THE EFFECTIVE THERMAL CONDUCTIVITY OF A FUEL ASSEMBLY IN A STORAGE CANISTER

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ABSTRACT

Thermal analysis for unconsolidated irradiated fuel assemblies required detailed modeling of individual fuel rods and consideration of various modes of heat transfer between rods. Greater accuracy in these results is achieved by considering the thermal effects of all the neighboring rods. To provide a simple and practical alternative, a method has been developed in which experimental results are combined with the analytical solution, producing an effective thermal conductivity that represents the complex fuel assembly arrangement as a homogenized solid medium.

INTRODUCTION

Within the inner regions of a fuel assembly, heat is transferred between fuel rods by means of radiation, conduction, and natural convection. Thermal analysis of an unconsolidated fuel assembly requires consideration of each fuel rod as a distinct region and introduction of the appropriate radiation shape factors for each region. The analysis becomes more involved when the effects of all the adjacent rods are accounted for.

To perform the thermal analysis for a fuel assembly, an equivalent or effective thermal conductivity for the fuel region is developed, utilizing experimental data obtained from the Spent Fuel Dry Storage Testing at E-MAD (1). These data provide the temperature distribution for different fuel assemblies with various decay heat loads and environments including air, vacuum, and helium. Once the effective thermal conductivity is determined, the fuel clad surface temperature at any location in the fuel assembly can be calculated. Application of this effective thermal conductivity is extended to include several fuel assemblies within a storage cask/canister.

In previous analysis (2), the maximum fuel rod surface temperature was obtained by using the Wooten-Epstein method (2). This methodology has been utilized as an independent verification of the subject analysis. The two methods provide very close correlation in predicting the maximum fuel rod surface temperature for a specified canister temperature.

ANALYTICAL DESCRIPTION

To calculate the effective thermal conductivity of the fuel region, the following method is developed. The fuel assembly can be considered as a finite heat generation slab of thickness 2a, surrounded by another slab of thickness b. The analytical model for the temperature distribution in a heat generation slab is shown in Fig. 1 (3). THe temperature difference between the fuel center and the fuel-canister boundary is equal to:

$$T_o - T_a = \frac{q''' a^2}{2k_f} \qquad \text{(Eq. 1)}$$

where,

a = Half width of the fuel assembly (inch)

k_f = Effective thermal conductivity of fuel region (Btu/min in °F)

q''' = Volumetric heat generation (Btu/min in^3)

T_o = Center fuel temperature (oF)

T_a = Temperature at the canister wall (°F)

The above equation can be rearranged in the form:

$$k_f = \frac{q''' a^2}{2} \frac{1}{(T_o - T_a)} \qquad \text{(Eq. 2)}$$

To develop the temperature dependent values of k_f, experimental results provided by the Spent Fuel Dry Storage Testing at E-MAD (1) are utilized. The data provides the temperature distribution for different fuel assemblies with different decay heat loads and environments including air, vacuum, and helium.

To verify the results, an independent method developed by Wooten-Epstein (2) is utilized. This method introduced a correlation which permits the calculation of maximum fuel rod surface temperatures attained in a fuel assembly. The correlation is as follows:

$$Q = \sigma C_1 F_1 A_1 (T_o^4 - T_a^4) + C_2 A_1 (T_o - T_a)^{4/3} \qquad \text{(Eq. 3)}$$

For a 15 x 15 fuel assembly generating 0.76 kW decay heat with an envelop of 8.9 x 8.9 inch and an active fuel length of 144 inches, the Eq. 3 parameters are:

Q = .76 kW = 2,594 (Btu/hr) Fuel Assembly Decay Heat

σ = 0.1713e 8 (Btu/hr ft^2 R^4) Boltzman's Constant

F_1 = 0.512 = Experimental constant for radiant heat transfer

A_1 = 144(8.9)4/144 = 35.6 ft^2 area of fuel assembly envelope

T_o = Maximum fuel rod surface temperature (° R)

T_a = Canister temperature (° R)

C_2 = 0.118 Experimental constant for convection heat transfer

$$C_1 = \frac{4N}{(N+1)^2} = \frac{4(15)}{(15+1)^2} = 0.2344$$

= geometric factor where N = Fuel rod array of fuel assembly

The experimental constants C2 and F1 were chosen so that the calculated power would be consistently on the low

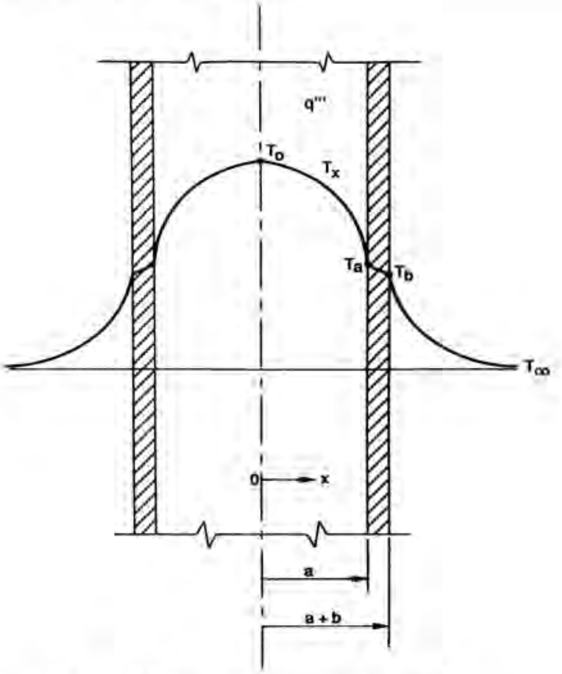


Fig. 1. Canister Temperature Profile.

side of the uncertainty in the measured power Q. Thus for a known Q, Eq. (3) will conservatively overpredict the maximum fuel rod temperature, To. The geometric constant C1 depends on the number of arrays of fuel rods in the assembly. The area of the fuel assembly envelope is designated by A1. Using the experimental canister temperatures to substitute for Ta, one can determine the resulting maximum fuel rod surface temperature.

RESULTS AND CALCULATIONS

For the purpose of this paper, data from the fuel assembly B-43 (1) is used to develop the numeric values of kf. For the fuel assembly B-43 filled with helium and heat generation of 0.76 kW, the canister wall was maintained at 250, 300, 400, and 500 F respectively and the temperature in the center was measured in each case, as shown in Fig. 2 and Table I. Substituting these data into Eq. 2 for To and Ta, the values of kf are developed as presented in Fig. 3 and Table II. The maximum percentage difference in fuel rod temperatures is 2.5%, which demonstrates good agreement between the two methods. As indicated graphically in Fig. 4, both methods provide very close correlation in predicting the maximum fuel rod surface temperature for a specified canister temperature. Similarly, when the helium backfill is replaced with vacuum, the effective thermal conductivity of the fuel assembly for a 0.71 kW heat load is presented in Fig. 5.

CONCLUSION

The effective thermal conductivity of a specific fuel assembly, generated by the combination of the analytical solution and experimental data, provides an essential tool to consider the fuel assembly as a homogenized solid medium. Once this effective thermal conductivity is determined, the fuel clad surface temperature at any point within the fuel assembly can be calculated. The need to obtain an effective thermal conductivity is greatly enhanced when thermal analysis of several fuel assemblies within a storage canister is to be performed. Furthermore, the effective thermal conductivity can be utilized to describe the fuel clad surface temperature distribution within the fuel assembly when the boundary conditions of the canister are non-symmetric.

REFERENCES

1. Spent Fuel Dry Storage Testing E-MAD (March 1978-March 1982), Westinghouse Electric Corporation, PNL-4533, September 1982.
2. Epstein, H. M. and R. O. Wooten, "Heat Transfer From a Parallel-Rod Fuel Assembly," J. A. Bucholz, Scoping Design and Analyses for Optimized Shipping Casks Containing 1-, 2-, 3-, 5-, 7- or 10-year Old PWR Spent Fuel, ORNL/CSD/TM-149 Appendix J, Union Carbide Corporation, Oak Ridge, Tennessee, 1983.
3. Carslaw, H. S. and J. C. Jaeger, Conduction of Heat in Solids, Oxford: Clarendon Press, 1947.

TABLE I

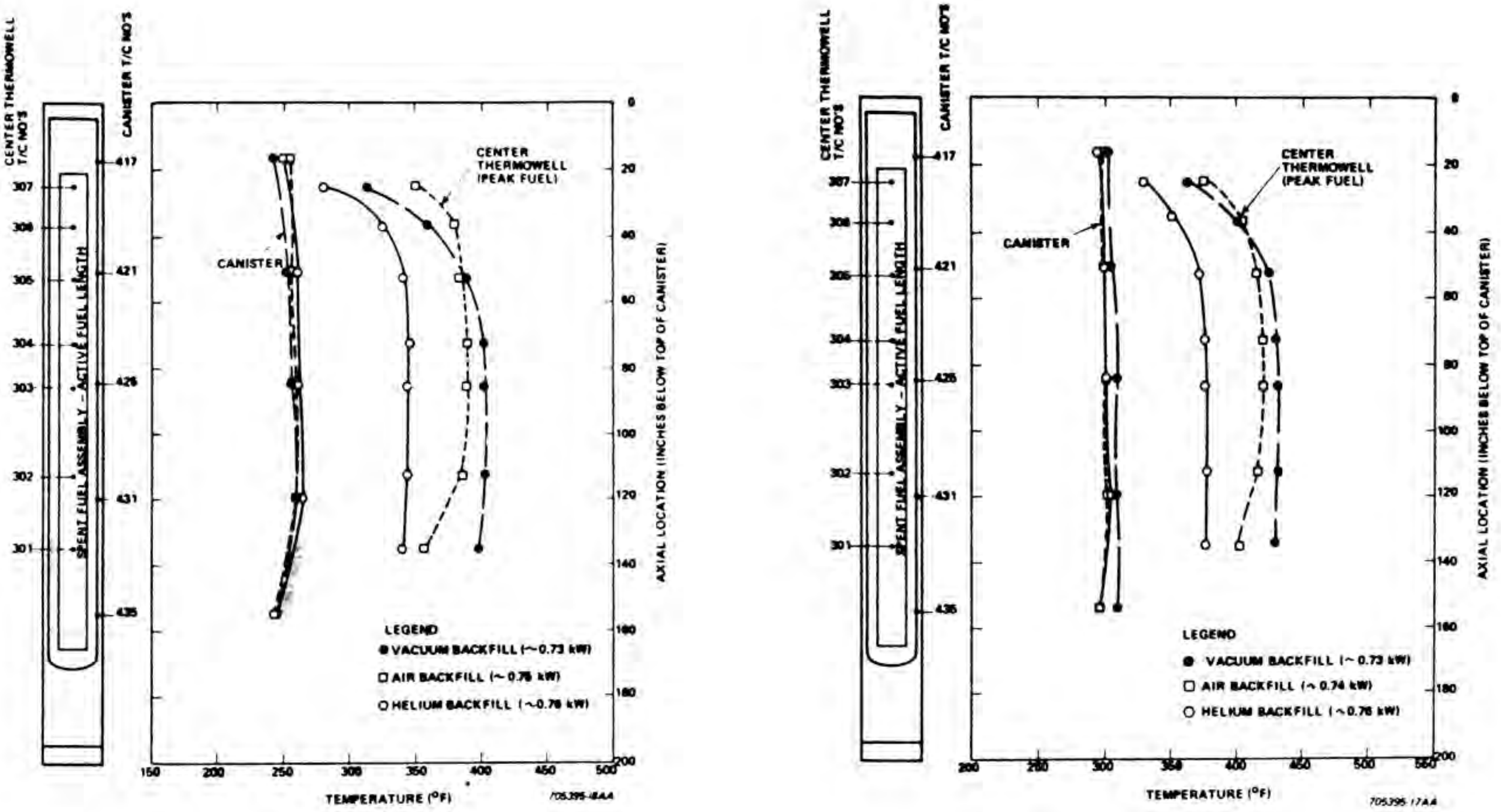
E-Mad Test Data Summary

PROFILE AND CANISTER BACKFILL	PREDICTED DECAY HEAT LEVEL (kW)	CANISTER TEMPERATURE (°F)	CENTER THERMOWELL TEMPERATURE (°F)
250°F CANISTER TEMPERATURE			
VACUUM	0.730	254	402
HELIUM	0.762	259	343
AIR	0.748	256	388
300°F CANISTER TEMPERATURE			
VACUUM	0.728	305	432
HELIUM	0.762	298	378
AIR	0.743	299	419
400°F CANISTER TEMPERATURE			
VACUUM	0.734	398	502
HELIUM	0.761	410	476
AIR	0.741	396	495
500°F CANISTER TEMPERATURE			
VACUUM	0.756	491	570
HELIUM	0.757	489	551
AIR	0.738	493	575

TABLE II

Effective Thermal Conductivity and Fuel Rod Temperature Comparison

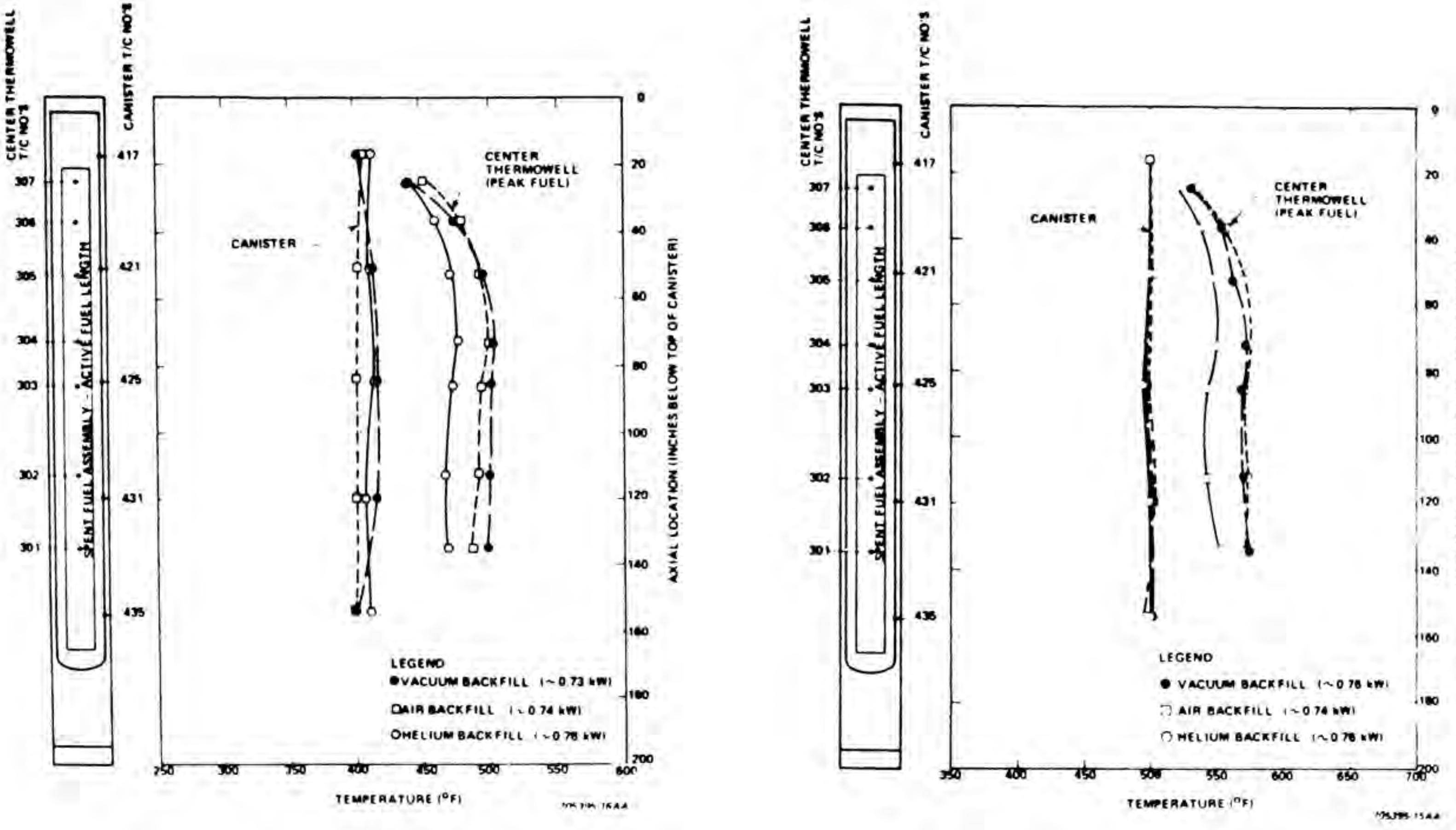
T_a Data (°F)	Westinghouse T_o Data (°F)	NUTECH's k_{eff} $\left(\frac{Btu}{min.\ inch.\ °F}\right)$	NUTECH's T_o (°F)	Wooten-Epstn T_o (°F)
259	345	4.47e-4	344	345
298	378	5.17e-4	370	379
410	476	6.43e-4	468	480
489	551	7.44e-4	548	551



250°F Uniform Canister
Temperature Profile Test
Temperature Profiles (F/A B43)

300°F Uniform Canister
Temperature Profile Test
Temperature Profiles (F/A B43)

Fig. 2. E-Mad Test Data.



400°F Uniform Canister
TemperatureProfile Test
Temperature Profiles (F/A B43)

500°F Uniform Canister
Temperature Profile Test
Temperature Profiles (F/A B43)

Fig. 2. E-MAD Test Data (Continued).

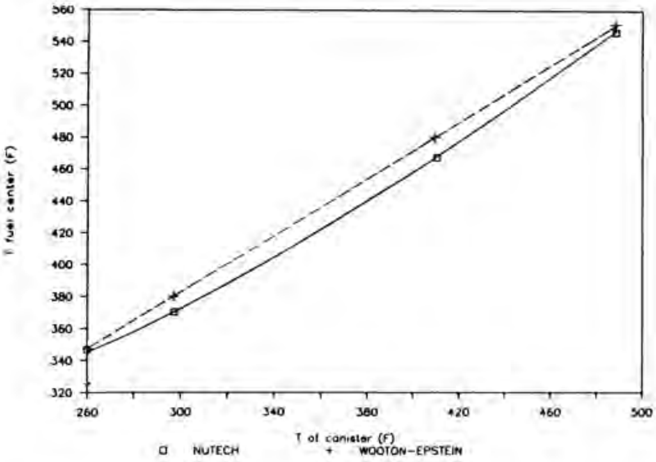


Fig. 3. Effective Thermal Conductivity of the Fuel Assembly (Helium Case).

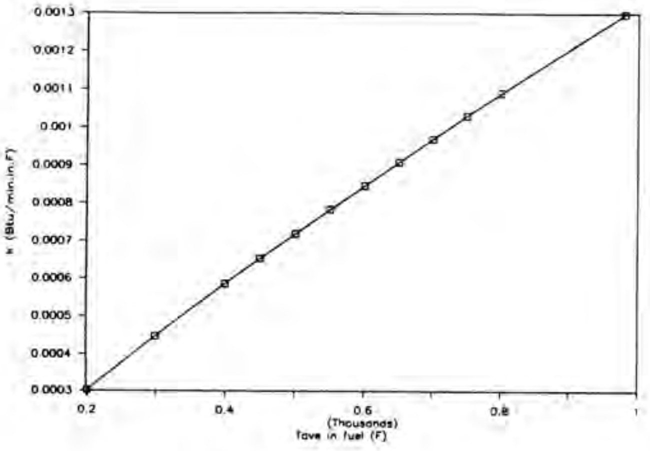


Fig. 4. Comparison of Nutech and Wooten-Epstein Results.

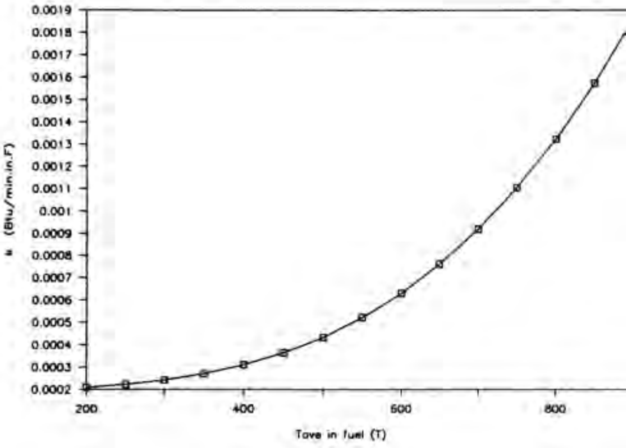


Fig. 5. Effective Thermal Conductivity of the Fuel Assembly Vacuum Case.