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AN ANALYSIS OF THE DISTURBANCE OF A URANIUM OXIDE CAPSULE SURFACE TEMPERATURE DISTRIBUTION RESULTING FROM A THERMOCOUPLE ATTACHED TO THE INSIDE SURFACE

P. H. Newell

ABSTRACT

This study was initiated to determine the precision with which surface temperature measurements could be made in irradiation capsules containing ceramic fuel. A thermocouple was considered to be positioned in a longitudinal groove prepared in the uranium oxide and metallurgically bonded to the inside surface of the stainless steel clad. A fuel capsule having a 3/4 inch outside diameter, designed as a segment of the EGCR fuel element, and operating with a heat generation rating of 27,500 Btu/hr/lineal foot was assumed. The finite difference approximation was employed to study both the grounded and the ungrounded types of thermocouple junctions. It was found that when a short dummy lead is positioned axially adjacent to the thermocouple junction deviations of about 118°F and 101°F are obtained for the grounded and ungrounded junction, respectively; in both cases the indicated temperatures are in excess of the undisturbed clad surface temperatures.

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INTRODUCTION

In October, 1959, the thermocouple conduction error was investigated by the author in conjunction with a gas-cooled capsule experiment. This study, concerned with the temperature distribution in the proximity of the thermocouple junction for the case where the leads approached the clad surface angularly from the fluid stream, indicated a temperature depression at the junction of 150 to 250°F, depending upon the geometry.

The relationship developed for this situation is

$$t_o = N - \frac{\sqrt{h' P k' A'}\,(N - t_g) - \pi r_s^2 q/A}{2 \pi k \delta \epsilon r_s K_1 (\epsilon r_s)/K_o (\epsilon r_s) + \sqrt{h' P k' A'}}$$

where t_o is the temperature indicated by the thermocouple, N is the "true" or undisturbed surface temperature, r_s is the radius of the thermocouple junction, δ is the clad thickness, t_g is the coolant temperature, k' is the effective thermal conductivity of the thermocouple leads, A' is the cross sectional area of the thermocouple leads, P is the perimeter of the thermocouple sheath, h' is the convective coefficient between the thermocouple leads and the coolant stream, k is the thermal conductivity of the clad material, ϵ is $\sqrt{h/k\,\delta}$ —h being the unit convective conductance between the clad surface and the coolant stream, q/A is the rate at which heat is being transferred through the clad material per unit area of clad surface, and K_1 (ϵr_s) is the first order modified Bessel function of the second kind.

In August, 1960, the study was resumed in conjunction with another gas cooled capsule experiment. The object of this endeavor was to determine the circumferential variation in the clad surface temperature ("Hot Streak Factors") resulting from thermocouple leads being attached to the cladding by weldments. The results indicated that a 20 to 100°F circumferential temperature variation could be expected depending upon the geometry of the weldment affixing the thermocouple lead to the clad surface. The clad temperature in the vicinity of the thermocouple lead would be greater than the undisturbed clad surface temperature for the parameters chosen (e.g. large convection coefficient). Deviation between the thermocouple indication and the unaffected clad temperature would be 90 - 130°F and err on the low side.

Thus it is seen that the measurement of clad surface temperatures which are exposed to a flowing fluid is at best inhibited when one attempts to bring thermocouples to the surface via the fluid stream.

It was the purpose of the present study to determine the feasibility of placing a thermocouple in an axial groove prepared in the uranium oxide and attached to the inside clad surface. See Figure 1.

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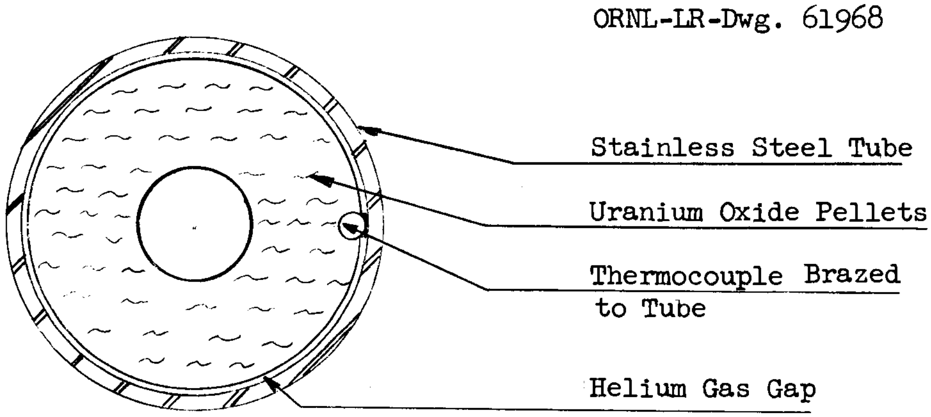

Fig. 1. Cross Sectional View of Capsule

STATEMENT OF THE PROBLEM AND THE PROBLEM PARAMETERS

To determine the effect of placing a thermocouple in an axial groove in the uranium oxide in a general manner would be desirable; however, the application of the boundary conditions to a formal solution would be tedious. The finite-difference approximation was employed in this study. The Matrix Package Routine was perused, and it was observed that the current memory capacity limited the number of equations and variables which could be handled to twenty. Having need for a somewhat finer mesh rendering 25 to 30 equations, the system of equations was solved utilizing Southwell's relaxation technique*.

The following is a description of the geometries involved and an identification of the parameters studied in the problem. Refer to Fig. 1. The clad material was taken as type 304 stainless steel tubing, 0.75 in. OD x 0.020 in. wall. The uranium oxide pellets were assumed to be 0.706 in. OD and 0.323 in. ID. The coolant was assumed to be helium at an average bulk temperature of 950°F and to exhibit an average convective heat transfer coefficient of 280 Btu/hr-ft^2 °F. The heat rate employed was assumed to result from uniform heat generation within the uranium oxide and amount to 140,000 Btu/hr per sq ft of clad surface (27,500 Btu/hr per lineal ft). Gamma heating was ignored since it is expected to be but a very small fraction of the total heat rate in the EGCR. The thermocouple was assumed to be type 347 stainless steel sheathed, magnesium oxide-insulated, 0.040 in. OD x 0.008 in. wall containing 0.005 in. dia. chromel-alumel wires.

The thermal conductance for the uranium oxide-clad interface was taken as a uniform 0.001 in. radial helium gas gap, while the uranium oxide-thermocouple interface conductance was studied for 0.001 in. and

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*The writer considered using a graduated network and developed a procedure for so doing, having found the current literature inadequate in this regard. This technique could be employed in any future analysis thus rendering a machine calculation applicable; or one could employ or devise some other machine program.

0.003 in. radial helium gas gaps. Based on the results of similar perturbation studies in this type of capsule, the simplification was imposed that the local temperature disturbance terminate on a radial boundary located at an angle of 30° with a similar radial line passing through the center of both the pellet and the thermocouple and close on a circumferential boundary at 0.2105 in. radius. See Figure 2. End effects and axial conduction were neglected. An evaluation of these assumptions will be given. Other properties which were germane are listed as follows:

Thermal conductivity of Uranium Oxide: 1.0 Btu/hr ft °F
Thermal conductivity of Stainless Steel: 12 Btu/hr ft °F
Thermal conductivity of Helium: 0.2 Btu/hr ft °F
Thermal conductivity of Magnesium Oxide: 0.35 Btu/hr ft °F
Thermal conductivity of Braze Metal: 12 Btu/hr ft °F

Utilizing the above design criteria, properties, and the logarithmic networks as shown in Figures 2, 3 and 4 for the finite difference approach, the following parametric variations were studied.

Case 1. Undisturbed Temperature Distribution
(i.e., No Groove Existing)

A closed, analytical solution was practicable for this case and is given as follows:

The outside clad surface temperature is ascertainable since

$$q = h\,A\,(t_{\text{outside clad surface}} - t_{\text{bulk fluid stream}})$$

thus

$$t_{\text{outside clad surface}} = \frac{140{,}000}{280} + 950 = 1450°F$$

The inside clad surface temperature may be found by

$$q = \frac{2\,\pi\,k\,\ell(t_{\text{inside clad surface}} - t_{\text{outside clad surface}})}{\ell n\,\frac{do}{di}}$$

whence

$$t_{\text{inside clad surface}} = \frac{27,500 \, \ell n \, \frac{0.75}{0.710}}{2 \, \pi \, (12)} + 1450 = 1470^{\circ}F$$

Similarly the outside surface temperature of the uranium oxide can be determined by the temperature drop across the helium gas annulus since

$$q = \frac{2 \, \pi \, k \, \ell \, (t_{\text{outside uranium oxide surface}} - t_{\text{inside clad surface}})}{\ell n \, \frac{d_{\text{inside clad surface}}}{d_{\text{outside uranium oxide surface}}}}$$

Then

$$t_{\text{outside uranium oxide surface}} = \frac{27,500 \, \ell n \, \frac{0.710}{0.708}}{2 \, \pi \, (0.21)} + 1470 = 1530^{\circ}F$$

At an arbitrary radius in the uranium oxide

$$\frac{q_r}{\ell} = -k \, (2 \, \pi \, r) \, \frac{dt}{dr} = G \, \pi \, (r^2 - r_i^2)$$

Then

$$-2 \, k \, dt = Grdr - Gr_i^2 \, \frac{dr}{r}$$

from which

$$-2 \, kt = G \, \frac{r^2}{2} - Gr_i^2 \, \ell n \, r + C \, ,$$

But

$$t_o = 1530^{\circ}F \text{ at } d_o = 0.706 \text{ inches.}$$

Then

$$C = G \, d_i^2 \, \ell n \, r_o - 1152 \, k \, t_o - G \, \frac{do^2}{2}$$

Accordingly, the temperature at any point in the ceramic fuel is

$$t = 1530 + 11,140 \left(\frac{0.498 - d^2}{2} - 0.1044 \, \ell n \, \frac{0.706}{d} \right)$$

<u>Case 2. Grounded Thermocouple Junction</u>

(0.001 inch Uranium Oxide-Thermocouple Clearance)

For this case and those to follow, an analytical solution was impracticable. Accordingly, an energy balance on each nodal point of Figs. 2, 3 and 4, yields the following sets of equations, each set being peculiar to the conditions set forth for each case. The left member of each equation is, of course, zero, but the residual notation has been employed for identification as well as to facilitate the numerical calculation. Referring to Figure 2, the following equations are obtained.

$$R_1 = t_2 + 2\ t_6 - 4\ t_1 + 2802$$
$$R_2 = t_1 + t_3 + 2\ t_7 - 4\ t_2 + 112$$
$$R_3 = t_2 + 2\ t_8 + 4.36\ t_4 - 7.36\ t_3 + 89$$
$$R_4 = 4.36\ t_3 + 16\ t_5 + 1.54\ t_9 - 21.9\ t_4$$
$$R_5 = 16\ t_4 + 10\ t_{10} - 27.15\ t_5 + 1093$$
$$R_6 = t_7 + t_{11} + t_1 - 4\ t_6 + 2802$$
$$R_7 = t_6 + t_2 + t_{12} + t_8 - 4\ t_7 + 112$$
$$R_8 = t_7 + t_9 + t_3 + t_{13} - 4\ t_8 + 146$$
$$R_9 = 9.25\ t_{10} + 0.5\ t_{14} + 0.77\ t_4 + t_8 - 11.52\ t_9 + 87$$
$$R_{10} = 9.25\ t_9 + 5\ t_5 + 5\ t_{15} - 20.4\ t_{10} + 1093$$
$$R_{11} = t_6 + t_{16} + t_{12} - 4\ t_{11} + 2802$$
$$R_{12} = t_7 + t_{17} + t_{11} + t_{13} - 4\ t_{12} + 112$$
$$R_{13} = t_8 + t_{14} + t_{12} + t_{18} - 4\ t_{13} + 146$$
$$R_{14} = t_{13} + 0.5\ t_{19} + 0.5\ t_9 + 9.25\ t_{15} - 11.25\ t_{14} + 87$$
$$R_{15} = 9.25\ t_{14} + 5\ t_{20} + 5\ t_{10} - 20.4\ t_{15} + 1093$$
$$R_{16} = t_{17} + t_{11} + t_{21} - 4\ t_{16} + 2802$$
$$R_{17} = t_{16} + t_{12} + t_{22} + t_{18} - 4\ t_{17} + 112$$
$$R_{18} = t_{13} + t_{23} + t_{19} + t_{17} - 4\ t_{18} + 146$$
$$R_{19} = t_{18} + 0.5\ t_{24} + 0.5\ t_{14} + 9.25\ t_{20} - 11.25\ t_{19} + 87$$
$$R_{20} = 9.25\ t_{19} + 5\ t_{25} + 5\ t_{15} - 20.4\ t_{20} + 1093$$
$$R_{21} = t_{22} + 2\ t_{16} - 4\ t_{21} + 2802$$
$$R_{22} = t_{21} + t_{23} + 2\ t_{17} - 4\ t_{22} + 112$$
$$R_{23} = t_{22} + t_{24} + 2\ t_{18} - 4\ t_{23} + 146$$
$$R_{24} = t_{23} + 9.25\ t_{25} + t_{19} - 11.25\ t_{24} + 87$$
$$R_{25} = 9.25\ t_{24} + 10\ t_{20} - 20.4\ t_{25} + 1093$$

Case 3. Grounded Thermocouple Junction

(0.003 inch Uranium Oxide-Thermocouple Clearance)

Referring to Figure 2, the following equations are obtained.

$$R_1 = t_2 + 2\,t_6 - 4\,t_1 + 2802$$
$$R_2 = t_1 + t_3 + 2\,t_7 - 4\,t_2 + 112$$
$$R_3 = t_2 + 2\,t_8 + 3.16\,t_4 - 6.16\,t_3 + 89$$
$$R_4 = 3.16\,t_3 + 1.15\,t_9 + 16\,t_5 - 20.3\,t_4$$
$$R_5 = 16\,t_4 + 10\,t_{10} - 27.15\,t_5 + 1093$$
$$R_6 = t_7 + t_{11} + t_1 - 4\,t_6 + 2802$$
$$R_7 = t_6 + t_2 + t_{12} + t_8 - 4\,t_7 + 112$$
$$R_8 = t_7 + t_9 + t_3 + t_{13} - 4\,t_8 + 146$$
$$R_9 = t_8 + 9.25\,t_{10} + 0.5\,t_{14} + 0.58\,t_4 - 11.33\,t_9 + 87$$
$$R_{10} = 9.25\,t_9 + 5\,t_5 + 5\,t_{15} - 20.4\,t_{10} + 1093$$
$$R_{11} = t_6 + t_{16} + t_{12} - 4\,t_{11} + 2802$$
$$R_{12} = t_7 + t_{17} + t_{11} + t_{13} - 4\,t_{12} + 112$$
$$R_{13} = t_8 + t_{14} + t_{12} + t_{18} - 4\,t_{13} + 146$$
$$R_{14} = t_{13} + 0.5\,t_{19} + 0.5\,t_9 + 9.25\,t_{15} - 11.25\,t_{14} + 87$$
$$R_{15} = 9.25\,t_{14} + 5\,t_{20} + 5\,t_{10} - 20.4\,t_{15} + 1093$$
$$R_{16} = t_{17} + t_{11} + t_{21} - 4\,t_{16} + 2802$$
$$R_{17} = t_{16} + t_{12} + t_{22} + t_{18} - 4\,t_{17} + 112$$
$$R_{18} = t_{13} + t_{23} + t_{19} + t_{17} - 4\,t_{18} + 146$$
$$R_{19} = t_{18} + 0.5\,t_{24} + 0.5\,t_{14} + 9.25\,t_{20} - 11.25\,t_{19} + 87$$
$$R_{20} = 9.25\,t_{19} + 5\,t_{25} + 5\,t_{15} - 20.4\,t_{20} + 1093$$
$$R_{21} = t_{22} + 2\,t_{16} - 4\,t_{21} + 2802$$
$$R_{22} = t_{21} + t_{23} + 2\,t_{17} - 4\,t_{22} + 112$$
$$R_{23} = t_{22} + t_{24} + 2\,t_{18} - 4\,t_{23} + 146$$
$$R_{24} = t_{23} + 9.25\,t_{25} + t_{19} - 11.25\,t_{24} + 87$$
$$R_{25} = 9.25\,t_{24} + 10\,t_{20} - 20.4\,t_{25} + 1093$$

Case 4. Ungrounded Thermocouple Junction

(0.003 in. Uranium Oxide - Thermocouple Clearance)

Referring to Figure 3, the following equations are obtained.

$$R_1 = t_2 + 2\ t_6 - 4\ t_1 + 2802$$
$$R_2 = t_1 + t_3 + 2\ t_7 - 4\ t_2 + 112$$
$$R_3 = t_2 + 2\ t_8 + 2.28\ t_C - 5.28\ t_3 + 89$$
$$R_4 = t_C + 2\ t_B + t_5 - 4\ t_4$$
$$R_5 = t_4 + 12.22\ t_B + 16\ t_{10} - 31.06\ t_5 + 1749$$
$$R_A = t_8 + t_9 + 0.707\ t_B - 2.707\ t_A$$
$$R_B = 5.4\ t_C + t_A + 0.884\ t_4 + 5.4\ t_5 - 12.684\ t_B$$
$$R_C = 3.65\ t_3 + 12.22\ t_B + t_4 - 16.87\ t_C$$
$$R_6 = t_7 + t_{11} + t_1 - 4\ t_6 + 2802$$
$$R_7 = t_6 + t_2 + t_{12} + t_8 - 4\ t_7 + 112$$
$$R_8 = t_7 + t_9 + t_3 + t_{13} - 4\ t_8 + 146$$
$$R_9 = t_8 + 9.24\ t_{10} + 0.5\ t_{14} - 10.74\ t_9 + 87$$
$$R_{10} = 1.85\ t_9 + t_5 + t_{15} - 4.08\ t_{10} + 218.6$$
$$R_{11} = t_6 + t_{16} + t_{12} - 4\ t_{11} + 2802$$
$$R_{12} = t_7 + t_{17} + t_{11} + t_{13} - 4\ t_{12} + 112$$
$$R_{13} = t_8 + t_{14} + t_{12} + t_{18} - 4\ t_{13} + 146$$
$$R_{14} = t_{13} + 0.5\ t_{19} + 0.5\ t_9 + 9.25\ t_{15} - 11.25\ t_{14} + 87$$
$$R_{15} = 1.85\ t_{14} + t_{20} + t_{10} - 4.08\ t_{15} + 218.6$$
$$R_{16} = t_{17} + t_{11} + t_{21} - 4\ t_{16} + 2802$$
$$R_{17} = t_{16} + t_{12} + t_{22} + t_{18} - 4\ t_{17} + 112$$
$$R_{18} = t_{13} + t_{23} + t_{19} + t_{17} - 4\ t_{18} + 146$$
$$R_{19} = t_{18} + 0.5\ t_{24} + 0.5\ t_{14} + 9.25\ t_{20} - 11.25\ t_{19} + 87$$
$$R_{20} = 1.85\ t_{19} + t_{25} + t_{15} - 4.08\ t_{20} + 218.6$$
$$R_{21} = t_{22} + 2\ t_{16} - 4\ t_{21} + 2802$$
$$R_{22} = t_{21} + t_{23} + 2\ t_{17} - 4\ t_{22} + 112$$
$$R_{23} = t_{22} + t_{24} + 2\ t_{18} - 4\ t_{23} + 146$$
$$R_{24} = t_{23} + 9.25\ t_{25} + t_{19} - 11.25\ t_{24} + 87$$
$$R_{25} = 1.85\ t_{24} + 2\ t_{20} - 4.08\ t_{25} + 218.6$$

Case 5. Groove Containing Helium Only

Referring to Figure 2, the following equations are obtained.

$$R_1 = t_2 + 2\ t_6 - 4\ t_1 + 2802$$
$$R_2 = t_1 + t_3 + 2\ t_7 - 4\ t_2 + 112$$
$$R_3 = 0.416\ t_4 + 2\ t_8 + t_2 - 3.416\ t_3 + 89$$
$$R_4 = 1.347\ t_3 + t_9 + 1.564\ t_5 - 3.911\ t_4$$
$$R_5 = t_4 + 20.7\ t_{10} - 24.08\ t_5 + 2260$$
$$R_6 = t_7 + t_{11} + t_1 - 4\ t_6 + 2802$$
$$R_7 = t_6 + t_2 + t_{12} + t_8 - 4\ t_7 + 112$$
$$R_8 = t_7 + t_9 + t_3 + t_{13} - 4\ t_8 + 146$$
$$R_9 = t_8 + 0.5\ t_{14} + 0.1543\ t_4 + 9.24\ t_{10} - 10.8943\ t_9 + 87$$
$$R_{10} = 9.25\ t_9 + 5\ t_5 + 5\ t_{15} - 20.4\ t_{10} + 1093$$
$$R_{11} = t_6 + t_{16} + t_{12} - 4\ t_{11} + 2802$$
$$R_{12} = t_7 + t_{17} + t_{11} + t_{13} - 4\ t_{12} + 112$$
$$R_{13} = t_8 + t_{14} + t_{12} + t_{18} - 4\ t_{13} + 146$$
$$R_{14} = t_{13} + 0.5\ t_{19} + 0.5\ t_9 + 9.25\ t_{15} - 11.25\ t_{14} + 87$$
$$R_{15} = 9.25\ t_{14} + 5\ t_{20} + 5\ t_{10} - 20.4\ t_{15} + 1093$$
$$R_{16} = t_{17} + t_{11} + t_{21} - 4\ t_{16} + 2802$$
$$R_{17} = t_{16} + t_{12} + t_{22} + t_{18} - 4\ t_{17} + 112$$
$$R_{18} = t_{13} + t_{23} + t_{19} + t_{17} - 4\ t_{18} + 146$$
$$R_{19} = t_{18} + 0.5\ t_{24} + 0.5\ t_{14} + 9.25\ t_{20} - 11.25\ t_{19} + 87$$
$$R_{20} = 9.25\ t_{19} + 5\ t_{25} + 5\ t_{15} - 20.4\ t_{20} + 1093$$
$$R_{21} = t_{22} + 2\ t_{16} - 4\ t_{21} + 2802$$
$$R_{22} = t_{21} + t_{23} + 2\ t_{17} - 4\ t_{22} + 112$$
$$R_{23} = t_{22} + t_{24} + 2\ t_{18} - 4\ t_{23} + 146$$
$$R_{24} = t_{23} + 9.25\ t_{25} + t_{19} - 11.25\ t_{24} + 87$$
$$R_{25} = 9.25\ t_{24} + 10\ t_{20} - 20.4\ t_{25} + 1093$$

Case 6. Grounded Thermocouple Junction

(0.003 in. Uranium Oxide - Thermocouple Clearance)

This case is actually case 3 repeated with a refined model or grid, viz., Fig. 4 in which t_A has been considered to be calculable from the linear interpolation, $(t_8 + t_9)/2$. Accordingly, referring to Fig. 4, the following equations are obtained.

$$R_1 = t_2 + 2\ t_6 - 4\ t_1 + 2802$$
$$R_2 = t_1 + t_3 + 2\ t_7 - 4\ t_2 + 112$$
$$R_3 = t_2 + 2\ t_8 + 3.16\ t_4 - 6.16\ t_3 + 89$$
$$R_4 = t_8 + t_9 + 5.48\ t_3 + 27.75\ t_5 - 35.2\ t_4$$
$$R_5 = 16\ t_4 + 10\ t_{10} - 27.15\ t_5 + 1093$$
$$R_6 = t_7 + t_{11} + t_1 - 4\ t_6 + 2802$$
$$R_7 = t_6 + t_2 + t_{12} + t_8 - 4\ t_7 + 112$$
$$R_8 = t_7 + t_9 + t_3 + t_{13} - 4\ t_8 + 146$$
$$R_9 = t_8 + 9.25\ t_{10} + 0.5\ t_{14} - 10.75\ t_9 + 87$$
$$R_{10} = 1.85\ t_9 + t_5 + t_{15} - 4.08\ t_{10} + 218.6$$
$$R_{11} = t_6 + t_{16} + t_{12} - 4\ t_{11} + 2802$$
$$R_{12} = t_7 + t_{17} + t_{11} + t_{13} - 4\ t_{12} + 112$$
$$R_{13} = t_8 + t_{14} + t_{12} + t_{18} - 4\ t_{13} + 146$$
$$R_{14} = t_{13} + 0.5\ t_{19} + 0.5\ t_9 + 9.25\ t_{15} - 11.25\ t_{14} + 87$$
$$R_{15} = 1.85\ t_{14} + t_{20} + t_{10} - 4.08\ t_{15} + 218.6$$
$$R_{16} = t_{17} + t_{11} + t_{21} - 4\ t_{16} + 2802$$
$$R_{17} = t_{16} + t_{12} + t_{22} + t_{18} - 4\ t_{17} + 112$$
$$R_{18} = t_{13} + t_{23} + t_{19} + t_{17} - 4\ t_{18} + 146$$
$$R_{19} = t_{18} + 0.5\ t_{24} + 0.5\ t_{14} + 9.25\ t_{20} - 11.25\ t_{19} + 87$$
$$R_{20} = 1.85\ t_{19} + t_{25} + t_{15} - 4.08\ t_{20} + 218.6$$
$$R_{21} = t_{22} + 2\ t_{16} - 4\ t_{21} + 2802$$
$$R_{22} = t_{21} + t_{23} + 2\ t_{17} - 4\ t_{22} + 112$$
$$R_{23} = t_{22} + t_{24} + 2\ t_{18} - 4\ t_{23} + 146$$
$$R_{24} = t_{23} + 9.25\ t_{25} + t_{19} - 11.25\ t_{24} + 87$$
$$R_{25} = 0.925\ t_{24} + t_{20} - 2.04\ t_{25} + 109.3$$

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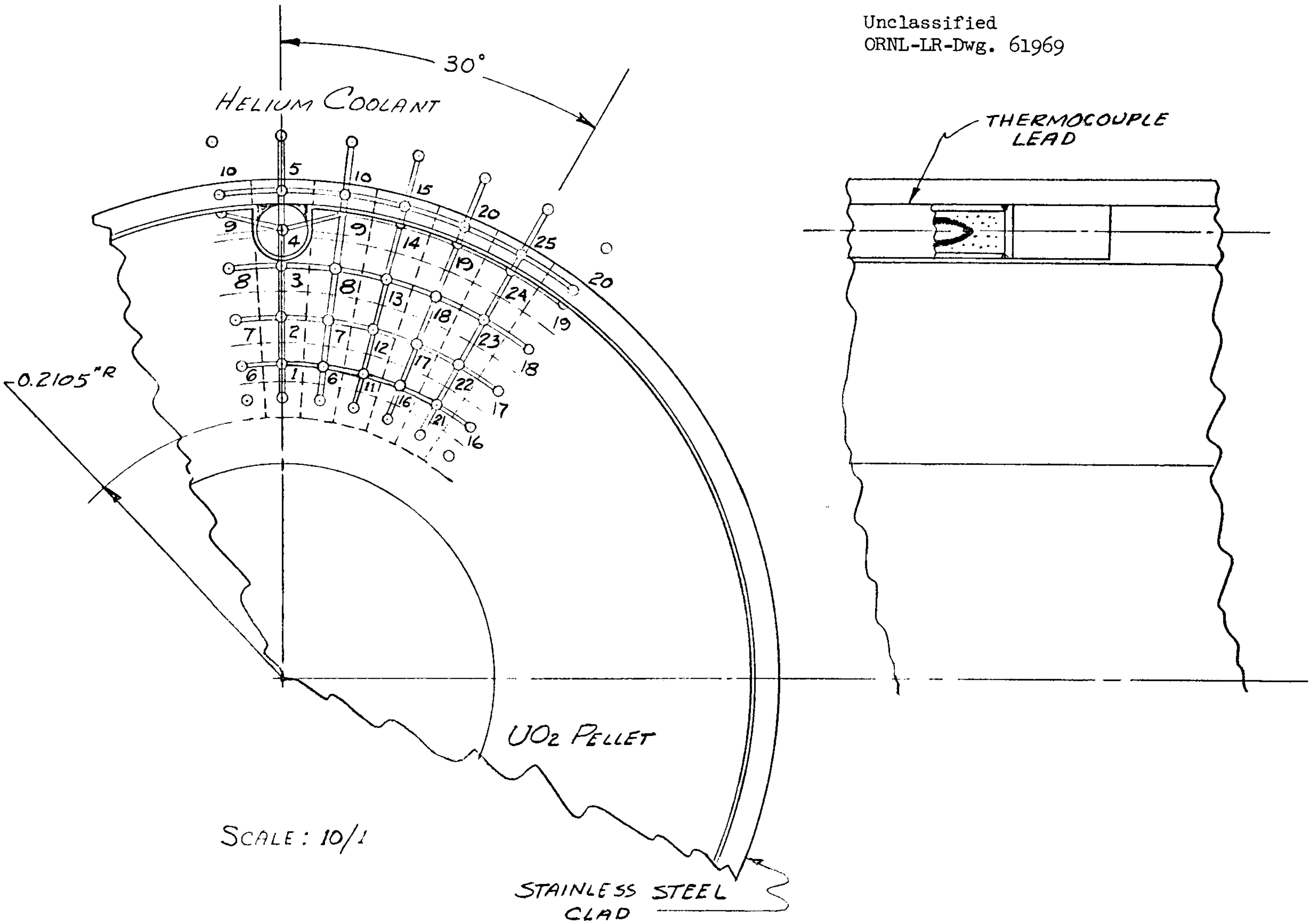

Fig. 2. Finite Difference Network Diagram for Instrumented Fuel Assembly.

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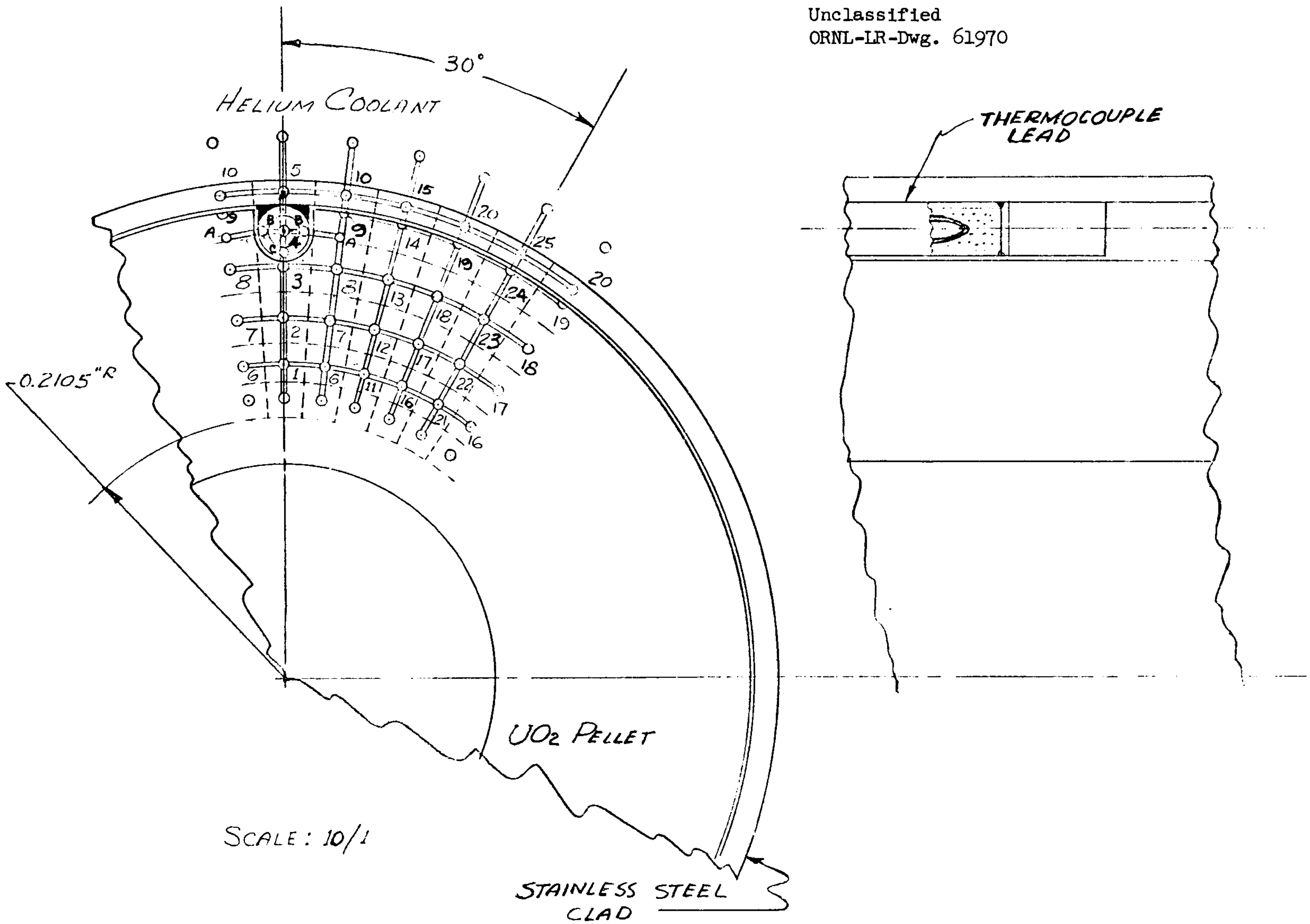

Fig. 3. Finite Difference Network Diagram for Instrumented Fuel Assembly.

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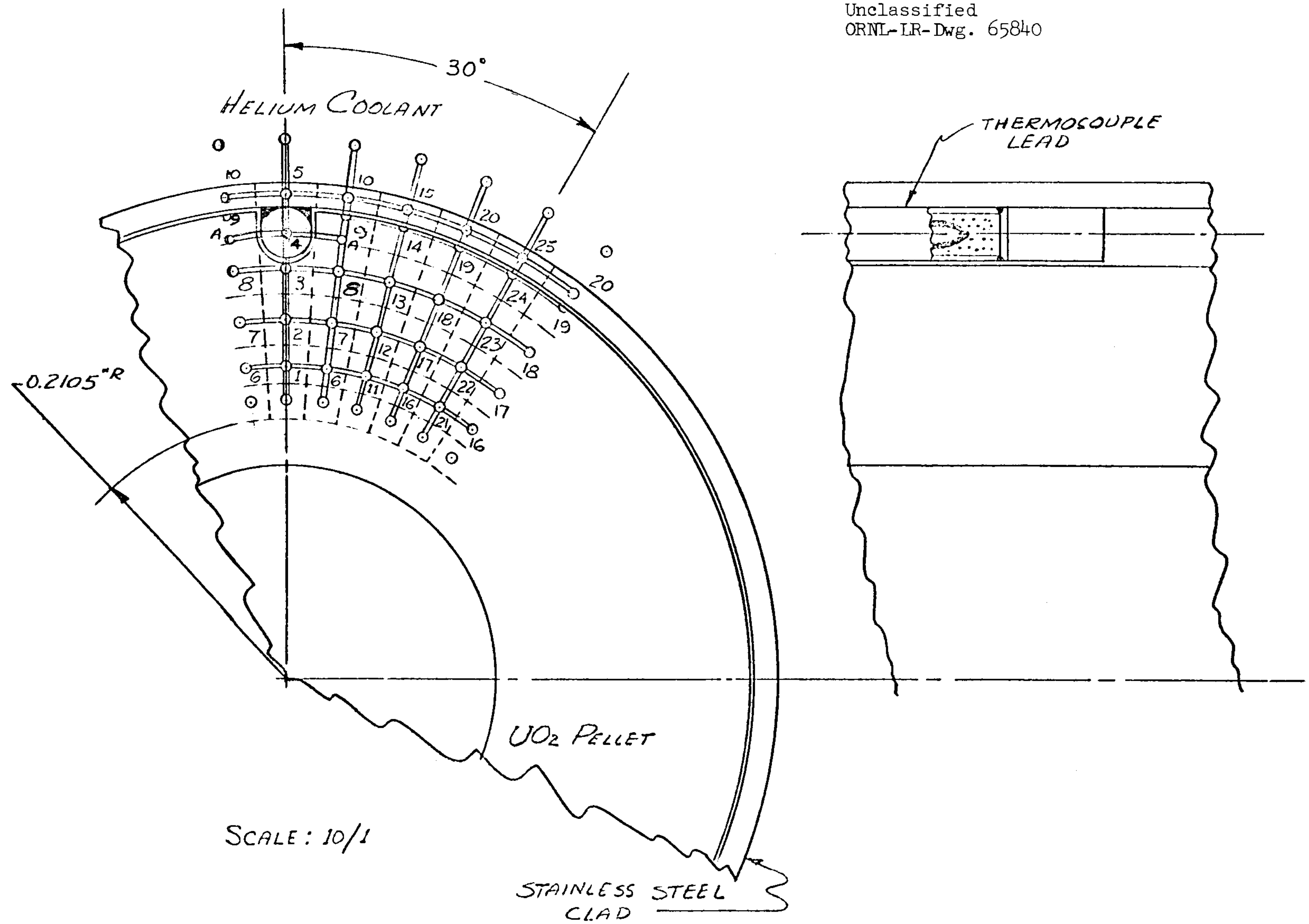

Fig. 4. Finite Difference Network Diagram for Instrumented Fuel Assembly.

RESULTS

The temperature corresponding to the nodal points depicted in Figs. 2, 3 and 4, have been tabulated for each case studied in Table 1.

Graphs depicting temperature versus distance along a radial line passing through the center of both the thermocouple and the uranium oxide pellet are presented in Figs. 5 and 6.

Table 1

	Temperature °F					
Node	Case 1 Undis-turbed	Case 2 Grounded 0.001 in.	Case 3 Grounded 0.003 in.	Case 4 Ungrounded 0.003 in.	Case 5 Void He Space	Case 6 Grounded 0.003 in.
1	2569	2540	2540	2553	2576	2547
2	2348	2250	2260	2298	2376	2275
3	2007	1762	1802	1904	2108	1827
4	1530	1553	1541	1561	1667	1578
5	1460	1498	1489	1474	1394	1515
6	2569	2550	2550	2556	2568	2556
7	2348	2293	2293	2313	2352	2306
8	2007	1928	1938	1964	2025	1950
9	1530	1528	1523	1515	1503	1534
10	1460	1473	1467	1457	1432	1480
11	2569	2561	2561	2563	2570	2563
12	2348	2322	2322	2326	2338	2326
13	2007	1981	1981	1986	2001	1986
14	1530	1525	1520	1518	1510	1522
15	1460	1465	1460	1457	1447	1462
16	2569	2569	2569	2569	2569	2569
17	2348	2336	2336	2336	2336	2336
18	2007	1998	1998	1998	1998	1998
19	1530	1522	1520	1519	1516	1519
20	1460	1461	1458	1457	1453	1457
21	2569	2569	2569	2569	2569	2569
22	2348	2338	2338	2338	2338	2338
23	2007	2001	2001	2001	2001	2001
24	1530	1523	1519	1519	1519	1519
25	1460	1461	1457	1457	1455	1457
A				1696		
B				1568		
C				1640		

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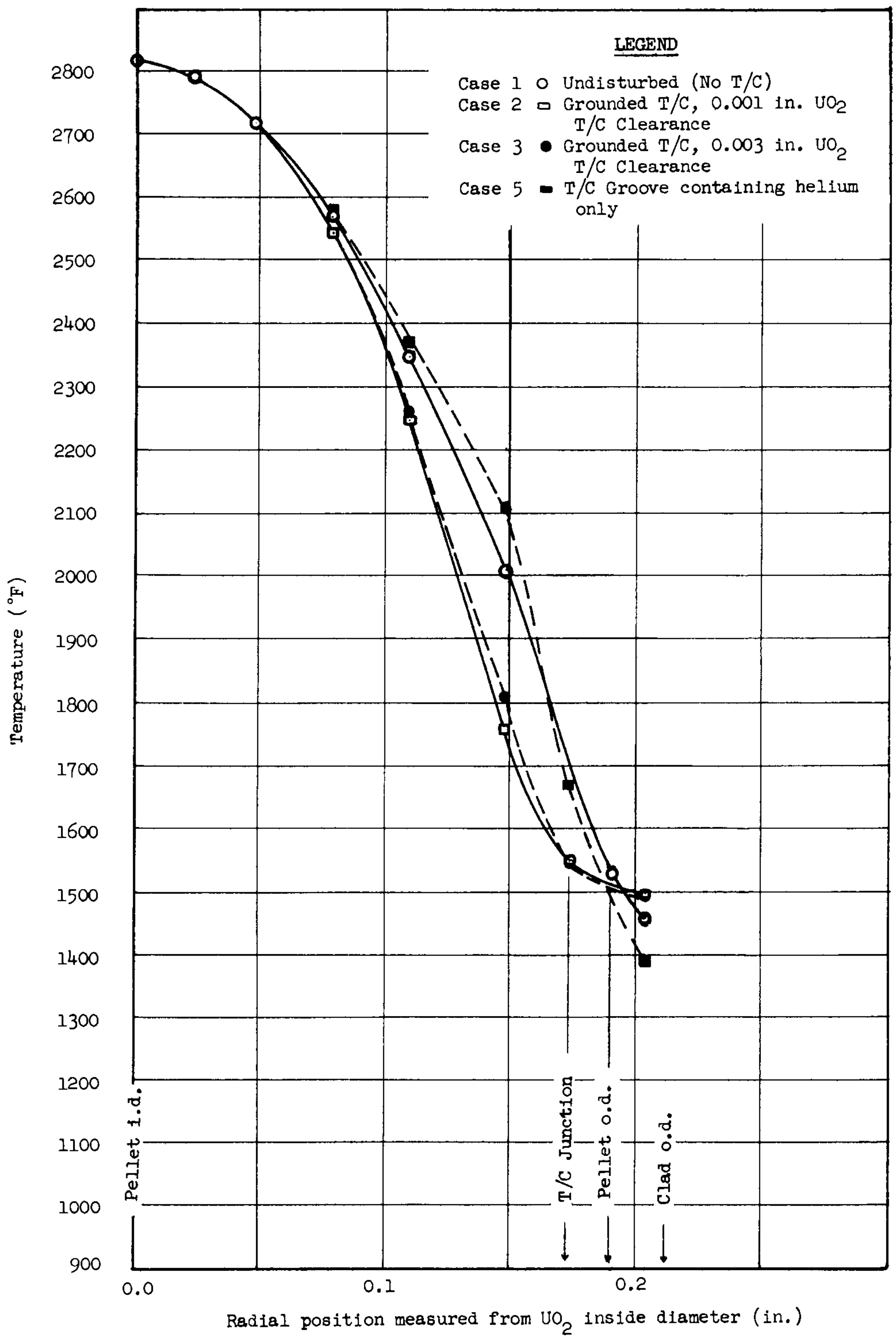

Fig. 5. Temperature Distribution in Instrumented Fuel Assembly for EGCR.

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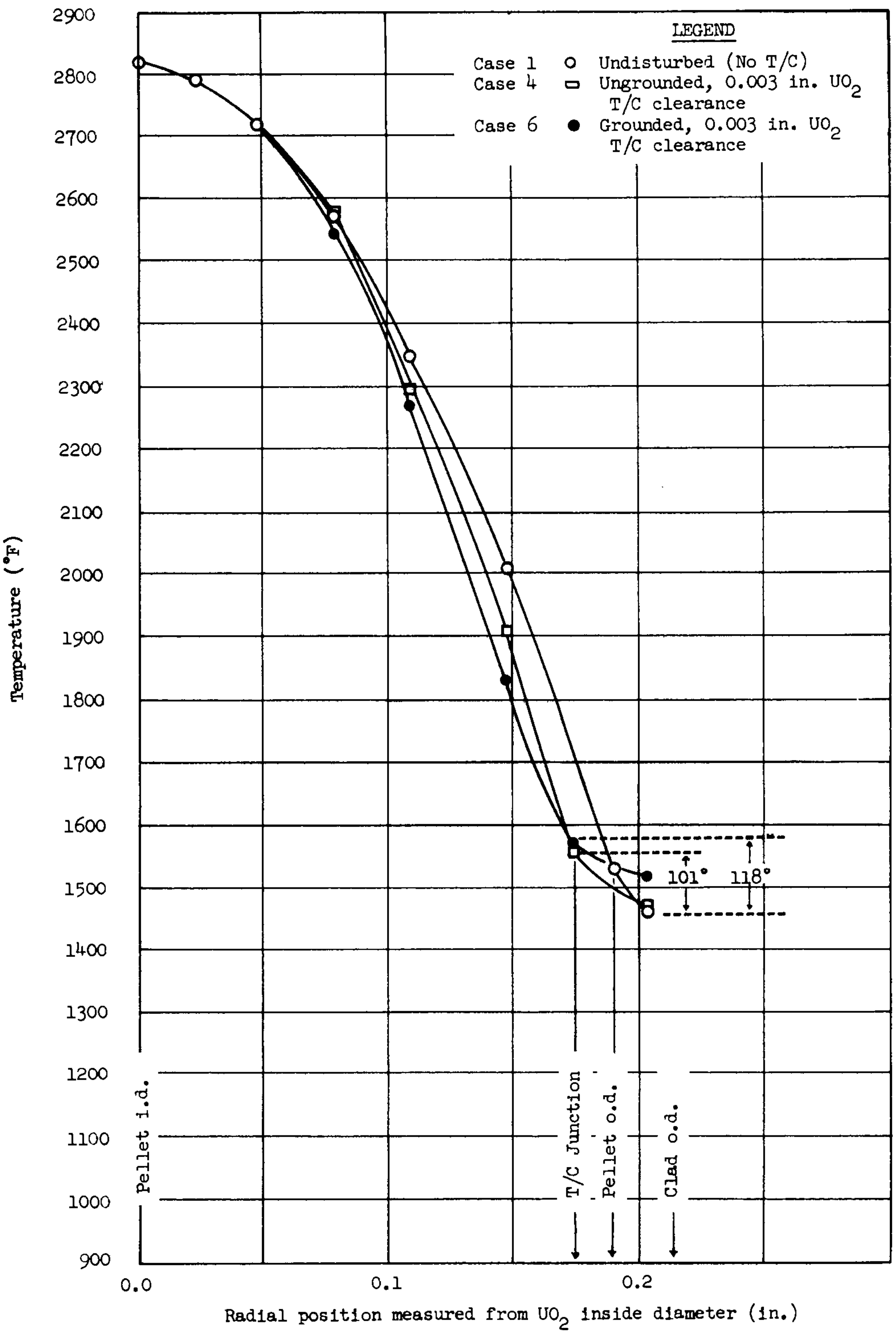


Fig. 6. Temperature Distribution in Instrumented Fuel Assembly for EGCR.

EVALUATION OF RESULTS

In regard to the assumption considering the termination of the disturbance radially and circumferentially, it should be pointed out that if the brunt of the temperature disturbance progressed further than the assumed boundary, the result would be a temperature indication error of decreased magnitude; whereas, should the disturbance progress to a lesser extent, the error will be enhanced. The sensitivity of the system to variation of these boundaries has not been evaluated. However, since perturbation studies were carried out previously for the "Hot Streak Factors" for a similar experimental program using a 45° circumferential terminal boundary, it was felt that the premise made was reasonable for a preliminary analysis.

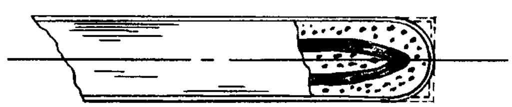
Concerning the uranium oxide - thermocouple conductance, the 0.003 in. clearance is more desirable than 0.001 in. between the uranium oxide and thermocouple, provided the deviation between the indicated temperature and the undisturbed clad surface temperature is to be minimized. It appears feasible to design this gap with a clearance greater than 0.003 in. so that the deviation between the indicated temperature and the undisturbed clad temperature is reduced. However, pellet stability is probably insufficient to warrant much attention to minute groove tolerances unless some endeavor is made to control shifting and maintain fuel fragments resulting from thermal stress failures in their original positions.

Braze geometry is another variable which must be ascertained and maintained at a known condition, as in any instrumentation or control system, before an analysis such as this could be interpreted as sufficient for calibration. Simplicity in the analysis influenced the assumption regarding the braze geometry. In actual practice, it is difficult to obtain a large fillet, and the calculated values probably are optimistic in this respect.

The assumption of a uniform thermal conductivity of uranium oxide produces an insignificant error over the temperature ranges involved. The numerical value for the thermal conductivity of the uranium oxide was taken as unity (Btu/hr ft $^{\circ}$F) although it is currently believed that

1.73[1] is a more realistic magnitude for the temperature range encountered here. Thus this analysis represents a conservative estimate for the thermocouple error since the lower value of the thermal conductivity represents the more severe thermal gradient in the ceramic fuel.

The consideration of end effects (axial conduction) appears necessary only provided it is decided to use the grounded junction type or to employ the ungrounded junction variety without a dummy lead. The dummy lead is simply a short length (approximately 1/4 to 1/2 in.) of thermocouple lead positioned axially adjacent to the thermocouple per se[2]. However, the axial conduction will produce only a slight effect on the temperature indicated by the insulated junction without a dummy lead since the maximum axial gradient affecting temperature of the junction is approximately 30° and exists in the magnesium oxide constituting the insulated junction. Moreover, this effect is counteracted somewhat by the reduced temperature of the clad surface adjacent to the helium gas space. This error can be eliminated by reducing the diameter of the cap on the thermocouple sheath as shown on the sketch below, thus providing a greater clearance between the thermocouple sheath and the uranium oxide of the end cap.



Deformed End Cap

It should be noted that the error due to axial conduction would be more severe using the grounded or uninsulated junction. In order to put a number on the effect, however, a three dimensional study will be required. Further, it should be observed (Figure 5) that it makes little difference whether the thermocouple junction is positioned axially adjacent to the UO_2 or in a helium filled groove when the dummy lead is not employed.

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[1] J. L. Bates, "Thermal Conductivity of UO_2 Improved at High Temperatures", Nucleonics 19 (6) 83 (June, 1961).

[2] The effect of the dummy lead could, of course, be obtained more preferably by prefabricating the junction in a recessed manner.

The physical explanation for the higher temperature which occurs with the grounded junction thermocouple is as follows. The solid metal (grounded junction) provides a better thermal-energy bridge between the uranium oxide and the coolant on the entire periphery than does the insulated junction. Therefore, the junction temperature indication will be greater with the grounded junction.

In regard to the reliability of the temperature indication over long periods of time, it should be noted that deviation from initial calibration (drifting) is commonplace when the thermometric properties are subject to change. Transmutation of the metals may, for example, effect such a change in the properties.

CLOSURE

Presently the problem of surface temperature measurement is being pursued further. The concept of placing a thermocouple in a groove prepared in the uranium oxide appears feasible and the method is desirable since the flow disturbances incurred when measurements are attempted via the fluid stream are obviated.

A complete analysis of the problem should be made in which a three dimensional consideration as well as optimization with respect to minimum deviation in temperature indication is included. Moreover, the sensitivity of the thermometric device to the uranium oxide - thermocouple sheath clearance, braze geometry, and thermocouple size should be explored. Further, the effects on the thermocouple sheath temperature, the deviation between the indicated surface temperature and the undisturbed clad surface temperature, and the uncertainty intervals for various parametric configurations should be ascertained. Work is currently proceeding in this direction. Interim the type of junction to be employed will probably be determined largely by the progress made in the development of fabrication techniques.

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