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TITLE

Proposal for Charging Test Fuel Element
with Corrugated Outer Jacket

GHE-10-62

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GEH-10-62

by

R. G. Wheeler and E. N. Heck

Fuel Element Design

Reactor and Fuels Research and Development

Hanford Laboratories

NOTICE

This test proposal is for the express purpose of providing information and data needed to obtain the required approvals for an experimental irradiation in the MTR or ETR. Subsequent to test approval, the decision to proceed with this irradiation test rests entirely with the experiment sponsor and is dependent upon program needs, internal scheduling priorities, and ETR or MTR scheduling requirements.

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PROPOSAL FOR CHARGING TEST FUEL ELEMENT
WITH CORRUGATED OUTER JACKET
GEH-10-62

I. PURPOSE

Localized tensile necking and splitting of the Zircaloy-2 clad on coextruded uranium cored fuel elements may represent an ultimate exposure limit. One way to increase the total energy capability of the fuel element is to corrugate the outside cladding so its perimeter is greater than that of a circle circumscribing the equivalent cross-sectional area. Thus swelling of the core will be accommodated by bending of the cladding rather than by large cladding tensile strains.

There is a dearth of reliable uranium swelling data for uranium operating in the temperature range of 840-1020 F. One purpose of this irradiation is to obtain such swelling data. Another feature of this irradiation is the absence of significant cladding constraint since it has been shown experimentally that 100 psi of internal pressure will increase the volume of the fuel jacket 10 percent. The constraint to swelling will, therefore, be the system pressure of 1600 psi and not the system pressure plus some unknown cladding constraint characteristic of a tubular fuel.

The principal purpose of the irradiation is to demonstrate that fuel with a corrugated outer cladding accommodates more swelling than a fuel with circular outer cladding and, therefore, can be irradiated with the core in the high alpha uranium temperature range to exposures greater than 2000 MWD/T.

It is requested, therefore, that GEH-10-62 be irradiated to a maximum exposure of 3000 MWD/T or to a volume increase of 5 percent as determined by weight measurements described in Section V.

II. IRRADIATION UNIT CHARGES

Charges for irradiation units for irradiation of GEH-10-62 should be made to Budget Activity Number 02 50 10 05 6, Metallurgical Development.

III. SUMMARY OF OPERATING CONDITIONS

TABLE I

Reactor and Loop Operating Conditions

Reactor Power Level	175 MW
Loop Flow Rate	80 gpm
Loop Pressure	1600 psi
Saturation Temperature	605 F
Bulk Outlet Temperature	485 F
Bulk Water ΔT (across fuel)	512 F
Pressure Drop Across Assembly	7 psi

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TABLE II

Experiment Operating Conditions

Coolant Velocity, Bore	15.1 ft/sec
Coolant Velocity, Annulus	15.6 ft/sec
Specific Heat Generation (peak)	72.2 kw/ft
Total Heat Generation	156,000 Btu/hr
Peak Heat Flux, Bore	675,000 Btu/hr-ft ²
Peak Heat Flux, Annulus	530,000 Btu/hr-ft ²
Water Film Heat Transfer Coefficient, Bore	5883 Btu/hr-ft ² -°F
Water Film Heat Transfer Coefficient, Annulus	6062 Btu/hr-ft ² -°F

<u>Fuel Temperatures</u>	<u>Calculated</u>	<u>Adjusted</u>
Clad Surface		
Bore	602.2 F	680 F
Annulus	569.9 F	606.1 F
Core Surface		
Bore	799.9 F	857.1 F
Annulus	708.5 F	745.2 F
Maximum Core Temperature	980 F	1040 F

Burnup Rate

Maximum	19.36 MW/T
Average	11.98 MW/T

IV. DESCRIPTION AND FABRICATION OF FUEL SPECIMENS

The test fuel element is 12-1/2 inches long, internally-externally cooled, Zircaloy-2 clad and natural uranium cored. Figure 1 represents a section through the fuel element and the inner basket. This fuel element has nearly the same amount of uranium per unit length (0.626 lbs/in.) as the New Production Reactor inner fuel tube (0.61 lbs/in.). In this respect, the fuel element is similar to that used in the GHH-10-44&45 irradiation, HW-67946.

The natural uranium fuel elements for this irradiation were made as indicated below:

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Inner and outer clad - extruded from a 3-1/2-inch diameter forging upset to fit a 4.050-inch diameter container.

- bright etched in HNO_3 - 5 percent HF.

Core - natural uranium machined from a 4-inch diameter bar which was previously extruded from an 11-inch diameter beta heat treated ingot.

- pickled in HNO_3

- 200 C vacuum dried, re-machined to remove 0.010 from OD and ID, vapor degreased, wire brushed and canned.

Assembly - components were sealed by electron beam vacuum welding, both the Zircaloy-2 components and the copper can.

Extrusion - the extrusion was made May 27, 1961. The billet was preheated three hours at 600 C, lubricated with a suspension of copper and graphite in oil, placed in a 450 C die container and extruded through a reduction ratio of 10.6:1 at a ram speed of 30 inches per minute.

The fuel rods were cut to length, chemically milled to take a 0.200-inch-thick end cap. End caps were brazed with Zircaloy-5 percent beryllium by FPD Engineering using their standard process. The braze closed ends were then faced flat and a second closure was made by electron beam welding the clad to the end caps.

All pieces were ultrasonic tested throughout for complete bonding of the clad to the uranium. Furthermore, all pieces were autoclaved at 400 C steam for 72 hours.

V. SPECIAL MEASUREMENTS AND INSTRUCTIONS

The usual data log information which permits determination of integrated exposure and fuel temperatures will be required. In addition, it is necessary to follow the swelling progress with exposure. The swelling or change in volume of the fuel will be observed by measuring the apparent change in the combined weight of the fuel element and inner basket assembly when these are weighed in the ETR canal. Equipment for making these measurements will be furnished and a separate letter will provide the information necessary to convert weight in water to percent change in volume of the fuel. First the fuel and inner basket will be weighed in the canal prior to insertion into the ETR. The second weighing of the assembly should be after about 600 MWD/T exposure.

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These measurements should be repeated about every 500 MWD/T incremental exposure thereafter, until the irradiation is terminated.

This weight change data should be reported by phone or directly to G. A. East or R. G. Wheeler as soon as it is taken so that a decision concerning the continuation of the irradiation can be made.

VI. OPERATING CONDITION REQUIREMENTS

The important parameters in this experiment are exposure and core temperature. Should it be necessary to operate the loop at reduced temperature for a portion of one or more cycles, this would not detract significantly from the value of the experiment providing the latter portion of the exposure (last cycle) is as requested in Section III.

VII. DESCRIPTION AND ASSEMBLY OF BASKET

The basket assembly for GEH-10-62 is fabricated from thin-wall stainless steel tubing (see Appendix for drawing). The three main components of the basket assembly are the outer basket, the quick-disconnect assembly, and the inner basket. The inner basket has three supports welded to its inner surface at each end (see Figure 1 for cross-section showing supports). The centers of the supports are concave toward the center of the basket so that they support three of the corrugation "peaks" on the fuel element. The top of the inner basket also has one hook on each side. Both hooks are engaged by a "T" bar on the bottom of the quick-disconnect assembly. The outer surface at the bottom of the inner basket is machined to seal with a mating surface in the outer basket.

VIII. INSERTION AND REMOVAL OF EXPERIMENT

The basket will be shipped empty and the fuel will be loaded at ETR. To load the fuel:

1. Remove the quick-disconnect in the normal manner. This will also remove the inner basket from the outer basket.
2. Disconnect the "T" bar from the inner basket.
3. Load the fuel element into the inner basket, numbered end up, so that the supports engage with the peaks of the corrugations. The top supports will guide the fuel element into the bottom supports. (Number is GEH-10-62).
4. Engage the "T" bar with the inner basket and lower the assembly into the outer basket. When the quick-disconnect is locked into the outer basket, everything is properly located and the experiment is ready for installation into the loop.

The above procedure is also used for loading or unloading the fuel remotely in the ETR canal during or after irradiation.

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IX. HAZARDS

A number of Zircaloy-2 clad, coextruded fuel elements, having the same amount of natural uranium per foot, have been irradiated successfully. Intentional rupture tests of both high exposure and un-irradiated elements in the ETR have not endangered the reactor or the tube facility. The ability of the corrugated outer jacket of this element to withstand the anticipated five percent fuel volume increase was tested by dissolving the core out of a similar element and pressurizing with hydraulic fluid the space formerly occupied with fuel. The corrugated jacket withstood a 37 percent increase in core volume before a leak developed. Five percent volume increase is the maximum anticipated in this test.

X. DISPOSITION OF SPECIMEN

On completion of the irradiation, the fuel element and inner basket assembly should be sent to R. E. Olson, Radiometallurgy Operation, 327 Building, 300 Area, General Electric Company, Richland, Washington.

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A HEAT GENERATION

1. DETERMINATION OF PROBABLE P-7 FLUX CONDITIONS:

POWER GENERATION - GEH-10-44, 45 100 KW (CYCLE-41)

LENGTH OF URANIUM - GEH-10-44, 45 28.88 IN.

SPECIFIC POWER GENERATION - 41.55 KW/FT

$$\Sigma_f = 200 \text{ CM}^{-1}$$

ASSUMED HEAT RELEASE - 200 MEV/FISSION

$$Q = 200 \frac{\text{MEV}}{\text{FISSION}} \times 1.6 \times 10^{-16} \frac{\text{KW-SEC}}{\text{MEV}} \times .2 \frac{\text{FISSIONS}}{\text{CM-NEUTRON}} \times \phi_{\text{EFF}} \\ \times \frac{1}{.061 \frac{\text{IN}^3}{\text{CM}^3}} \times \frac{\pi}{4} (1.183^2 - 0.489^2) \times 12 \frac{\text{IN}^3}{\text{FT.}}$$

$$\phi_{\text{EFF}} = 0.362 \times 10^{14} \frac{\text{N}}{\text{CM}^2\text{-SEC}}$$

$$\text{AXIAL } \frac{\text{PEAK FLUX}}{\text{AVERAGE FLUX}} = 1.14$$

$$\text{EFFECTIVE PEAK AXIAL FLUX} = 1.14 \times (.362 \times 10^{14}) = 0.4127 \times 10^{14}$$

$$\text{FLUX DEPRESSION FACTOR (METALLIC U)} = 0.30$$

$$\text{UNDISTURBED PEAK AXIAL} = \frac{.4127}{0.30} = 1.375 \times 10^{14} \frac{\text{N}}{\text{CM}^2\text{-SEC}}$$

$$\text{HORIZONTAL PEAKING FACTOR} = 1.52$$

$$\text{ABSOLUTE PEAK, UNDISTURBED FLUX} =$$

$$1.375 \times 1.52 = 2.09 \times 10^{14}$$

PLANNED ETR SUMMER (62) CORE WILL CAUSE ESTIMATED 6% REDUCTION IN 3x3 FLUX WITH RESPECT TO CYCLE 41

2. HEAT GENERATION FOR GEH-10-62

$$\text{WEIGHT OF U/FT} = 12 \times 0.643 = 7.716 \text{ LB/FT}$$

$$\text{DENSITY OF U} = 18.90 \text{ GM/CC}$$

$$= \frac{18.90 \times 16.39}{454} = 0.682 \text{ LB/IN}^3$$

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$$\text{VOLUME OF FUEL} = \frac{7.716 \text{ LB/FT}}{0.682 \text{ LB/IN}^3} = 11.31 \text{ IN}^3/\text{FT}$$

$$\Sigma f = 0.200 \text{ CM}^{-1}$$

$$\text{PEAK AXIAL UNPERTURBED FLUX} = 1.375 \times 10^{14} \frac{\text{N}}{\text{CM}^2 \cdot \text{SEC}}$$

$$\text{DISPERSION FACTOR} = 0.3$$

$$\text{PEAK PERTURBED FLUX} = 0.4125 \times 10^{14}$$

CORRECTION FACTOR FOR HORIZONTAL PEAKING IS 1.52

$$\text{PEAK PEAK PERTURBED FLUX} = 1.52 (.4125) = 0.627 \times 10^{14}$$

$$\text{PEAK AXIAL/AVERAGE AXIAL} = 1.062$$

$$\text{AVERAGE PERTURBED EFF. FLUX} = \frac{.4125}{1.062} = 0.3884 \times 10^{14} \frac{\text{N}}{\text{CM}^2 \cdot \text{SEC}}$$

PEAK SPECIFIC POWER

$$Q_P = \frac{200 \times 1.6 \times 10^{16} \times 0.2 \times 0.602 \times 11.31}{.061} = 72.15 \frac{\text{KW}}{\text{FT}}$$

AVERAGE SPECIFIC POWER

$$Q_A = 72.15 \times \frac{0.3884}{0.6270} = 44.69 \frac{\text{KW}}{\text{FT}}$$

B. FLOW CALCULATIONS

1. ANNULUS FLOW AREA

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$$\cos (\angle CEH) = \frac{\overline{OA}^2 + \overline{AC}^2 - \overline{OC}^2}{2(\overline{OA})(\overline{AC})} = .8556, \angle CEH = 31.2^\circ$$

$$\overline{AH} = \overline{AE} \sin (31.2^\circ) = 35224$$

FLOW AREA (ANNULUS)

$$AREA = 12 \left[\left(\frac{\pi \times 1.758^2 \times 30}{4 \times 360} \right) - \frac{\pi (1.050)^2 \times 61.2}{360} - \frac{.35224 \times 1180}{2} + \frac{\pi (1.630)^2 \times 31.2}{360} \right]$$

$$AREA = (.202277 - .001335 - .20923 + .108064) 12 = \underline{1.973 \text{ IN}^2}$$

$$WETTED PERIMETER = 12 [\overline{BC} + \overline{CH} + \overline{DF}]$$

$$= \frac{12(2\pi)}{360} (.05 \times 61.2 + 0.630 \times 31.2 + .879 \times 30) = \underline{10.281 \text{ IN.}}$$

2. FLOW SPLIT

SUBSCRIPTS: 1 - CHANNEL AHEAD OF FUEL

2 - FUEL ELEMENT BORE

3 - FUEL TO BASKET ANNULUS

$$A_1 = \frac{\pi}{4} (1.758)^2 = 2.427 \text{ IN}^2, D_{c1} = 1.758 \text{ IN}, A_1^2 = 5.8903$$

$$A_2 = \frac{\pi}{4} (.4342)^2 = .1481 \text{ IN}^2, D_{c2} = .4342, A_2 = 0.02193$$

$$A_3 = 1.1973 \text{ IN}^2, D_{c3} = \frac{1.1973 \times 4}{10.281} = .4658, A_3^2 = 1.4335$$

LENGTH OF FUEL = 12.69 IN.

$$V_1 = \frac{65 \text{ GPM} \times 1.44 \text{ IN}^2 / \text{FT}^2}{7.48 \text{ GAL} / \text{FT}^3 \times 60 \frac{\text{SEC}}{\text{MIN}} \times 2.427 \text{ IN}^2} = 8.5932 \text{ FT/SEC}$$

$$\frac{\Delta P_2}{\Delta P_3} = 1 = \frac{(K_{ENT,2} + f_2 \frac{L}{D_{c1}}) V_2^2 + (V_3 - V_1)^2}{(K_{ENT,3} + f_3 \frac{L}{D_{c3}}) V_3^2 + (V_3 - V_1)^2}$$

SINCE THE ENTRANCE TO BOTH CHANNELS IS ROUNDED, THE ENTRANCE LOSS COEFFICIENT IS ASSUMED $\leq .04$

f_2 ASSUMED .0155 } ON BASIS OF PRIOR CALCULATIONS
 f_3 ASSUMED .0152 }

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THEN:

$$1 = \frac{(.047 + .0155 \frac{12.69}{.4342}) (V_2^2) + (V_3 - V_1)^2}{(.047 + .0152 \frac{12.69}{.4658}) V_3^2 + (V_3 - V_2)^2}$$

$$1 = \frac{1.493 V_2^2 + V_3^2 - 2 V_1 V_2 + V_2^2}{1.454 V_3^2 + V_3^2 - 2 V_1 V_3 + V_1^2} = \frac{1.493 V_2^2 - 17.1864 V_2 + 73.843}{1.454 V_3^2 - 17.1864 V_3 + 73.843}$$

ALSO: $A_1 V_1 = A_2 V_2 + A_3 V_3$ OR

$$V_2 = \frac{A_1 V_1 - A_3 V_3}{A_2} = \frac{(2.427)(8.5932) - 1.1973 V_3}{.1481}$$

$$V_2 = 140.822 - 8.0844 V_3$$

$$V_2^2 = 19,830.836 - 2276.9228 V_3 + 65.3575 V_3^2$$

$$1.454 V_3^2 - 17.1864 V_3 + 73.843 = 1.493 [19830.8357 - 2272.9228 V_3 + 65.3575 V_3^2] - 17.1864 (140.822 - 8.0844 V_3) + 73.843$$

$$1.454 V_3^2 - 17.1864 V_3 + 73.843 = 27,261.0575 - 3260.5040 V_3 + 97.5787 V_3^2$$

$$= 27187.2145 - 3243.3176 V_3 + 96.1246 V_3^2$$

$$V_3^2 - 33.741 V_3 + 282.8331 = 0$$

$$V_3 = \frac{33.741 \pm \sqrt{7.122681}}{2} = \frac{33.741 \pm 2.6688}{2}$$

$$V_3 = 15.5536$$

$$V_2 = 140.822 - 8.0844 V_3 = 15.0805 \text{ ft/sec}$$

REYNOLD'S NUMBER (550 F, 2000 PSI)

$$N_{Re_2} = \frac{D_{c_2} V P}{\mu} = \frac{(1.4342)(15.0505)(3600)(46.5)}{12 \times .235}$$

$$= 388,697. = 3.887 \times 10^5$$

$$N_{Re_3} = \frac{D_{c_3} V P}{\mu} = \frac{(1.4658)(15.5536)(3600)(46.5)}{12 \times .235}$$

$$N_{Re_3} = 4.3004 \times 10^5$$

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FRICTION COEFFICIENT

BORE FROM FIG. 1-5.1 REACTOR HANDBOOK 2

$$\frac{\epsilon}{D} = .00015$$

FROM FIG 1.52

$$f = .0155 \text{ @ CALCULATED CONDITIONS (AS ASSUMED)}$$

ANNULUS

$$\frac{\epsilon}{D} = .00015$$

$$f = .0152 \text{ @ CALCULATED CONDITIONS (AS ASSUMED)}$$

FLOW SPLIT

$$\text{BORE } \frac{A_2 V_2}{A_1 V_1} \times 100 = \frac{(.1481)(15.0805)}{(2.427)(8.5932)} = 10.709\%$$

ANNULUS

$$\frac{A_2 V_2}{A_1 V_1} \times 100 = \frac{(1.1923)(15.5536)}{(2.427)(8.5932)} = 89.291\%$$

CHECK

$$\begin{aligned} \Delta P_{\text{BORE}} &= \left[K_{\text{ENT}_2} + f_2 \frac{L}{D_{\text{CE}}} \right] V_2^2 + (V_2 + V_1)^2 \left] \frac{L}{144 \times 64.4} \right. \\ &= \left[(.04 + .453)(15.0805)^2 + (15.0805 - 8.5932)^2 \right] \frac{46.5}{144 \times 64.4} \\ &= .7926 \text{ PSI} \end{aligned}$$

$$\begin{aligned} \Delta P_{\text{ANNULUS}} &= \left[.454(15.5536)^2 + (15.5536 - 8.5932)^2 \right] .005014 \\ &= (109.853 + 18.447) .005014 \\ &= .7937 \text{ PSI} \end{aligned}$$

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C. Geometry of Fuel

1. Fuel Area

$$\text{FUEL AREA} = 12 \left[\text{AREA (OAB)} + \text{AREA (ABC)} - \text{AREA (OGP)} - \text{AREA (DCH)} \right]$$

$$\angle CED = \left[\text{ARC COS } \frac{1.188^2 + .690^2 - .671^2}{2(1.188)(.690)} \right] = \frac{1.4372}{1.6394} = 28.76^\circ$$

$$\overline{AE} = .690 \sin 28.76^\circ = .33196$$

$$\text{AREA} = 12 \left[\frac{.33196 \times 1.188}{2} + \frac{\pi (.040^2) (58.76)}{360} - \frac{\pi (.2421)^2 (30)}{360} - \frac{\pi (.690^2) (28.76)}{360} \right]$$

$$= 12 (.19718 + .000820 - .015344 - .01604)$$

$$= 12 (.07662) = \underline{\underline{.914 \text{ IN}^2 \text{ OR IN}^2/\text{IN}}}$$

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GMH-10-62 EXPERIMENT CROSS SECTION

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2. Size of Equivalent Cylindrical Fuel Element

Equivalent Cylinder:

$$\text{Volume} = .91944 \text{ in}^3/\text{in}$$

$$\text{ID}_{\text{fuel}} = .4842 \text{ in}$$

$$.91944 = \pi(r_o^2 - .2421^2)$$

$$.3513 = r_o^2$$

$$r_o = .5927 \text{ in}$$

Then Fuel Dimensions are:

$$\text{Outer Clad OD} = \underline{1.2254 \text{ in}}$$

$$\text{Outer Clad ID} = \underline{1.1854 \text{ in}}$$

$$r_o = .5927$$

$$\text{Inner Clad OD} = \underline{.4842 \text{ in}}$$

$$r_1 = .2421$$

$$\text{Inner Clad ID} = \underline{.4342 \text{ in}}$$

D. Heat Transfer for Cylindrical Fuel Element1. Adiabatic Radius

Temperature Drop From Adiabatic Radius to Bore or Annulus

$$\text{Overall } \Delta T = \Delta T_{\text{film}} + \Delta T_{\text{clad}} + \Delta T_{\text{bond}} + \Delta T_{\text{uranium}}$$

$$q^1 = \text{heat generation, kw/ft}$$

$$r_m = \text{adiabatic radius}$$

$$R_1 = \text{inner clad inner radius} \quad .2171 \text{ in}$$

$$R_2 = \text{outer clad outer radius} \quad .6127 \text{ in}$$

$$r_1 = \text{fuel inner radius} \quad .2421 \text{ in}$$

$$r_o = \text{fuel outer radius} \quad .5927 \text{ in}$$

$$\frac{r_m^2 - r_1^2}{r_o^2 - r_1^2} = \text{proportion of total heat which goes to bore}$$

$$\frac{r_o^2 - r_m^2}{r_o^2 - r_1^2} = \text{proportion of total heat which goes to annulus}$$

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h_b = heat transfer coefficient for U-Zirc bond

$$= 30,000 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$$

h_f = water film heat transfer coefficient:

$$\text{inner} = 5883 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$$

$$\text{outer} = 6062 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$$

k_c = clad conductivity

k_u = uranium conductivity

Heat Transferred to Fuel Element Bore

$$\text{Film } \Delta T = \frac{q^1 \times 3413 \times 12}{2\pi R_1 \times h_{f1}} \left[\frac{r_m^2 - r_1^2}{r_o^2 - r_1^2} \right]$$

$$\text{Clad } \Delta T = \frac{q^1 \times 3413}{2\pi k_{c1}} \ln \frac{r_1}{R_1} \left[\frac{r_m^2 - r_1^2}{r_o^2 - r_1^2} \right]$$

$$\text{Bond } \Delta T = \frac{q^1 \times 3413}{2\pi r_1 \times h_b} \left[\frac{r_m^2 - r_1^2}{r_o^2 - r_1^2} \right]$$

$$\text{Uranium } \Delta T = \frac{q^1 \times 3413}{4\pi k_{u1}} \left[\frac{r_m^2 \ln \left(\frac{r_m}{r_1} \right)^2}{r_m^2 - r_1^2} - 1 \right] \left[\frac{r_m^2 - r_1^2}{r_o^2 - r_1^2} \right]$$

Overall ΔT Core-to-bore:

$$\frac{q^1 \times 3413}{2\pi (r_o^2 - r_1^2)} \left\{ 12 (r_m^2 - r_1^2) \left[\frac{1}{R_1 h_{f1}} + \frac{\ln \frac{r_1}{R_1}}{12 k_{c1}} + \frac{1}{r_1 h_b} \right] + \frac{1}{2 k_{u1}} \right. \\ \left. \left[r_m^2 \ln \left(\frac{r_m}{r_1} \right)^2 - (r_m^2 - r_1^2) \right] \right\}$$

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$$\frac{q^1 \times 3413}{2\pi (r_o^2 - r_1^2)} \left\{ 12 (r_m^2 - r_1^2) \left[\frac{1}{R_1 h_{f1}} + \frac{\ln \frac{r_1}{R_1}}{12 k_{c1}} + \frac{1}{r_1 h_b} \right] + \frac{1}{2 k_{u1}} \right. \\ \left. \left[r_m^2 \ln \left(\frac{r_m}{r_1} \right)^2 - (r_m^2 - r_1^2) \right] \right\}$$

Heat Transferred to Fuel Element Annulus

$$\text{Film } \Delta T = \frac{q^1 \times 3413 \times 12}{2\pi R_2 h_{f0}} \left[\frac{r_o^2 - r_m^2}{r_o^2 - r_1^2} \right]$$

$$\text{Clad } \Delta T = \frac{q^1 \times 3413}{2\pi k_{c0}} \ln \frac{R_2}{r_o} \left[\frac{r_o^2 - r_m^2}{r_o^2 - r_1^2} \right]$$

$$\text{Bond } \Delta T = \frac{q^1 \times 12 \times 3413}{2\pi r_o h_b} \left[\frac{r_o^2 - r_m^2}{r_o^2 - r_1^2} \right]$$

$$\text{Uranium } \Delta T = \frac{q^1 \times 3413}{4\pi k_{u0}} \left[1 - \frac{r_m^2 \ln \left(\frac{r_o}{r_m} \right)^2}{r_o^2 - r_m^2} \right] \left[\frac{r_o^2 - r_m^2}{r_o^2 - r_1^2} \right]$$

Overall ΔT , Core-to-annulus:

$$\frac{q^1 \times 3413}{2\pi (r_o^2 - r_1^2)} \left\{ 12 (r_o^2 - r_m^2) \left[\frac{1}{R_2 h_{f0}} + \frac{\ln \frac{R_2}{r_o}}{12 k_{c0}} + \frac{1}{r_o h_b} \right] + \frac{1}{2 k_{u0}} \right. \\ \left. \left[r_o^2 - r_m^2 - r_m^2 \ln \left(\frac{r_o}{r_m} \right)^2 \right] \right\}$$

Adiabatic Radius

$$\text{Let } A = \frac{1}{R_1 h_{f1}} + \frac{\ln \frac{r_1}{R_1}}{12 k_{c1}} + \frac{1}{r_1 h_b}$$

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$$\text{Let } B = \frac{1}{R_2 h_{f_o}} + \frac{\ln \frac{R_2}{r_o}}{12 k_{c_o}} + \frac{1}{r_o h_b} \quad \text{Then,}$$

$$\Delta T_{\text{to bore}} = \frac{q^1 \times 3413}{2\pi (r_o^2 - r_1^2)} \left\{ 12 (r_m^2 - r_1^2) A + \frac{1}{2 k_{u_1}} \left[r_m^2 \ln \left(\frac{r_m}{r_1} \right)^2 - r_m^2 + r_1^2 \right] \right\}$$

$$\Delta T_{\text{to annulus}} = \frac{q^1 \times 3413}{2\pi (r_o^2 - r_1^2)} \left\{ 12 (r_o^2 - r_m^2) B + \frac{1}{2 k_{u_o}} \left[r_o^2 - r_m^2 - r_m^2 \ln \left(\frac{r_o}{r_m} \right)^2 \right] \right\}$$

The bulk water temperature in the bore is equal to that in the annulus, then the above two equations are equal, and that $k_{u_1} = k_{u_o}$

$$12 (r_m^2 - r_1^2) A + \frac{1}{2 k_{u_1}} \left[r_m^2 \ln \frac{r_m}{r_1}^2 - r_m^2 + r_1^2 \right] = 12 (r_o^2 - r_m^2)$$

$$B + \frac{1}{2 k_u} \left[r_o^2 - r_m^2 \ln \left(\frac{r_o}{r_m} \right)^2 \right]$$

$$r_m^2 \ln \frac{r_o}{r_1}^2 - (r_o^2 - r_1^2) = 24 k_u \left[r_o^2 B + r_1^2 A - r_m^2 (A + B) \right]$$

$$r_m^2 \left[\ln \frac{r_o}{r_1}^2 + 24 k_u (A + B) \right] = 24 k_u (r_o^2 B + r_1^2 A) + r_o^2 - r_1^2$$

$$r_m = \sqrt{\frac{24 k_u (r_o^2 B + r_1^2 A) + r_o^2 - r_1^2}{\ln \left(\frac{r_o}{r_1} \right)^2 + 24 k_u (A + B)}}$$

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2. Bulk Water ΔT

Inlet Water Conditions:

Temperature = 500 F μ = .2588
Pressure = 1600 psi Pr = .8508
Cp = 1.163 ρ = 49.2 lb/ft³
k = .3541

Flow

65 gpm

Flow Split

Bore 10.71 % = 6.96 gpm or 2,747 lb/hr
Annulus 89.29 % = 58.04 gpm or 22,905 lb/hr

Heat Split

As a first assumption, assume that 30 % of the total heat is transferred to the bore, and 70 % goes to the annulus.

At average power generation of 44.7 kw/ft:

Heat-to-bore = .3 x 44.7 = 13.41 kw/ft
Heat-to-annulus = .7 x 44.7 = 31.29 kw/ft

ΔT Within Bore:

$$Q = W C_p \Delta T$$

$$\frac{13.41 \text{ kw/ft} \times 12.29 \text{ in.} \times 3413 \text{ Btu lb}^{-1} \text{ } ^\circ\text{F}}{2747 \text{ lb/hr} \times 12 \text{ in/ft} \times \text{hr} \cdot \text{kw} \times 1.163 \text{ Btu}} = \Delta T$$

$$\Delta T = 14.69 \text{ } ^\circ\text{F}$$

with additive and hot channel factor: $\Delta T = 22.6^\circ$

ΔT Within Annulus:

$$\frac{31.29 \times 12.29 \times 3413}{22,905 \times 12 \times 1.163} = 4.10 \text{ } ^\circ\text{F}$$

with additive and hot channel factor: $\Delta T = 10.45$

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Bulk ΔT Across Fuel

$$\begin{aligned} W &= 25,652 \text{ lb/hr} \\ \rho &= 49.2 \text{ lb/ft}^3 \\ C_p &= 1.163 \\ Q &= 44.7 \text{ kw} \end{aligned}$$

$$\frac{44.7 \times 12.29 \times 3413}{25,652 \times 12 \times 1.163} = 5.22 \text{ F}$$

with additive and hot channel factor: $\Delta T = 11.75 \text{ F}$

3. Hot Spot and Hot Channel Factors

	<u>Hot Channel Factor, Fb</u>	<u>Hot Spot Factor, Fh</u>	<u>Additive Factors ΔT Add</u>
A. Mechanical Tolerances (Hydraulic Effects)			
(1) Effect on mass flow - External Effects (End boxes, etc.)	1	1	
(2) Effect on mass flow - Entrance and Exit Effects	1	1	
(3) Effect on mass flow- Channel Effects	1	1	
(4) Effect of D Variation	1	1.04	
B. Mechanical Distortion			
(1) Effect on mass flow - External Effects (End Boxes, etc.)	1	1	
(2) Effect on mass flow - Entrance Effects	1	1	
(3) Effect on mass flow - Channel Effects	1	1	
(4) Effect of D Variation	1.02	1.02	
C. Correlation Equation on h	1	1.2	
D. Determination of Critical Parameters			
(1) Flow Measurement	1.03	1.03	1.4
(2) Temperature Measurements (metal)			
(3) Pressure measurements	1	1	4.3
(4) Temperature Measurements (coolant)			

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	<u>Hot Channel Factor, Fb</u>	<u>Hot Spot Factor, Fh</u>	<u>Additive Factors ΔT Add</u>
E. Flow Distribution Effects			
(1) Plenum Effects	1	1	
(2) Edge Effects	1	1	
F. Neutron and Gamma Flux Distribution			
(1) Vertical Distribution	1	1	
(2) Horizontal Distribution	1	1	
(3) Internal Distribution	1	1	
G. Neutron and Gamma Flux Uncertainty			
(1) Unperturbed flux source	1	1	
(2) Average Depression	1	1	
(3) Internal Distribution	1	1	
(4) Experimental Power Generation Variation Timewise	1.1	1.1	
H. Heat Flux Over Element Surface			
(1) Fuel Homogeneity	1	1.02	
(2) Mechanical Effects (Meat and Clad Thickness)	1	1	
I. Effects Peculiar to Experiment			
(1)	1	1	
(2)	1.16	1.47	5.7
(3)			
(4)			

4. Heat Transfer

Film Coefficients

Bore

Inlet temperature = 500 F
 ΔT to point of maximum heat generation = 14.7 F
 Temperature core midplane = 500 + 7.4 = 507.4 F
 Assume ΔT_{film} = 110 F
 Average film temperature = 507.4 + $\frac{110}{2}$ = 563 F

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$$h_1 = bK \text{ (Figure 7-B, page 52, IDO-16343)}$$

where

$$K = \frac{V^{0.8}}{D_e^{0.2}}$$

$$\text{Velocity of 6.96 gpm in bore} = 15.081 \text{ ft/sec}$$

$$D_e \text{ of bore} = .4342 \text{ in}$$

$$K = \frac{15.081^{0.8}}{.4392^{0.2}} = \frac{8.8}{.8466} = 10.394$$

$$b = 566 \text{ (Figure 7-B)}$$

$$h_1 = bK = \underline{5883 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}}$$

Annulus

$$\text{Inlet temperature} = 500 \text{ F}$$

$$\Delta T \text{ to point of maximum heat generation} = 2.05^\circ$$

$$\text{Temperature at core midplane} = 500 + 2.05 = 502.0 \text{ F}$$

$$\text{Assume } \Delta T \text{ Film} = 90 \text{ F}$$

$$\text{Then } T_s = 502 + 45 = 547 \text{ F}$$

$$b = 578 \text{ (Figure 7-B, page 52, IDO-16343)}$$

$$K = \frac{V^{0.8}}{D_e^{0.2}}$$

$$V = 15.554 \text{ ft/sec}$$

$$D_e = .4658 \text{ in}$$

$$K = \frac{15.554^{0.8}}{.4654^{0.2}} = \frac{9.00}{.8581} = 10.488$$

$$h_o = bK = (10.488)(578) = 6062 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$$

Determine r_m for Equivalent Cylindrical Fuel Element

$$r_m = \sqrt{\frac{24 k_u (r_o^2 B + r_1^2 A) + r_o^2 - r_1^2}{\ln \left(\frac{r_o}{r_1} \right)^2 + 24 k_u (A + B)}}$$

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Where r_m is the adiabatic radius,

$$A = \left(\frac{1}{R_1 h_{f1}} + \frac{\ln \frac{R_1}{R_2}}{12 k_{e1}} + \frac{1}{r_1 h_b} \right)$$

$$B = \left(\frac{1}{R_2 h_{f0}} + \frac{\ln \frac{R_2}{R_0}}{12 k_{e0}} + \frac{1}{r_0 h_b} \right)$$

$$k_{e1} = \text{at } 712 \text{ F} = 7.52$$

$$h_{f1} = 5883$$

$$k_{e0} = \text{at } 652 \text{ F} = 7.42$$

$$h_{f0} = 6062$$

$$U_0 = \text{at } 870 \text{ F } (465.66) = 20.23$$

$$A = \frac{1}{.2171 (5883)} + \frac{\ln \frac{.2421}{.2171}}{12 (7.52)} + \frac{1}{(.242) 30,000} = .00212849$$

$$B = \frac{1}{.6127 \times .6062} + \frac{\ln \frac{.6127}{.5927}}{12 (7.42)} + \frac{1}{.5927 (30,000)} = .00069530$$

$$A + B = .00282379$$

$$r_m = \sqrt{\frac{24 (20.23) (.35129 \times .00069530 + .058612 \times .00212849) + .292678}{1.79 + 24 (20.23) (.00282379)}}$$

$$r_m = \sqrt{\frac{24 (20.23) (.000369008) + .292678}{1.79 + 24 (20.23) (.00282379)}}$$

$$r_m = \sqrt{\frac{.471976}{3.15745}} = \sqrt{.14948}$$

$$r_m = .38663 \text{ in.}$$

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Heat Split for This r_m

$$\text{Proportion to Bore} = \frac{r_m^2 - r_1^2}{r_o^2 - r_1^2} = \frac{.14948 - .058612}{.292678} \\ = .3105 \text{ or } 31.05\%$$

$$\text{Proportion to Annulus} = \frac{r_o^2 - r_m^2}{r_o^2 - r_1^2} = \frac{.35129 - .14948}{.292678} \\ = .6895 \text{ or } 68.95\%$$

This is close enough to the assumed heat split that no additional adjustment need be made in bulk water temperatures.

5. Temperature Calculations

Fuel Element Core to Center Coolant

Film ΔT

$$\Delta T_f = \frac{q^1 \times 3413 \times 12}{2\pi (R_1)(h_{f_1})} \left[\frac{r_o^2 - r_m^2}{r_o^2 - r_1^2} \right]$$

$$= \frac{72.2 \times 3413 \times 12}{2\pi (.2171)(5883)} (.3105)$$

$$= 114.8 \text{ F}$$

With hot spot factor 168.7 F

Clad ΔT

$$\Delta T_c = \frac{q^1 \times 3413 \times \ln \frac{r_1}{r_1}}{2\pi k_{c_1}} (.3105)$$

$$= \frac{72.2 \times 3413 \times .109 \times .31050}{2\pi (7.52)} = 176.9 \text{ F}$$

Bond ΔT

$$\Delta T_b = \frac{72.2 \times 3413 \times 12 (.3105)}{2\pi (.2141)(30,000)} = 20.15 \text{ F}$$

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Core ΔT

$$\Delta T_{ui} = \frac{72.2 \times 3413}{4\pi (20.23)} (.3105) \left[\frac{.14948 \ln \frac{.14948}{1.25861}}{.09087} - 1 \right]$$

$$= \frac{72.2 \times 3413 (.3105)}{4\pi (20.23)} (.5380) = 162.1 \text{ F}$$

Fuel Element Core to Annulus

Film ΔT

$$\Delta T_{film} = \frac{72.2 \times 3413 \times 12}{2\pi (.6127)(6062)} (.6895)$$

$$= 87.4 \text{ F}$$

With hot spot factor: $\Delta T_{film} = 128.5 \text{ F}$

Clad ΔT

$$\Delta T_{clad} = \frac{72.2 \times 3413 \times .6895}{2\pi (7.42)} \ln \frac{.1127}{.5927} (.03315)$$

$$= 120.8 \text{ F}$$

Bond ΔT

$$\Delta T_{bond} = \frac{72.2 \times 12 \times 3413 \times .6895}{2\pi (.5927)(30,000)}$$

$$= 18.28 \text{ F}$$

Core ΔT

$$\Delta T_{core} = \frac{72.2 \times 3413 \times .6895}{4\pi (20.23)} \left[1 - \frac{.14948 \ln \frac{.35129}{.14948}}{.35129 - .14948} \right]$$

$$= \frac{72.2 \times 3413 \times .6895 (.36671)}{4\pi (20.23)} = 244.5 \text{ F}$$

6. Summary of Operating Temperatures

<u>From Bore Outward</u>	<u>Calculated</u>	<u>Adjusted</u>
Bulk inlet water temperature	500 F	500 F
Bulk ΔT to midplane (bore)	7.4	11.3
Bulk temperature at midplane	502.4	511.3
Film ΔT (bore)	114.8	168.7
Inner clad surface temperature	622.2	680.0
Inner clad ΔT	176.9	176.9

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From Bore Outward

	<u>Calculated</u>	<u>Adjusted</u>
Bond temperature	799.1	856.9
Bond ΔT	20.2	20.2
Uranium inner surface temperature	819.3	877.1
Uranium ΔT to adiabatic radius	162.1	162.1
Maximum uranium temperature	981.4	1039.2

From Annulus Inward

Bulk inlet water temperature	500 F	500 F
Bulk ΔT to core midplane	2.0 F	5.3 F
Bulk water temperature midplane	502 F	505.3 F
Film ΔT (annulus)	87.4 F	120.8 F
Outer clad surface temperature	580.4 F	626.1 F
Outer clad ΔT	120.8 F	120.8 F
Bond surface temperature	710.2 F	746.9 F
Bond ΔT	18.3 F	18.3 F
Uranium surface temperature	728.5 F	765.2 F
Uranium ΔT to adiabatic radius	244.5 F	244.5 F
Maximum uranium temperature	973.0 F	1009.7 F

Coolant Saturation Temperature = 605 F.

Since the inner clad surface temperature is 622 F, the inlet water temperature should be reduced from 500 F to 480 F. This change should not significantly affect the values calculated for ΔT , but will reduce all the temperatures listed above by 20 F. The reduced values are shown in the tabular information at the beginning of this proposal.

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END