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CALCULATIONS OF THE SURFACE HEAT FLUX AND FUEL TEMPERATURES FOR PRTR MK-I PuO_2-UO_2 FUEL ELEMENT WITH SEGREGATED PuO_2

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CALCULATIONS OF THE SURFACE HEAT FLUX AND FUEL TEMPERATURES FOR PRTR MK-I PuO_2-UO_2 FUEL ELEMENT WITH SEGREGATED PuO_2

F. R. Zaloudek and G. M. Hesson

INTRODUCTION

The methods used to fabricate the present loading of PuO_2-UO_2 fuel elements for the Plutonium Recycle Test Reactor have resulted in alternating bands of high and low PuO_2 concentration along each rod of the 19-rod elements. These bands are repeated every 1/2 or 1 inch along the length of the rod, depending on whether the loading of the oxides was done in 160 or 80 increments. This non-uniform distribution of PuO_2 results in alternate regions of high and low heat generation rates with a direct influence on surface heat flux and fuel temperatures. Since the heat generation rates in the regions of high PuO_2 are as much as six times greater than the rates for a uniform distribution, calculations have been performed to determine the maximum values of heat flux and fuel temperatures that would result. Such calculations are reported here.

SUMMARY

Calculations were performed to determine the local surface heat fluxes and fuel temperatures in a rod of a PRTR 19-rod cluster PuO_2-UO_2 fuel element in which the PuO_2 enrichment is segregated into narrow bands as a result of the incremental loading process used to fabricate the fuel. The results indicated that peak to average flux ratios of 2.37 could occur for fuel rods loaded in 80 increments (1 inch total band length) if no mixing of the PuO_2-bearing powder occurs with the UO_2 powder. This would result in maximum heat flux of 660,000 Btu/hr-sq ft for a fuel element operating at a tube power of 1200 KW. For a rod loaded in 160 increments (1/2 inch total band length), the peak heat flux ratio was calculated to be 1.35 (475,000 Btu/hr-sq ft for a 1200 KW fuel element). These heat flux ratios as well as fuel temperatures are shown in Figures 1 through 4 for two different values of maximum PuO_2 concentration.

DISCUSSION

In the fabrication of UO_2-PuO_2 fuel for the Plutonium Recycle Test Reactor, an incremental loading technique is employed to charge the UO_2 and PuO_2 powders into the cladding tube prior to the vibrational compaction or swaging processes. As it is presently performed, this incremental loading technique consists of the simultaneous dumping of small quantities of two powder mixtures into the tubes which will later serve as the fuel cladding. One of these powder mixtures consists of UO_2 to which 5 per cent by weight of PuO_2 has been added. The second powder is entirely UO_2. The fine fractions of the resulting fuel mixture are contributed primarily by the first mentioned powder mixture, and the medium and large fractions are contributed by the second. These incremental loadings are repeated until the tube is full, and it is then ready for the compaction process. The quantities of the two powder mixtures are adjusted so that it takes either 80 or 160 incremental loadings to fill the tube. This means that each incremental load will contribute either about 1 inch or 1/2 inch of fuel to the completed fuel rod assembly.

Ideally, a perfect mixing of the two component powders should occur during the loading and subsequent compaction processes resulting in a uniform 0.48 weight per cent PuO_2 enrichment over the entire length of the fuel rod. However, such perfect mixing has not been attained in practice. Autoradiographs of several completed fuel rods have provided evidence of non-uniformity of PuO_2 concentration in the axial direction and also radially to a lesser extent. Regions of high PuO_2 concentration along the length of the fuel rod and adjacent regions of low PuO_2 concentration correspond in frequency and length to the supposed pattern of the incremental fuel loadings; that is, either 80 or 160 regions of high PuO_2 concentration generally occur along the length of the fuel rod. Preliminary destructive tests have indicated peak PuO_2 concentrations as high as 1.5 per cent by weight.

These regions of high PuO_2 concentration along the length of the fuel rods are also regions of high heat generation when the fuel elements are in the reactor. PuO_2 concentrations of 1.5 per cent will produce specific powers more than double that of the normal 0.48 per cent concentration, and 5 per cent concentration will produce approximately 6 times the specific power of the uniform case. However, surface heat fluxes will not be increased by corresponding amounts, since a redistribution of some of the heat generated in the region of high PuO_2 concentration to the regions of low concentration will be effected by conductive heat transport.

Conventional numerical methods employing the "relaxation" technique were used in this computer study of the heat conduction within a PRTR fuel rod. Since the actual variation of the PuO_2 concentration is influenced by essentially random disturbances occurring during loading and compaction of the fuel powder, no attempt was made to consider observed special variations in PuO_2 concentration in these calculations. Instead, hypothesized distributions of the "step-function" nature were assumed such that all of the PuO_2 was collected in bands of either 5 or 1.5 weight per cent concentration. These bands were assumed to be surrounded by regions of UO_2 entirely devoid of PuO_2. Both 80 and 160 uniformly spaced bands were considered to exist along the fuel rod length. This is consistent with the autoradiographic observation mentioned earlier. Also, for control purposes, a uniform 0.48 weight per cent PuO_2 was considered.

Physics calculations indicated that the following specific powers can be expected from each region of specified PuO_2 concentration:*

5.00 w/o PuO_2 - 73.68 KW/ft
1.50 w/o PuO_2 - 26.26 KW/ft
0.48 w/o PuO_2 - 12.29 KW/ft
0.00 w/o PuO_2 - 6.60 KW/ft

*R. E. Peterson, Personal communication, Dec. 17, 1962.

Using this information, the axial variation of the specific power was constructed. Since the segregation of the PuO_2 results in the development of a greater average specific power than obtained in the case of uniform distribution, these axial variations were altered somewhat by reducing both the peak and minimum specific powers by the same percentage to obtain an average specific power of 12.3 KW/ft. This takes into account a 1.3 axial and a 1.1 radial peaking factor. The resulting axial distributions of specific power referred to the case of uniform PuO_2 concentration is given in Figure 1.

A film coefficient of 5000 $B/hr/ft^2/F$ was assumed to occur at the heat transfer surface, and an interfacial contact coefficient of 2500 was assumed to occur between the core and the Zr-2 cladding. The thermal conductivity of the core material was assumed to remain constant at 1.5 B/hr/ft/F, and that of the cladding was assumed to be 8 B/hr/ft/F.

Due to the symmetry of the specific power distributions, it was possible to decrease the extent of the system mathematically considered to a 1/2-inch length of fuel rod for the case of a 160 increment rod and a 1 inch length for a 80 increment rod.

Since the results obtained by the numerical method of "relaxation" approaches that produced by an exact solution as the number of incremental "relaxation volumes" is increased, the system considered was divided into as many increments as consistent with the time available for this analysis. Accordingly, the 1/2 inch length section was divided into 60 incremental volumes (6 radial divisions and 10 longitudinal divisions) and the 1 inch length section into 120 incremental volumes (6 radial and 20 longitudinal divisions).

A heat balance was written for each incremental volume taking into account the heat generated within the volume and that conducted into or out of the volume from adjacent incremental volumes. The resulting system of 60 (or 120) equations were solved simultaneously by an iterative or "relaxation" technique with the aid of the IBM 7090 computer. The results of these computations yielded detailed internal temperature distributions as well as surface heat flux information for the system considered.

The calculated axial distributions of the surface heat flux for a typical rod in the PRTR 19-rod cluster PuO_2-UO_2 fuel element with various nonuniform distributions of PuO_2 are given in Figure 2. In these curves, the local surface heat fluxes were referred to that which occurs on a rod with the normal uniform distribution of 0.48 per cent by weight of PuO_2; that is, about 280,000 $B/hr/ft^2$.

First, consider the case of the 5 per cent peak PuO_2 concentrations characterized by curves in Figure 1. These would correspond to the situation if absolutely no axial mixing occurred between the two constituent powder mixtures during loading and compaction. For an 80 increment rod, the calculations indicated that a peak heat flux of 2.37 times the normal value would occur; that is, a peak local heat flux of more than 660,000 $B/hr/ft^2$ would be produced by a fuel element developing 1200 KW. This is considerably greater than the present reactor boiling burnout limit of 400,000 B/hr/ft^2. For a 160 increment rod, the peak local heat flux for this maximum PuO_2 concentration would be 1.45 times normal or about 405,000 B/hr/ft^2.

For a peak PuO_2 concentration of 1.5 per cent and a specific power distribution given by curves (2) and (4) in Figure 1, the calculations indicated peak local heat fluxes of 1.70 and 1.35 times the normal value for the 80 and the 160 increment rods respectively. These correspond to peak local heat fluxes of 475,000 B/hr/ft^2 and 378,000 B/hr/ft^2. These values are possibly more indicative of actual fuel element behavior since the peak PuO_2 distributions approximate those values determined by actual destructive tests of completed fuel rods as discussed earlier.

Figures 3 and 4 are representations of the calculated axial centerline temperatures and mean cladding temperatures for the cases considered. Although the curves presented in these figures are for a specific power of 12.3 KW/ft, they may also be used for other specific powers by simply multiplying the given value of (Temperature - coolant temperature) by the ratio of the new specific power to the value 12.3 KW/ft. This is permissible because the calculations considered temperature-independent thermal conductivity.

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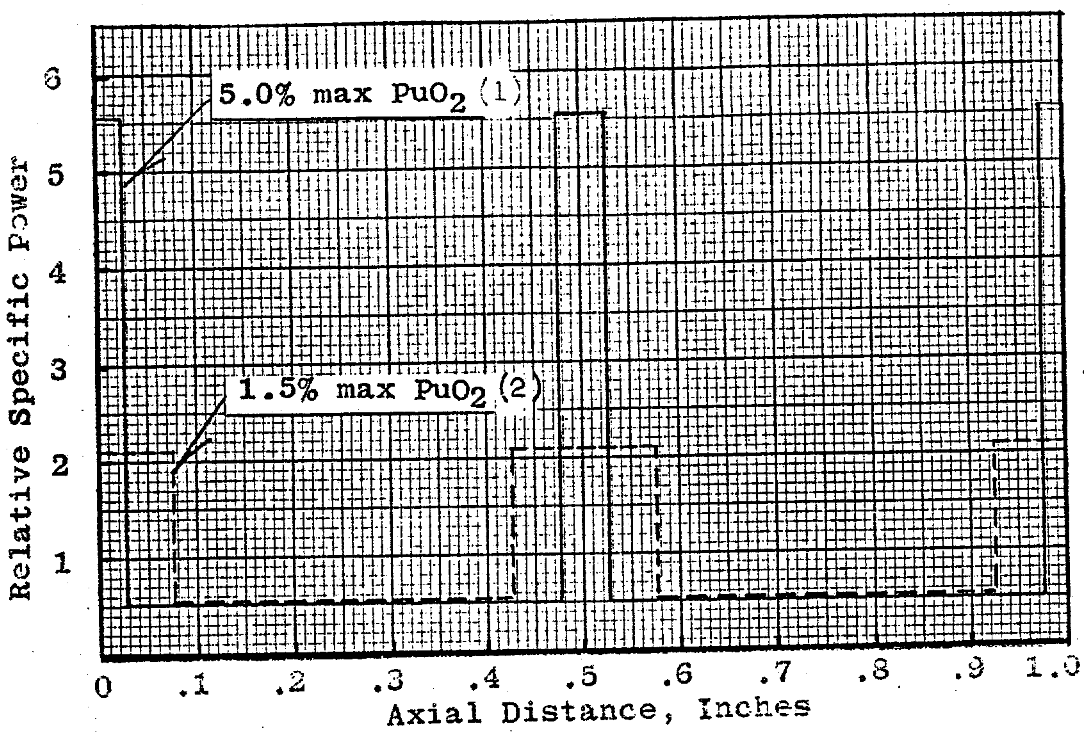

Figure 1a. The Assumed Relative Specific Power Distribution for a 160 Increment PRTR PuO_2-UO_2 Fuel Rod With Axially Segregated PuO_2 Referred to the Case of Uniform PuO_2 Distribution

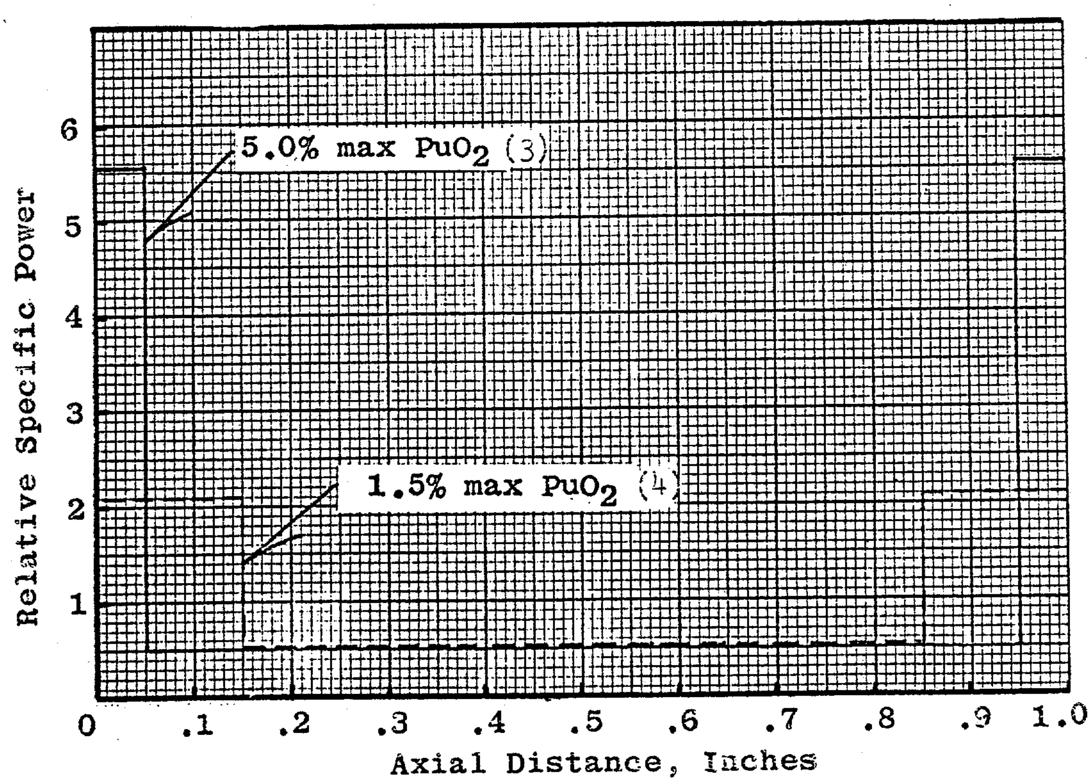

Figure 1b. The Assumed Relative Specific Power Distribution for an 80 Increment PRTR PuO_2-UO_2 Fuel Rod With Axially Segregated PuO_2 Referred to the Case of Uniform PuO_2 Distribution

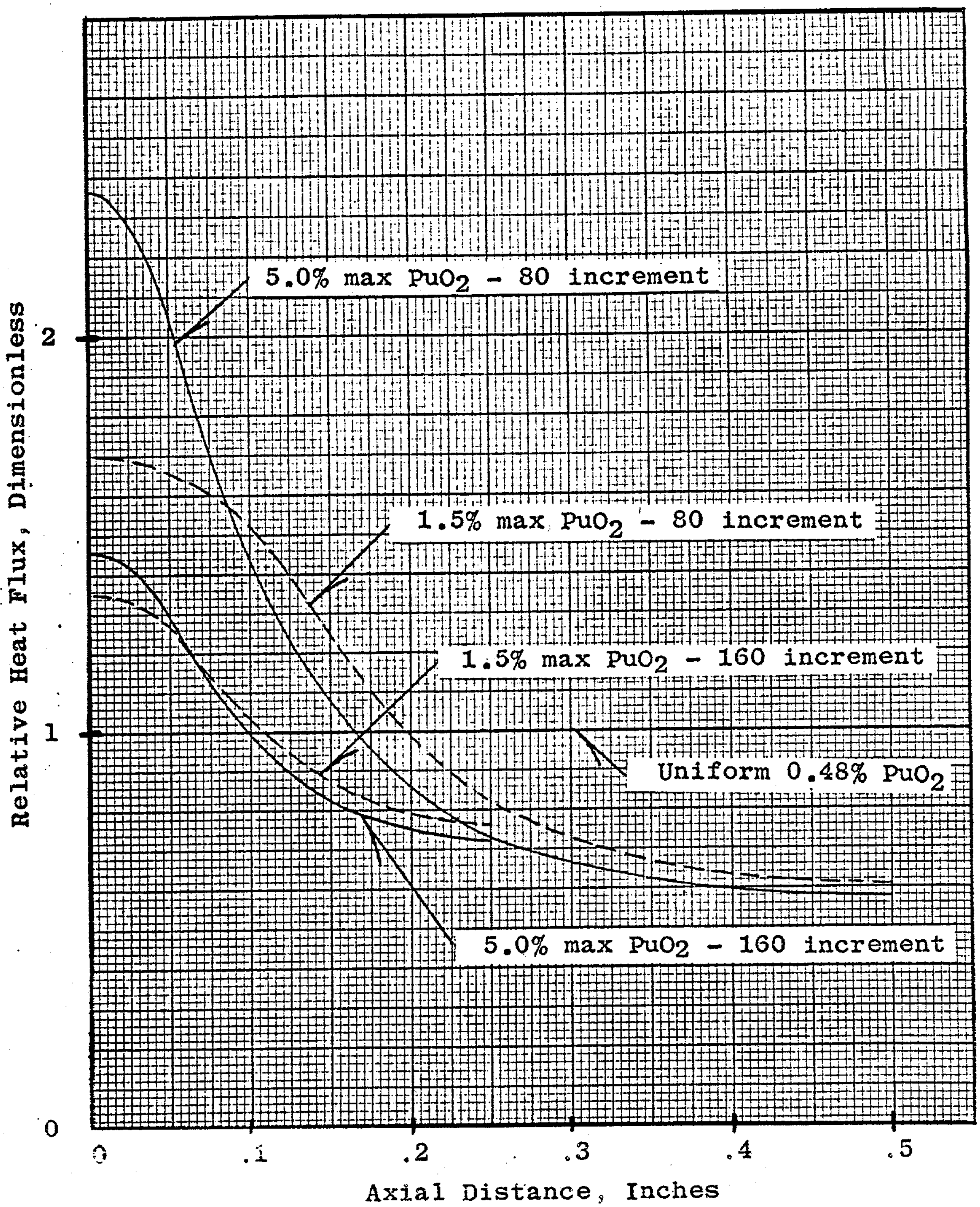

Figure 2. The Calculated Relative Heat Flux Distribution for a PRTR PuO_2-UO_2 Fuel Rod With Axially Segregated PuO_2 Referred to the Case of Uniform PuO_2 Distribution

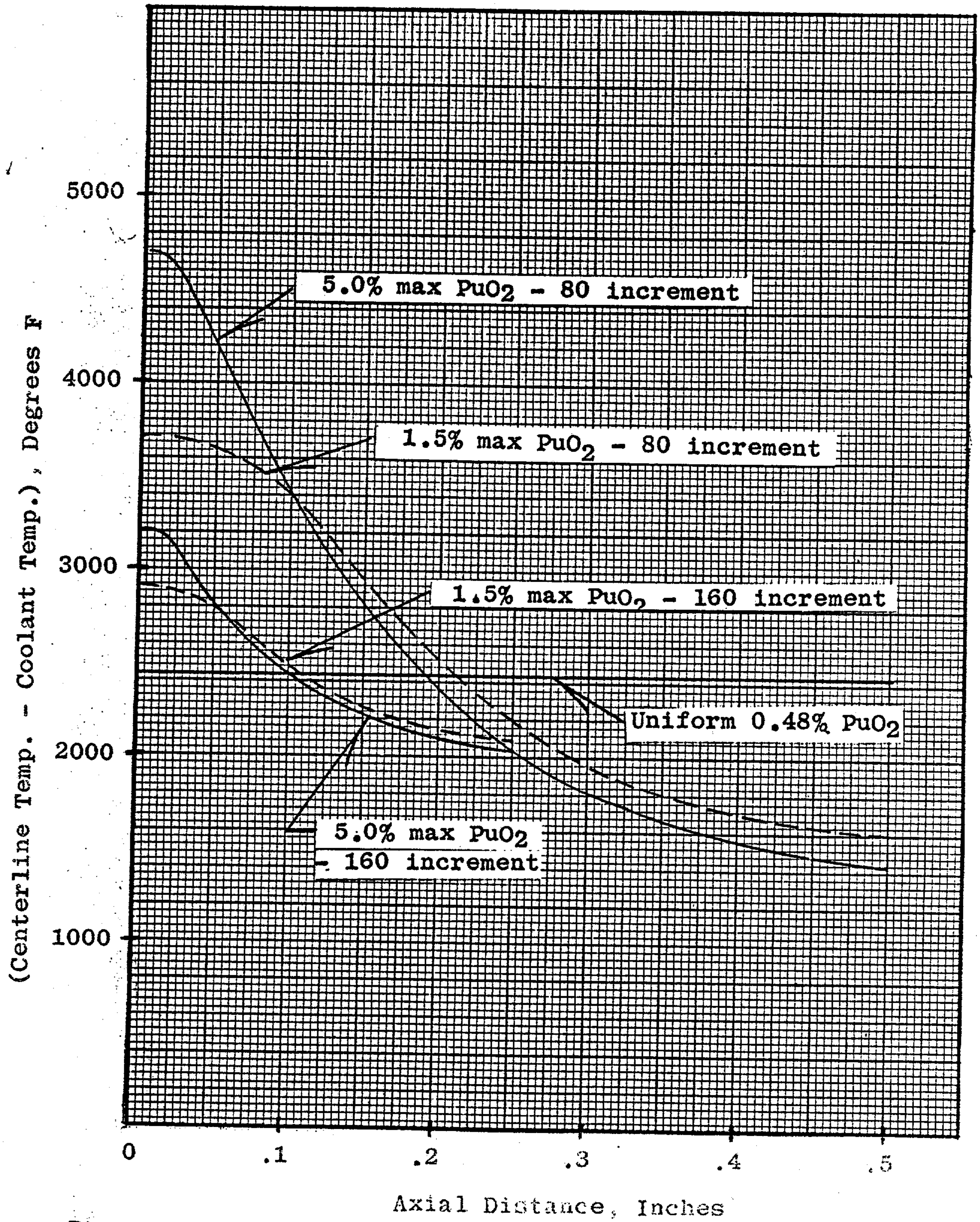

Figure 3. The Calculated Axial Centerline Temperature Distribution for a PRTR PuO_2-UO_2 Axially Segregated Fuel Rod. Specific Power = 12.3 KW/ft

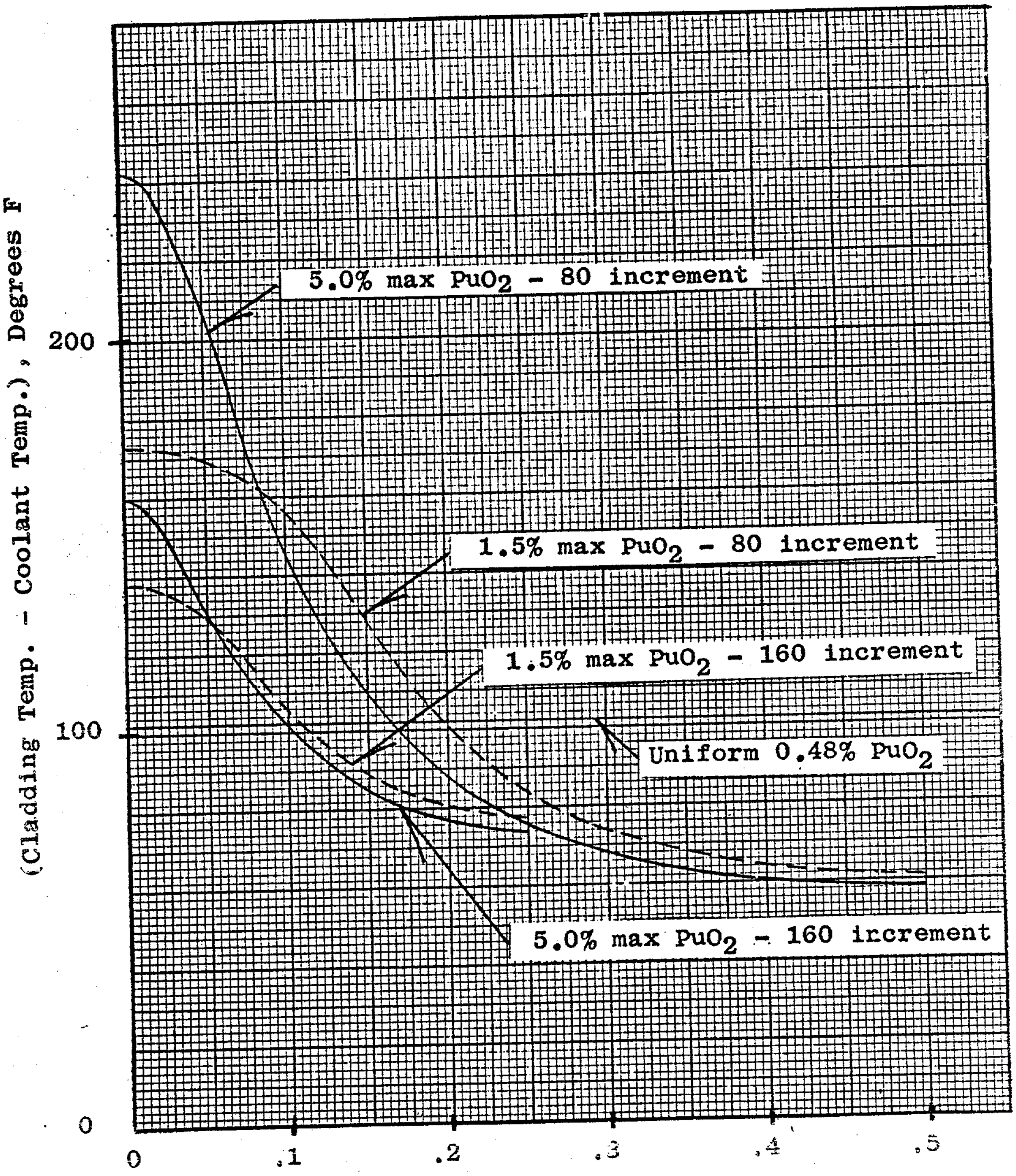

Figure 4. The Calculated Average Cladding Temperagure Distribution for a PRTR PuO_2-UO_2 Fuel Rod With Axially Segregated PuO_2. Specific Power = 12.3 KW/ft.