PHOENIX MEMORIAL LABORATORY

MEMORANDUM REPORT NO. 5

# Fission Product Heating in the Ford Nuclear Reactor

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## INTRODUCTION

The subject of fission product heating in the core of the FNR was briefly considered in Memorandum Report Number 2, dated June 1962. However, the conclusions of Report No. 2 were based on a misinterpretation of units for the power density of the ORR fuel elements. This report makes use of the corrected power density to re-examine the capabilities of the FNR core to dissipate the fission product power in the event of a severe pool water leak. The postulated accident under consideration is that of a pool water leak which results in the loss of coolant water from the reactor core. The leak is assumed to be 8 inches in diameter and uncontrollable. The reactor is assumed to have a power history of 100 hours at a power level of 2 MW. Experimental data and theoretical considerations are presented which lead to the conclusion that fuel clad melting due to fission product heating will not occur under the conditions of the postulated accident.

## I. THEORETICAL CONSIDERATIONS

Since the location of the leak is not completely predictable, two significantly different situations are possible. The two different situations are 1) a leak which results in the final water level being below the bottom of the core and 2) a leak which results in the final water level being somewhere between the top and the bottom of the core. Memorandum Report No. 2 indicated that a minimum of 690 seconds is required before the water level falls below the top of the core. Since the pool level alarm would result in a manual scram of the reactor during the first 90 seconds, the minimum fission product decay time is 600 seconds. Thus, the fission product power is estimated by assuming total absorption of all the beta and gamma energy, 600 seconds after shutdown following 2 MW operation for 100 continuous hours.

The F. P. density distribution is assumed to be the same as the operating flux density distribution, i.e., the operating power density distribution. To assess the distribution of the fission product heat-power it must be noted that it will be directly dependent on the beta and gamma absorption distribution. For a conservative approximation, the F. P. heat-power will be made the same as the flux distribution of the operating reactor core. From Memorandum Report No. ~~2~~ 1 dated, June 1962 the ratio of the maximum to average power density for the operating reactor was found to be 1.63. Hence, the power density in the center of the central element will be 63% higher than the average for the total core. The axial distribution for the central element has a maximum to average power density of 1.11, thus the average power density in the central element is:

$$\bar{P}_{(central)} = \frac{1.63\,\bar{P}_{(core)}}{1.11} = 1.47\,\bar{P}_{(core)}$$

After a review of the geometrical arrangement of the central fuel element in the FNR core, it is condluded that the important mechanisms for heat transfer are: 1) internal convection between individual fuel plates, 2) conduction up and down fuel plates to air and/or water at the ends, and 3) in the event of boiling water at the bottom, steam convection up the coolant channels.

The geometrical arrangement for the FNR is too complex to permit calculations of sufficient rigor to yield reliable results. The application of ultra-conservative assumptions simplifies the equations and permits solutions but the results are inconclusive. Fortunately experimental results exist which can be interpreted to provide meaningful information for the FNR.

## II. EXPERIMENTAL INFORMATION

Experimental work which can be extrapolated to the FNR conditions was reported by J. F. Wett, Jr.(1) Using the data presented in figure 7 of Wett's paper, one may plot fuel element power vs maximum cladding temperature. Since the fuel elements are very similar, this curve can be extrapolated to FNR conditions to predict an expected maximum cladding temperature.

Since the central element of the FNR is surrounded by fuel elements and not stagnant air, corrections for external radiation and convection losses for a single fuel element suspended in air must be applied to the ORR data before a comparison to FNR conditions can be made. These losses are subtracted from the total power of the ORR element to arrive at the power dissipated by internal convection, end conduction and end radiation. This will be defined as the net power.

### A. Radiation Losses

The temperature profiles for ORR fuel element OR-164 are presented in figure 1. The curves are duplicates of those shown in figure 7 of Wett's paper except for the omission of Wett's data points for clarity. Assuming that the outside surface temperature is equal to the inner plate temperature shown in figure 1, conservative estimates of the radiation loss will be made for each of the three decay levels noted in figure 1.

The radiation losses are proportional to $T^4$, thus a significant error is introduced if a uniform temperature equal to T max is assumed. To reduce this error the temperature profiles in figure 1 were approximated by a clipped-sine function of the form

$$T_{(x)} = T_{max} \operatorname{Sin} \pi \left( \frac{x + C}{L + 2C} \right).$$

where x = length along the fuel plate

L = length of the fuel plates

C = fitting parameter

Using this equation and a properly selected value for the fitting parameter C, calculations of $T_{(x)}$ were made for several values of x. The results of the calculations are displayed in figure 1 as small black circles. It is noted that each equation fits the data on the conservative side, i.e. the radiation loss estimate will be high.

The equation for the radiated power for each case is developed in Appendix I and is given by:

$$Q = p\sigma\epsilon \left( \frac{T_{max}}{100} \right)^4 \left( \frac{L + 2C}{\pi} \right) \left\{ \left[ \frac{1}{32} \operatorname{Sin} 4 t_u - \frac{1}{4} \operatorname{Sin} 2 t_u + 3/8\, t_u \right] - \left[ \frac{1}{32} \operatorname{Sin} 4 t_L - 1/4 \operatorname{Sin} 2 t_L + 3/8\, t_L \right] \right\} - p\sigma\epsilon \left( \frac{T_a}{100} \right)^4 \left( X_u - X_L \right)$$

where $t_U = \pi \left( \frac{X_U + C}{L + 2C} \right)$

$$t_L = \pi \left( \frac{X_L + C}{L + 2C} \right)$$

To include the radiation loss from the end pieces, the values for the limits on X are:

$X_L$ = -.50 ft.

$X_U$ = +2.5 ft.

The only temperature dependent emissivity data for oxidized aluminum found in the literature[2] is plotted in figure 2. Since the emissivity increases with temperature, using the emissivity corresponding to $T_{max}$ will give a conservative result.

Sample calculations for the radiation loss are given in Appendix 1. The results of the calculations for each decay level of OR-164 are listed in Table 1 under radiation loss.

B. Convective Losses

The external surface convection loss is made conservative by assuming a uniform surface temperature equal to the maximum temperature measured in each case. The pertinent correlation equation,

$$Nu = 0.59 \ (Gr \ Pr)^{0.25}$$

where Nu = Nusselt's number

Gr = Grashof's number

Pr = Prandtl's number

was taken from McAdams[3] (eq. 7-4b). The results for the three cases are listed in Table 1 under convection loss. Sample calculations are given in Appendix II.

C. Total Element Power

The fission product power in OR-164 was calculated by the Way-Wigner formula[1],

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$$\frac{P}{P_o} = 6.22 \times 10^{-2} \left[ t^{-0.2} - (T + t)^{-0.2} \right].$$

t = cooling time (sec)
T = Reactor ON time (sec)

Using this equation the total power of the ORR element for each of the three decay levels was calculated and listed in Table 1.

The net power i.e., the power dissipated by mechanisms other than external radiation and external convection is estimated by subtracting the sum of the radiation loss and the convection loss, from the total (Way-Wigner) F. P. power. The results for each decay power level for OR-164 are presented in Table 1 under the heading Net Power. Figure 3 is a plot of the net power for OR-164 vs the maximum observed cladding temperature (figure 1). This curve displays the relationship between the maximum cladding temperature and the fuel element heat dissipated by mechanisms other than external radiation and external convection.

Using the same Way-Wigner correlation shown above, the F. P. power for the central element of the FNR, 10 minutes after shutdown from 100 hours operation at 2 MW, gives:

$$FNR_{max} = 1.83 \text{ KW}$$

Table 1 - Summary of Calculations

| Cooling - Hrs. | Way-Wigner F. P. Power | Radiation Loss | Convection Losses | Net Power | $T_{max}$ (°F) in Element |
|---|---|---|---|---|---|
| 19.25 | 2220 | 200 | 209 | 1811 | 650 |
| 40.25 | 1668 | 85 | 166 | 1417 | 520 |
| 61.0 | 1370 | 52.3 | 143.5 | 1174 | 460 |

Note: All power and loss numbers are in units of watts.

Since the central element of the FNR cannot dissipate heat by external radiation or external convection the 1.83 KW is defined as a net power dissipation requirement. From figure 3 it is noted that extrapolation to a net power of 1.83 KW predicts a maximum cladding temperature of 660°F.

The net power of the FNR central element and the 19 hour decay OR-164 element are sufficiently close to permit a direct extrapolation of the partial submergence data shown in figure 11 of Wett's report. It is noted that any water level along the fuel plates results in lower maximum temperatures than the free air case.

The ORNL experiment did not investigate temperature profiles for water levels below the bottom of the fuel plates. Since this results in an 18 fold decrease in the conduction area to the water it is expected that this would result in the highest cladding temperature for the partial submergence case.

The final question to be answered is whether or not water levels below the fuel plates will result in cladding temperatures greater than those predicted for the free air case. This question has been resolved experimentally by constructing a fuel channel mock-up and observing the temperature profiles with and without water blocking the bottom of the channel.

## III. DISCUSSION OF EXPERIMENT

A single fuel channel was constructed in accordance with the material and dimensional specifications for the FNR fuel element. A sketch of this channel is shown in figure 4. The side pieces were extended down below the fuel plates as in the actual element and were milled to give a total cross-sectional area equal to 1/18 the total cross-sectional area of an FNR fuel element at any section between the bottom of the fuel plates and the top of the end piece. The simulated conduction area thus corresponds to the region of minimum axial conduction area.

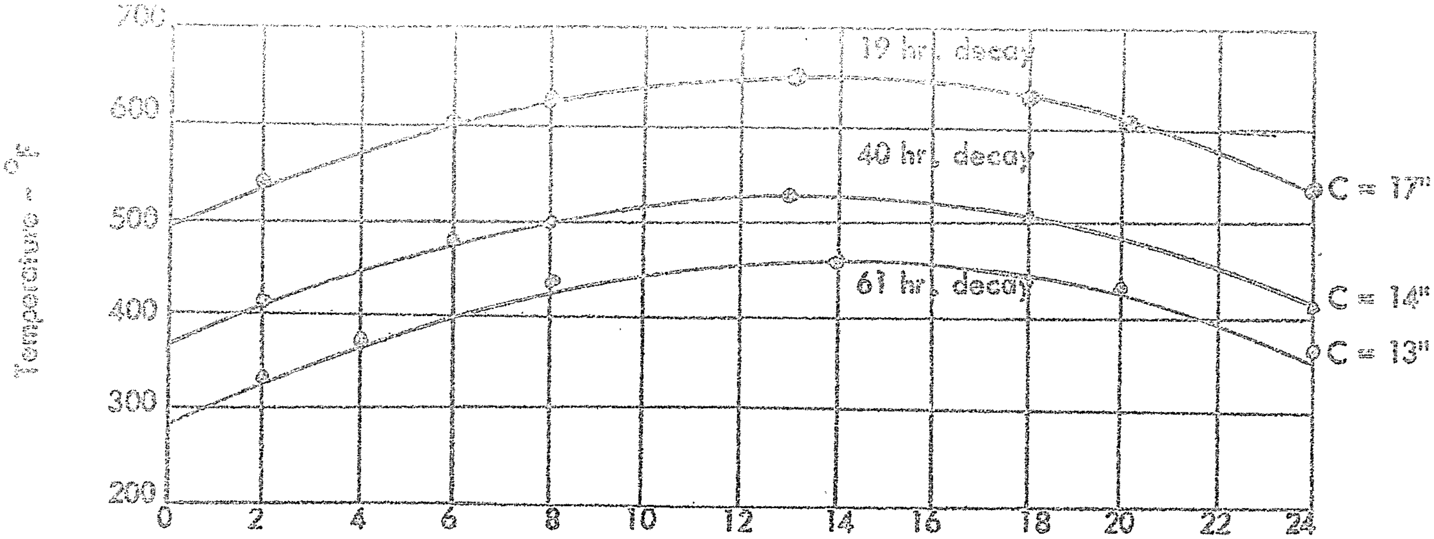
The channel was heated by a specially constructed muffle oven equipped with a guard heater and 8 gradient measuring thermocouples. See figure 5. The channel was carefully sealed in the oven channel with the side edges extending out the bottom into a 1.0 liter water reservoir. The experiment was performed with a channel power of 150 watts which is 8% higher than the F. P. power from Perkins and King[4] and 31% higher than the Way-Wigner correlation. The increased power in the experiment was to insure that any errors in power determination be on the conservative side. Three thermocouples were attached to the fuel channel plate and the temperatures recorded at the equilibrium condition with water at the bottom of the channel. The water was then removed and upon reaching equilibrium it was noted that all the channel temperatures increased. The results are as follows:

| Thermocouple Location | Reading | Experimental Condition |
|---|---|---|
| 2" from top | 536°F | Wet |
| Center of plate | 586°F | Wet |
| 2" from bottom | 447°F | Wet |
| 2" from top | 566°F | Dry |
| Center of plate | 632°F | Dry |
| 2" from bottom | 532°F | Dry |

## IV. CONCLUSIONS

The calculations in this report have all been made with conservative assumptions to insure that the predicted cladding temperature for the FNR central fuel element be a conservative maximum. Both the experimental work done at the laboratory and the interpretation of the ORNL data have neglected the effect of the aluminum grid plate in which the FNR elements are seated when in the reactor core. Experimental data on the LITR[5] indicates that conduction to the grid plate may significantly lower the maximum cladding temperature.

In view of the considerations and results presented above, it is concluded that the maximum temperature of the cladding material in the FNR, 10 minutes after shutdown following 100 hour operation at 2 MW, will be less than 700°F.




Note: The circles indicate points calculated from the clipped sine function with the indicated value of C.

Figure 1

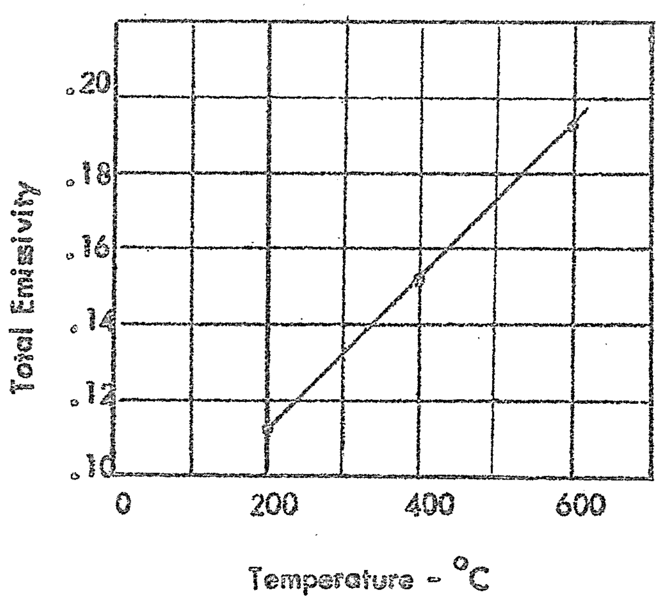



Figure 2 - Total Emissivity of Oxidized Aluminum vs Temperature.

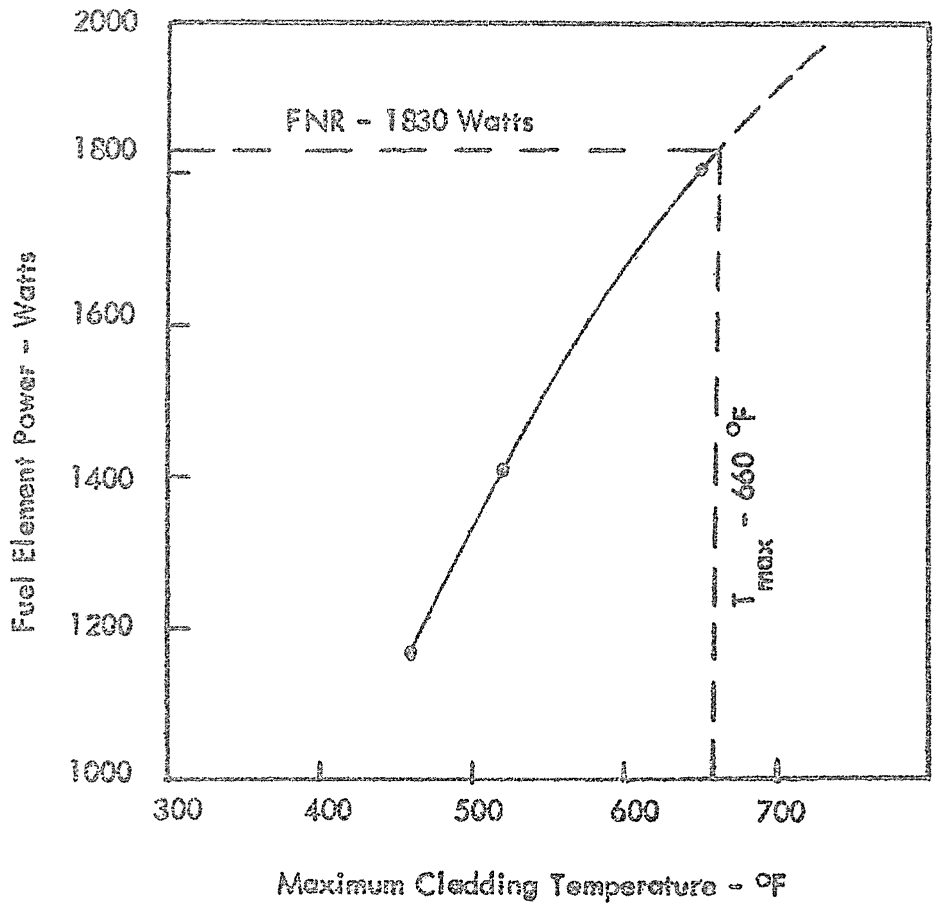



Figure 3 - Maximum Cladding Temperature vs Fuel Element Power.

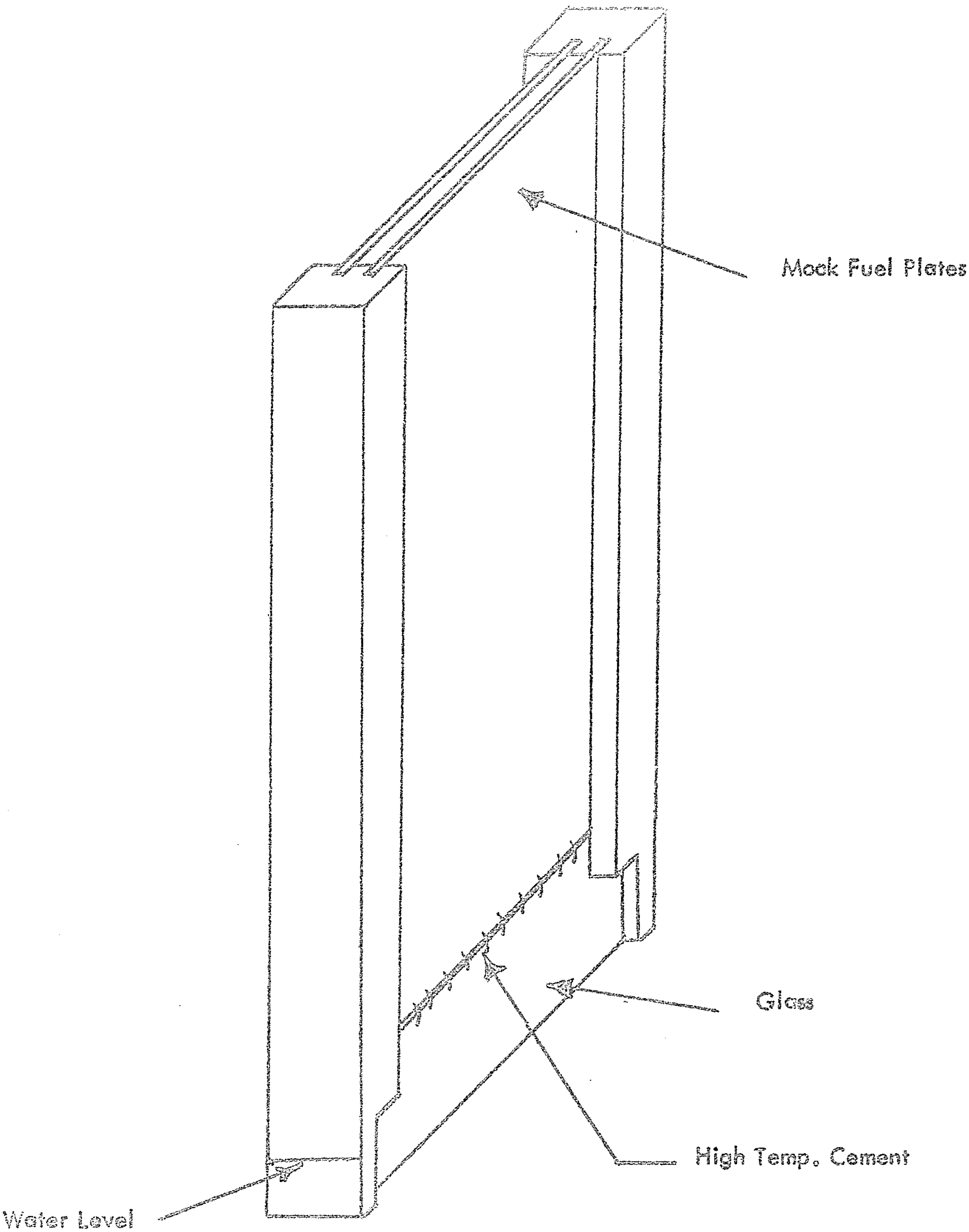



Figure 4 - Sketch of Fuel Channel Mock-up

MUFFLE OVEN

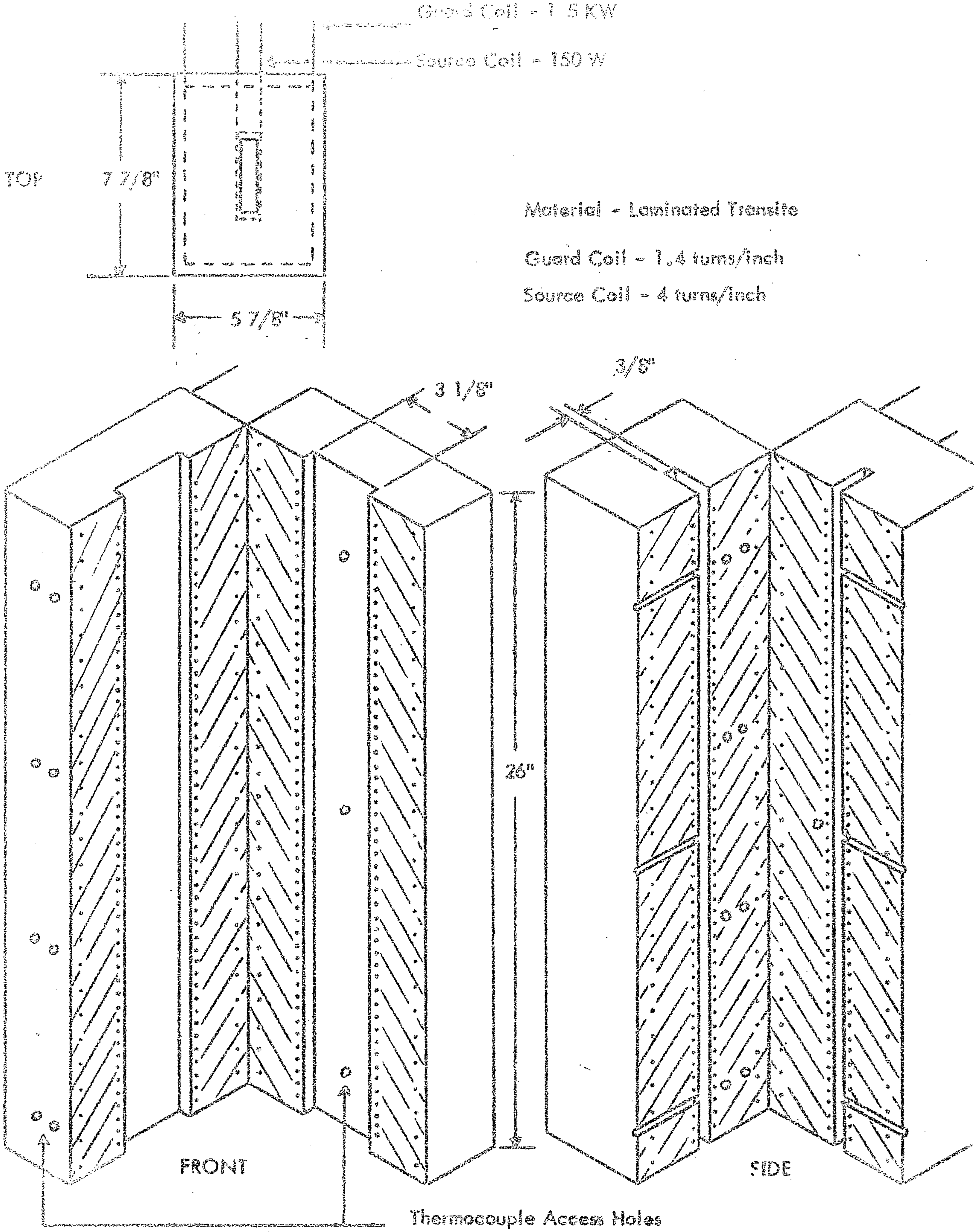



**Figure 5 Muffle Oven**

# APPENDIX I

## Radiation Loss Calculations

From equation 4-9 of Reference 3, the fundamental radiation equation is given as:

$$Q/A = C_1 \left[ \left( \frac{T}{100} \right)^4 - \left( \frac{T_a}{100} \right)^4 \right] \tag{1}$$

The temperature of the ORR element is not constant but over a small axial segment dx it may be considered constant, so

$$dQ/pdx = C_1 \left[ \left( \frac{T_{(x)}}{100} \right)^4 - \left( \frac{T_a}{100} \right)^4 \right] \tag{2}$$

where p is the perimeter of the element (1.0 ft.). If the temperature is now represented by the clipped sine function

$$T_{(x)} = T_{max} \operatorname{Sin} \pi \left( \frac{x + C}{L + 2C} \right) \tag{3}$$

Equation (2) may be written as

$$dQ = pC_1 \left[ \left( \frac{T_{max}}{100} \right)^4 \operatorname{Sin}^4 \pi \left( \frac{x + C}{L + 2C} \right) - \left( \frac{T_a}{100} \right)^4 \right] dx \tag{4}$$

The total heat radiated from an element of length L is then obtained by integrating equation (4) as follows:

$$Q = pC_1 \left(\frac{T_{max}}{100}\right)^4 \int_0^L \sin^4 \pi \left(\frac{x + C}{L + 2C}\right) dx - pC_1 \left(\frac{T_a}{100}\right)^4 \int_0^L dx \quad (5)$$

or

$$Q = pC_1 \left(\frac{T_{max}}{100}\right)^4 \left(\frac{L + 2C}{\pi}\right) \left[\frac{1}{32} \sin 4t - \frac{1}{4} \sin 2t + \frac{3}{8} t\right] \Bigg|_{t(lower)}^{t(upper)}$$

$$- pC_1 \left(\frac{T_a}{100}\right)^4 \left(X_u - X_L\right) \quad (6)$$

where $t = \pi \left(\frac{x + C}{L + 2C}\right)$

so that:

$$t_{(lower)} = \pi \left(\frac{X_{lower)} + C}{L + 2C}\right) \quad (7)$$

and

$$t_{(upper)} = \pi \left(\frac{X_{(upper)} + C}{L + 2C}\right) \quad (8)$$

As indicated in the text, the final calculations included radiation losses from the end pieces of the ORR element which extend 1/2 ft. past the 2.0 ft. fuel plates. The proper values of the parameter to be used in evaluating equation (6) are:

$$t_{(lower)} = \pi \left( \frac{-.50 + C}{2.0 + 2C} \right) \qquad (9)$$

and

$$t_{(upper)} = \pi \left( \frac{2.5 + C}{2.0 + 2C} \right) \qquad (10)$$

The numerical evaluation of equation (6) requires the following constants:

$$C_1 = \sigma \epsilon$$

where

$\sigma$ = Stefan-Boltzmann constant which is .0502 watts/ft.$^2$ $^\circ R^4$ when used with $(T/100)^4$. (Pg. 59 ref. 3)

$\epsilon$ = Select the value from figure 2 corresponding to $T_{max}$ for each case being evaluated.

L = Length of fuel plate - 2.0 ft.

C = Select appropriate value from figure 1 and convert to units of feet.

p = Perimeter of element cross-section - 1.0 ft.

$T_a$ = Ambient temperature 544 $^\circ$R.

$T_{max}$ = Maximum measured temperature $^\circ$R.

Calculated values for the individual terms are presented in Table 2 as follows:

Table 2

| Decay Case | $T_{max}$ | $\epsilon$ | C | $\frac{L + 2C}{\pi}$ | $t_u$ | $t_L$ | $Sin4t_u$ | $Sin4t_1$ | $Sin2t_u$ | $Sin2t_1$ | $pC_1\left(\frac{T_a}{100}\right)^4 (X_u \; X_L)$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 19.25hr. | 650°F | .170 | 1.42ft. | 1.54ft. | 2.71ft. | .60ft. | -.839 | .656 | -.629 | .933 | 23 watts |
| 40.25 | 520 | .140 | 1.17 | 1.38 | 2.65 | .486 | -.940 | .927 | -.809 | .825 | 19 |
| 62.0 | 460 | .128 | 1.08 | 1.33 | 2.70 | .437 | -.895 | .982 | .643 | .766 | 17 |

## APPENDIX II

Example of Convection Loss Calculations

<u>Case - 19.25 hr. decay</u>

Assuming $T_{amb.} = 70^{\circ}F$

$\Delta T = 360^{\circ}F$

From figure 7-8 of reference 3

$\phi = 2.2 \times 10^{5}$

Since $L = 2.0$ and

$Gr\ Pr = L^{3} \Delta T \phi$

$(Gr\ Pr)^{.25} = 159$

Since $Nu = 0.59 \left(Gr\ Pr\right)^{.25}$

$Nu = 93.8 = \dfrac{hL}{K_f}$.

So $h = .99$ BTU/hr. - ft.$^{2}$ - $^{\circ}F$

Or $Q = 209$ watts

# REFERENCES


1. Wett, Jr., J. F., Surface Temperature of Irradiated ORR Fuel Elements Cooled in Stagnant Air. ORNL-2892, Oak Ridge National Laboratory; Oak Ridge, Tenn., 1960.

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5. Beall, S. E., An Experimental Determination of Fission Product Heating After Shutdown of the LITR, ORNL-1075, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 1951