

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ABSTRACT

A major design concern of a cask for the transport of spent fuel assemblies is the determination of the maximum fuel pin temperature. Normally the determination of the maximum steady state fuel pin temperature requires the thermal analysis (two-dimensional or three-dimensional) of the cask to be performed in conjunction with the fuel assemblies. This, in general, would require extensive effort and computer time. However, by performing a sensitivity analysis for fuel pin temperature for various boundary conditions it was possible to decouple the heat transfer analysis of the cask from that of the fuel assemblies. This paper presents the scaling law that was obtained for maximum fuel pin temperature as a function of emissivity, heat generation rate and assembly wrapper temperature for hex-shaped fuel assemblies.

INTRODUCTION

The Breeder Spent Fuel Handling (BSFH) Program was directed at the development of a truck shipping cask for transporting spent nuclear fuel assemblies from a reactor site to a reprocessing facility and the resultant High Level Waste (HLW) to a repository (1). Because the initial fuel to be used in the breeder cycle will originate from Boiling Water Reactors (BWRs) and Pressurized Water Reactors (PWRs), the cask will be designed as a multipurpose cask (via interchangeable cask baskets) which can handle spent BWR, PWR, and Fast Flux Test Facility (FFTF) fuel assemblies. In order to determine if a cask complies with the Nuclear Regulatory Commission (NRC) thermal requirements for normal conditions of transport (2), a thermal analysis for the BSFH shipping cask was required. The FFTF spent fuel assemblies presented the largest power densities, thus the analysis centered on hex-shaped FFTF fuel assemblies. The major thermal design criteria was that the spent fuel cladding temperature not exceed 1170°F (the probability of cladding rupture increases substantially for temperatures above this limit). Previous experimental work has been performed on a full-scale mock-up of a hex-shaped assembly of tubes (3) for temperatures ranging from 350°F to 650°F. However preliminary thermal analysis of the BSFH cask indicated that for BSFH cask payloads in excess of three FFTF fuel assemblies (at thermal payloads on the order of 1.4 kW), temperatures in the fuel assemblies would be much greater than 650°F. Thus, for payloads of four to six FFTF fuels assemblies, experimental data could not be used and a different analysis method was required. A computer simulation of the radiative heat transfer among the hex-shaped array of 217 fuel pins within the hex wrapper was performed. Results were obtained for a range of surface emissivities and hex wrapper boundary conditions and a thermal scaling law was derived.

GEOMETRY

A cross section of an initial design of the BSFH shipping cask can be seen in Fig. 1, which shows a cask with six FFTF fuel assemblies. The cask basket uses borated aluminum for neutron absorption and has hex-shaped cavities to hold the FFTF fuel assemblies. The clearance between the cask basket and the assemblies is 0.5 inch to allow for bowing of the FFTF fuel assemblies. The fuel assemblies have dimensions given in Table I, and schematics of FFTF driver fuel assemblies (DFAs) can be seen in Fig. 2. The DFAs have a pin diameter of 0.29 inches, and an active core length of 36 inches. The cask body uses 5.4 inches of depleted uranium for gamma shielding and 3 inches of boro-silicone for neutron shielding. These dimensions, coupled with the inability to use liquid coolants (sodium), results in very large power densities over the active core length. The thermal analysis for the BSFH, thus, requires detailed knowledge of the fuel assembly heat transfer relationships at high temperatures.

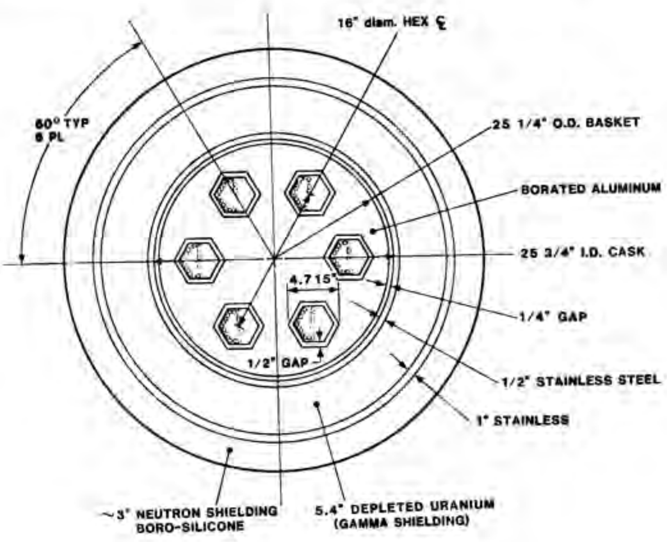

Fig. 1. Cross Section of BSFH Shipping Cask.

ANALYSIS OF THE FFTF FUEL ASSEMBLY

Preliminary heat transfer analysis of the BSFH cask was performed for various fission product decay heat from the FFTF fuel assemblies. A maximum

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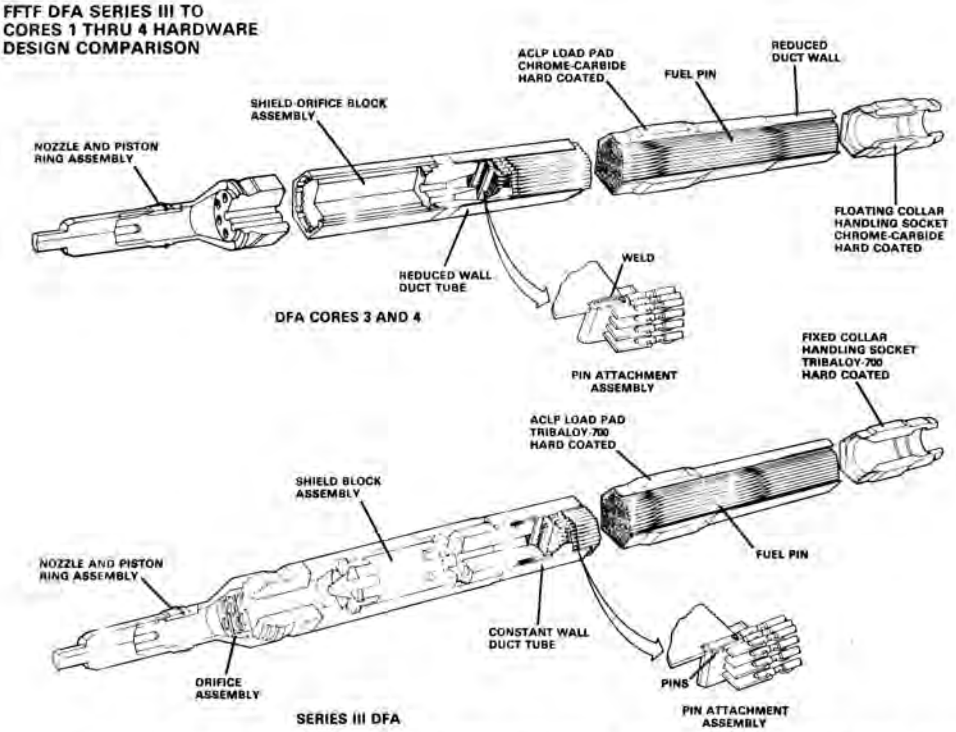

Fig. 2. Schematic of FFTF Driver Fuel Assemblies. (Taken from Ref. 1.)

TABLE I*

FFTF Driver Fuel Assembly Physical Parameters

	FFTF
Fuel Pin	
Active Fuel Length	36.0 in. (0.914 m)
Clad Material	316 SST
Clad Thickness	0.015 in. (0.38 mm)
Pin Dimensions	
- Diameter	0.228 in. (5.80 mm)
- Length	93.7 in. (2.38 m)
Driver Fuel Assembly	
Shape (Diameter)	Hex 0.120 m (4.72 in.)
Length	144.0 in. (0.567 m)
Weight	500.0 lb. (227 kg)
No. of Pins/Assembly	217
Fuel Pin Array Pitch	0.29 in. (7.3 mm)
Heavy Metal Weight	72.8 lb. (33.0 kg)
Initial Enrichment $\frac{Pu}{Pu + U}$ %	Range 22.4 to 30.9
End-of-Burnup Enrichment $\frac{Pu}{Pu + U}$ %	Range 21.4 to 29.1

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* Source: Ref. 1

design decay heat of 1.4 kW/assembly was determined from fuel burnup calculations performed for the FFTF fuel (1). This decay heat value corresponds to the maximum decay heat rate that was expected to be allowed for shipment in a BSFH cask and is obtainable from various combinations of fuel burnup and decay time (see Table II and Fig. 3). Preliminary heat transfer analysis indicated that the fuel pin temperatures would be on the order of 1000°F. Experimental data were not available for FFTF assemblies (in the absence of sodium) at temperatures of this magnitude. Analysis was thus performed with use of the pure radiative heat transfer code "HEX" (4). Although this code does not include the thermal phenomena of conduction and convection, it was considered applicable because: 1) at the high temperatures of interest, radiation is the dominate heat transfer mechanism 2) the predicted temperatures will conservatively over predict actual maximum fuel pin *temperatures* and 3) previous experience indicated that the thermal analysis of large fuel assemblies by radiative heat transfer coupled with other phenomena (conduction or convection) was very time consuming and computationally expensive (5). The code "HEX" was used to compute the configuration view factors (via Hottel's crossed-string method (6)) for each of the 217 fuel elements to its adjacent neighbors and to solve the thermal radiative heat transfer relationships. Solutions for dimensionless temperatures (from which temperature values can be calculated) were obtained, and selective results for a FFTF fuel assembly with a wrapper temperature of 850°F, a heat generation rate of 1.4 kW/assembly and radiative emissivity values of 0.5 (for all emitting surfaces) can be seen in Fig. 4. Further analysis was performed for a wide variety of wrapper temperatures, surface emissivities and element pitch-to-diameter ratios (so that other hex-shaped assemblies could be analyzed). Using the results as a database, a simplified empirical relationship was obtained by using a singular value decomposition (SVD) to fit the database with a desired basis function in the linear least square sense (see Appendix C of Ref. 3 for details). From that analysis, the constants C_1 through C_6 that are to be used in the basis function were obtained. The bivariate empirical fit for the dimensionless temperature (Y_{max}) was good to $\pm$ 4.7 percent

(i.e., standard deviation = 1.5) for pitch-to-diameter ratios of 1.0 to 2.0 and for surface emissivities of 0.2 to 0.9. The empirical fit is given by:

$$Y_{max} = \exp(C_1 + C_2\epsilon + C_3\epsilon^2 + C_4\epsilon\,PDR + C_5PDR + C_6PDR^2) \quad (1)$$

where Y_{max} = maximum dimensionless temperature of fuel elements for hex-shaped fuel assemblies

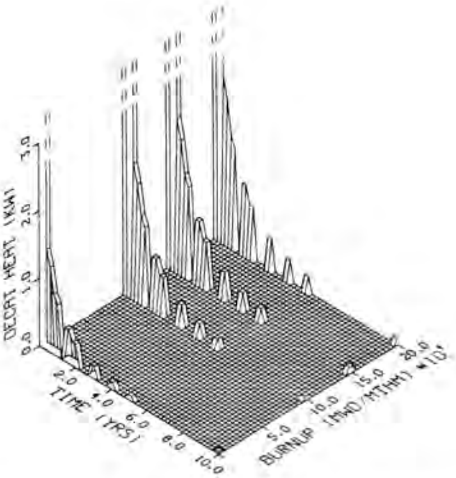

Fig. 3. Heat Generation Rates for FFTF DFAs for Various Fuel Burnup and Age Values.

TABLE II*

FFTF Fuel Assembly, Fission Product Decay Heat (kW)/Assembly

Decay Time (Years)	50 MWD/MTHM 3 Cycles TOTAL	100,000 MWD/MTHM 6 Cycles TOTAL	150,000 MWD/MTHM 9 Cycles TOTAL	200,000 MWD/MTHM 12 Cycles TOTAL
0	292.0	295.0	298.0	300.0
0.5	1.49	1.98	2.25	2.45
0.75	1.02	1.43	1.66	1.84
1.0	0.769	1.12	1.32	1.47
1.5	0.504	0.759	0.920	1.04
2.0	0.354	0.545	0.674	0.777
3.0	0.189	0.305	0.394	0.471
4.0	0.111	0.190	0.257	0.318
5.0	0.073	0.132	0.186	0.238
10.0	0.033	0.066	0.099	0.131

One Cycle

5.5 MW - 100 days
0.0 MW - 40 days

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* Source: Ref. 1

ϵ = emissivity of inner hex wrapper surface and fuel element surfaces (assumed to be the same on all surfaces)

PDR = pitch-to-diameter rate of the hex-shaped fuel element assembly

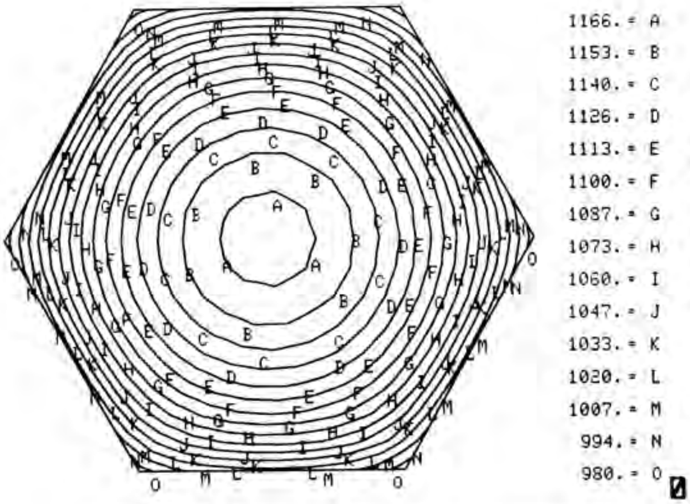

Fig. 4. Fuel Pin Temperature for a Wrapper Temperature of 850°F, Surface Emissivity of 0.5 and Heat Generation Rate of 1.4 kW/assembly.

C_1 to C_6 = constants obtained through SVD analysis

$C_1 = 6.6655369$

$C_2 = -2.0442799$

$C_3 = 1.4936566$

$C_4 = -0.35363993$

$C_5 = -1.7768804$

$C_6 = 0.31144457$

The relationship between temperature and the dimensionless temperature is given by:

$$Y_{max} = \frac{\sigma(T_{max}^4 - T_w^4)}{Q/A} \qquad (2)$$

where T_{max} = maximum fuel element temperature (°R)

T_w = wrapper temperature (°R)

σ = Stefan-Boltzmann constant (Btu/(h ft^2 °R^4))

Q = heat generation rate for an individual fuel element (assumed to uniform for all 217 elements and is determined from fuel burnup calculations) (Btu/h)

A = cylindrical surface area of an individual fuel element (ft^2)

Rewritten, Eq. 2 is given by:

$$T_{max} = \sqrt[4]{T_w^4 + \frac{Y_{max}\, Q}{\sigma A}} \qquad (3)$$

RESULTS AND CONCLUSION

By using Eqs. 1 and 3, the maximum fuel element temperature for a 217-element, hex-shaped fuel assembly can be estimated by simple calculations. The estimated temperature corresponds to a value that would be predicted by thermal radiative heat transfer analysis and is applicable to high temperature environments. Using the above methodology, FFTF fuel assemblies, with a maximum heat generation rate of 1.4 kW/assembly, Table III and Figs. 4 and 5 were obtained. For square assemblies from PWRs and BWRs, a similar set of results can be obtained by using the above methodology.

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TABLE III

Maximum FFTF Fuel Pin Temperature (°F) for Various Wrapper Temperatures and Surface Emissivities

Wrapper Temperature (°F)	Emissivity							
	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
500	1179.	1117.	1070.	1033.	1008.	991.	984.	985.
550	1189.	1129.	1083.	1047.	1022.	1007.	1000.	1001.
600	1202.	1143.	1098.	1063.	1039.	1024.	1017.	1019.
650	1215.	1158.	1114.	1081.	1058.	1043.	1037.	1038.
700	1231.	1175.	1133.	1101.	1078.	1064.	1058.	1059.
750	1248.	1194.	1153.	1122.	1101.	1087.	1081.	1082.
800	1266.	1214.	1175.	1145.	1125.	1112.	1106.	1107.
850	1286.	1237.	1199.	1171.	1151.	1139.	1133.	1134.
900	1308.	1260.	1224.	1197.	1179.	1167.	1162.	1163.

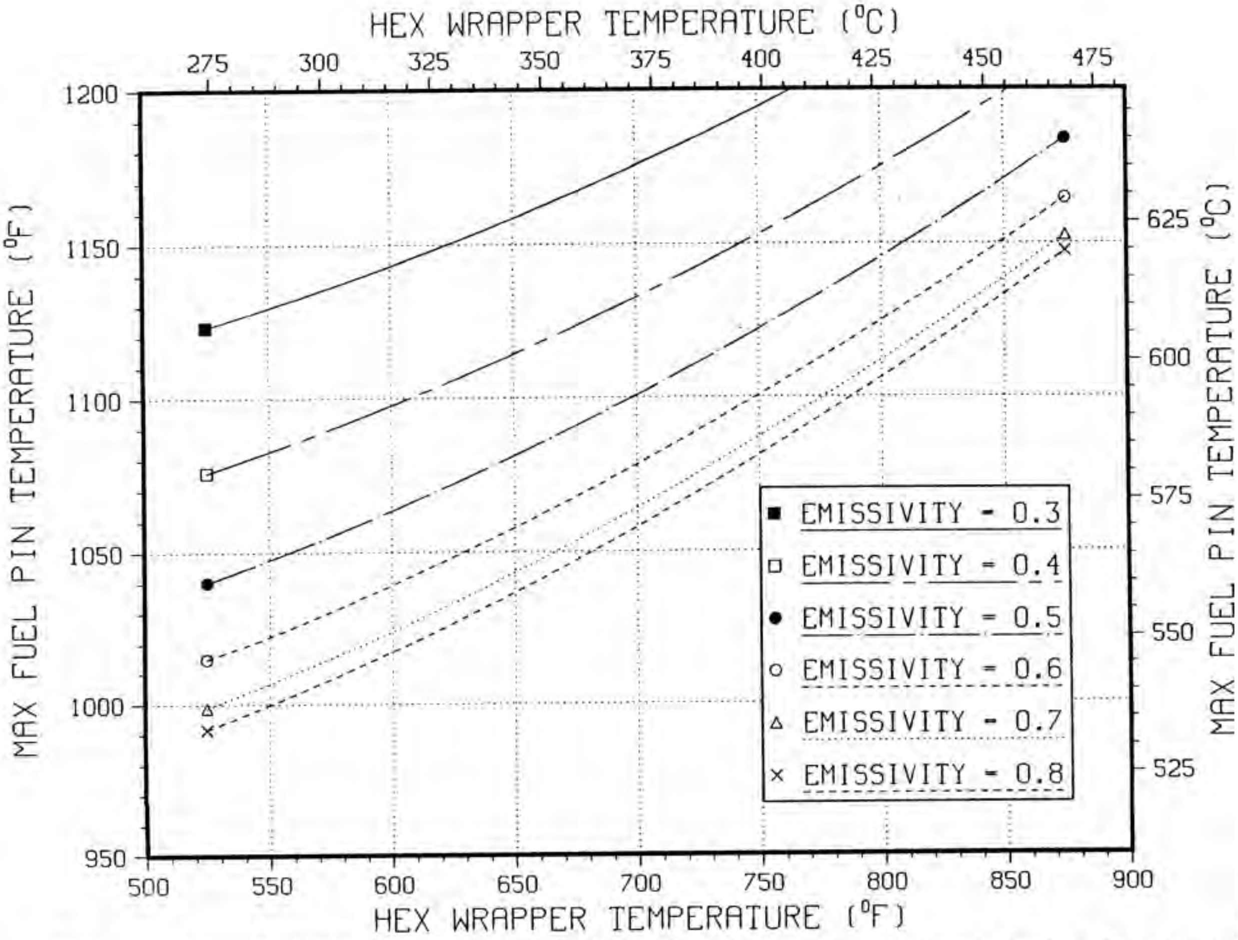

Fig. 5. Maximum Fuel Pin Temperature for Various FFTF Wrapper TEmperatures and Surface Emissivities at a Heat Generation Rate of 1.4 kW/assembly.