# SPENT FUEL PIN TEMPERATURE PC CODE*

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## ABSTRACT

During an annual outage, a Pressurized Water Reactor (PWR) may discharge 60 or more spent fuel bundles into its storage pool. Most early PWRs were built to store 3-5 years of spent fuel in their pools and are beginning to exceed their capacities. One method currently being developed and licensed for expanding spent fuel storage capabilities is the dry storage of spent fuel in large casks. To reduce the probability of gross failures of fuel cladding during dry storage in casks, the fuel pin temperatures must be shown to remain within acceptable limits.

LLNL has developed, for the Nuclear Regulatory Commission, a personal computer (PC) code for calculating fuel pin temperatures on the IBM PC. The code uses the Wooton-Epstein Correlation to calculate the pin temperatures and has been benchmarked against test data. An iterative type of solution is used to calculate the fuel pin temperatures for specified heat fluxes and pin configurations. The PC code is useful in performing confirmatory analyses and comparing the results with those submitted by applicants applying for storage licenses.

## INTRODUCTION

Many of the utilities are running out of storage space in their reactor pools for storing spent fuel. Some of the utilities are considering the use of on-site Independent Spent Fuel Storage Installations (ISFSIs) to store this excess spent fuel. All ISFSIs, both wet and dry types, must be licensed under 10CFR72. To license an ISFSI, a utility must submit a Safety Analysis Report (SAR) to demonstrate that the ISFSI design, construction, and operation complies with the requirements of 10CFR72. For cask storage systems, the SAR may reference a Topical Safety Analysis Report (TSAR) which has been submitted by a cask manufacturer and shows compliance with 10CFR72.

One of the requirements that must be evaluated in a TSAR or SAR is contained in 10CFR72.73(h) which states that the fuel cladding shall be protected against degradation and gross rupture. The primary approach currently used to demonstrate compliance with 10CFR72.73(h) is to limit the fuel pin temperature to a maximum value and to demonstrate that the maximum temperature value is not exceeded during storage operations. Several methods, including computer codes, have been developed or are being developed for calculating the maximum temperatures of fuel pins in fuel bundles.[1-5] The validity and complexity of any method used is usually dependent on the assumptions used in modeling the radiative heat transfer.

One calculational method used extensively in licensing casks for transporting spent fuel is the Wooton-Epstein Correlation (WEC), which was developed at the Battelle Memorial Institute in 1963.[1] The WEC is based on a simplified radiative heat transfer model which replaces the fuel pin rows with equivalent concentric tubes. This paper describes the development and benchmarking of a pin temperature computer code that is based upon the WEC concentric tube model. The pin temperature code is programmed in Basic for the IBM personal computer. The code is used in the evaluation of TSAR and SAR submittals to check their compliance with 10CFR72.73(h).

## SYMBOLS

The symbols used in this paper are the same as those used in Ref. 1 except for changes or additions made for clarification and the use of SI units.

- $A_m$ = Heat transfer area ($m^2$)
- $A_1$ = Area of fuel bundle envelope ($m^2$)
- $C_1$ = Geometric constant (radiation)
- $C_2$ = Empirical dimensional constant (free convection) ($Kw/m^2\ °K^{4/3}$)
- $F_1$ = Empirical constant (radiative)
- I = Ith tube or fuel pin row
- N = Number of rods or pins on side of an array
- Q = $Q_{10}$ =Heating rate of bundle (Kw)
- $T_E$ = Maximum fuel cladding temperature (°K)
- $T_c$ = Cask wall temperature (°K)
- m = Row number beginning at outer row
- n = m - 1
- $\varepsilon$ = Surface emissitivity
- $\sigma$ = Boltzmann constant ($Kw/m^2\ °K^4$)

## ANALYSIS

R. Wooton and H. Epstein performed their investigations with a simulated 17 x 17 PWR bundle in the horizontal position. The tests were performed in atmospheric air and resulted in the following correlation for radiative and convective heat transfer

$$Q = \sigma C_1 F_1 A_1 [T_E^4 - T_c^4] + C_2 A_1 [T_E - T_c]^{4/3} \qquad (1)$$

The determinations of the constants $C_1$, $F_1$, and $C_2$ are discussed in Ref. 1. Wooton and Epstein thought that their correlation, Eq. (1), might be valid for other fuel assembly geometries through the use of appropriate constants, but did not have sufficient data to support their contention. In 1978, R. Cox performed several experiments under vacuum conditions with the hexagon fuel bundle shown in Fig. 1.[2] In reviewing Cox's work, it occurred that his experimental data

* This work was supported by the United States Nuclear Regulatory Commission under a Memorandum of Understanding with the United States Department of Energy.

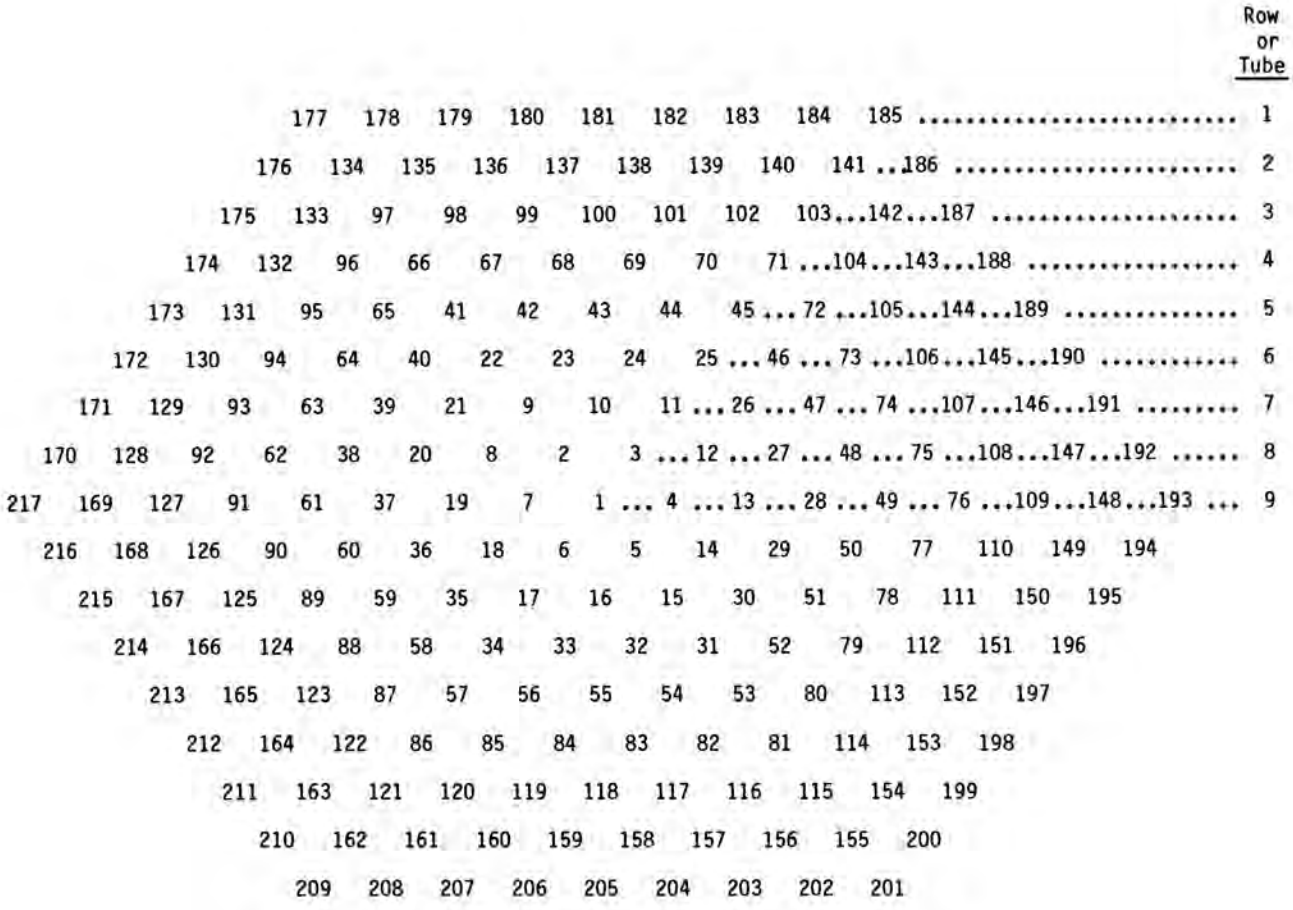


**Fig. 1. Numbering of Fuel Pins and Rows for hexagon array in Ref. 1.**

could be used to benchmark the WEC, Eq. (1), for a hexagon fuel bundle in a vacuum ($C_2 = 0$). Applying the WEC concentric tube model for radiative heat transfer, the configuration factors for hexagon fuel bundles are derived in the following paragraphs.

The hexagon bundle in Fig. 1 has 217 fuel pins and can be modeled as nine equivalent concentric hexagon tubes. The first or outer tube has 9 fuel pins on each of the six sides. The second tube has 8 pins on a side, the third has 7 pins and so on until the ninth tube has only one pin. The radiative heat transfer between any two adjacent tubes is calculated from the relation

$$Q_{mn} = \sigma A_m F_{mn} (T_m^4 - T_n^4) \qquad (2)$$

where

$$F_{mn} \doteq F_1 = \left(\frac{1}{\epsilon_m} + \frac{1}{\epsilon_n} - 1\right)^{-1} \qquad (3)$$

as approximated in Ref. 1. For a series of concentric tubes, the temperature of the Ith hexagon tube is

$$\sum_{m=1}^{I} (T_m^4 - T_n^4) = \frac{1}{\sigma F_1} \sum_{m=1}^{I} \frac{Q_{mn}}{A_m} \qquad (4)$$

or after multiplying and dividing by $Q_{10}/A_1$

$$\sum_{m=1}^{I} (T_m^4 - T_n^4) = \frac{Q_{10}}{\sigma F_1 A_1} \sum_{m=1}^{I} \frac{Q_{mn}}{Q_{10}} \frac{A_1}{A_m} = \frac{Q_{10} C_1}{\sigma F_1 A_1} \qquad (5)$$

As in Ref. 1, $A_m$ is proportional to the number of fuel pins in one side of the hexagon tube and $Q_{mn}$ is proportional to the number of fuel pins inside the tube,

$$\frac{A_1}{A_1} = \frac{9}{9}, \frac{A_1}{A_2} = \frac{9}{8}, \frac{A_1}{A_3} = \frac{9}{7}, \cdots \frac{A_1}{A_m} = \frac{N}{(N - m + 1)} \qquad (6)$$

and

$$\frac{Q_{10}}{Q_{10}} = \frac{217}{217}, \frac{Q_{21}}{Q_{10}} = \frac{169}{217}, \frac{Q_{32}}{Q_{10}} = \frac{127}{217}, \cdots$$
$$\frac{Q_{mn}}{Q_{10}} = \frac{3(N-m+1)(N-m) + 1}{3N(N-1) + 1} \qquad (7)$$

or

$$\frac{Q_{mn} A_1}{Q_{10} A_m} = \left[\frac{N}{N - m + 1}\right] \left[\frac{3(N-m+1)(N-m) + 1}{3N(N-1) + 1}\right] \qquad (8)$$

The temperature of the Ith tube then becomes

$$\sum_{m=1}^{I} (T_m^4 - T_n^4) = \frac{Q_{10}}{\sigma F_1 A_1} \left[\frac{N}{3N(N-1) + 1}\right] \sum_{m=1}^{I} \frac{3(N-m+1)(N-m) + 1}{(N-m+1)} \quad (9)$$

for N = 9 and I = 9

$$T_E = \left[.218\left(\frac{Q_{10}}{\sigma F A_1}\right) + T_c^4\right]^{.25} \quad (10)$$

## COMPUTER CODE

A computer code was written in Basic for the IBM personal computer for calculating fuel pin temperatures for hexagon and square fuel bundles. For hexagon bundles in a vacuum, Eq. (9) is used to calculate the temperature of each fuel pin row of interest. For square bundles in a vacuum, the fuel pin temperature is calculated from

$$\sum_{m=1}^{I} (T_m^4 - T_n^4) = \frac{Q_{10}}{\sigma F_1 A_1} \sum_{m=1}^{I} \frac{N - (2m-2)}{N} \quad (11)$$

When air is present, the fuel pin temperature is initially calculated for vacuum conditions using either Eq. (9) or (11). The resultant heat flow is then calculated using Eq. (1) and the appropriate $C_1$, $F_1$, and $C_2$ values and compared to the specified heat flow. If the difference between the resultant and specified heat flow is greater than .1 percent, a revised pin temperature is calculated as the initial temperature plus 1 percent of the heat flow difference divided by the specified heat flow. This process of revising the fuel pin temperature is repeated until the resultant heat flow converges to within .1 percent of the specified heat flow.

## BENCHMARK RESULTS

Experimental data for five tests are contained in Ref. 1. Using the computer code for a hexagon array, the fuel pin temperatures for each test condition and fuel pin row was calculated. As seen in Table I for the first test, the calculated and measured results for each fuel pin row agree quite well with each other for a clad emissivity equal to .55, which is typical for stainless steel for the described coloration and temperature conditions. The agreement between the calculated and measured results begins to diverge at the three outer rows, which might be expected for this simple model which replaces the pins with equivalent tubes.

The calculated and measured results for the other four experiments were also in good agreement. In Table II, the temperature results for the central pin are summarized for the five experiments. Agreement between the temperature results was improved for the last two experiments which used a different test assembly when the assumed emissivity was .6.

## CONCLUSIONS

The benchmark results show that the WEC can be used to calculate spent fuel pin temperatures in hexagon fuel assemblies under vacuum conditions. Under atmospheric conditions with air or helium, the empirical convection constant, $C_2$, measured by Wooton and Epstein, may be used to conservatively calculate the heat flow due to convection and conduction. Although the WEC and the associated computer code are limited to analyzing symmetrical geometries and temperature distributions, they have been useful at the Lawrence Livermore National Laboratory in performing sensitivity studies and evaluating SAR submittals for a variety of spent fuel configurations and conditions.

**TABLE I**
Fuel Pin Temperatures
Run No. 1 from Ref. 1
Assumed $\varepsilon$ = .55

| Row No. | Pin No. | Measured Temperature °K | Calculated Temperature °K |
|---|---|---|---|
| 1 | 209 | 568 | 564 |
| 1 | 185 | 572 | 564 |
| 1 | 170 | 578 | 564 |
| 1 | 196 | 588 | 564 |
| 2 | 155 | 601 | 606 |
| 2 | 147 | 617 | 606 |
| 3 | 97 | 635 | 636 |
| 3 | 126 | 643 | 636 |
| 4 | 71 | 656 | 658 |
| 5 | 57 | 672 | 675 |
| 6 | 31 | 684 | 686 |
| 9 | 1 | 700 | 699 |

**TABLE II**
Center Pin Temperatures
Five Experiments from Ref. 1

| Run No. | PDR | Measured Temperature °K | Assume $\varepsilon$ | Calculated Temperature °K |
|---|---|---|---|---|
| 1 | 1.36 | 700 | .55 | 699 |
| 2 | 1.36 | 812 | .55 | 811 |
| 3 | 1.36 | 702 | .55 | 709 |
| 4 | 1.24 | 703 | .60 | 716 |
| 5 | 1.24 | 810 | .60 | 812 |

## REFERENCES


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