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TECHNICAL DATA RECORD

NAA-SR-TDR
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PAGE 1 OF 17

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GO NO. 7602

TITLE
SRE Core III Fuel Elements Thermal Analysis

S/A NO. 4405

TWR 50022

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STATEMENT OF PROBLEM Perform a steady-state thermal analysis of the fuel elements of SRE Core III. Present the thermal performance information for the core based upon certain specified conditions of operation. Show that the thermal constants or limitations imposed are satisfied.

ABSTRACT: The initial 30 Mw SRE Core III loading will contain a total of 33 fuel elements. Of these, the central 7 fuel elements are test elements and the remaining 26 are driver elements; 4 of the 7 test elements are designated as standard test elements. These elements are identical to the driver elements with the exception of the active fuel length. The remaining 3 test elements are designated as special test elements and incorporate fuel rods of smaller diameter and increased enrichment to obtain higher burnup rates, greater specific power, and higher fuel temperatures. Geometry design data for the various elements considered in the analysis was obtained from Dwg. No. 7602-918008. ⁽¹⁾ Inlet coolant temperature was specified at 650°F, the mixed-mean coolant outlet temperature for the core at 1200°F ($\pm 15^\circ\text{F}$), the maximum average temperature on the cladding at 1275°F, and the maximum fuel temperature in the range of 2000 to 2100°F.

The thermal performance of the fuel elements was analyzed with the SORTD code ⁽²⁾ and the Heating code ⁽³⁾. The results of the analysis are presented in tabular form. Axial temperature profiles are also presented for representative fuel elements. The core outlet coolant mixed-mean temperature was found to be 1185°F. For the special test, standard test, and highest powered driver elements the coolant outlet temperature is limited to values below 1200°F because of the specified maximum value of cladding temperature. For the remaining elements the coolant outlet temperature is 1200°F. Maximum fuel temperatures are at values less than 2000°F with the exception of the special test elements. These have maximum fuel temperatures in the range of 2000 to 2100°F. Recently, the "highest powered driver element" as presented in this report has been re-designated as "standard test element" because of the high power level associated with this fuel element position. ⁽⁹⁾

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I. Results

The overall SRE Core III thermal performance data are listed in Table II. The core power distribution, normalized to an average element power of 0.91, is illustrated in Figure 1 for the case of "all control rods out" and in Figure 2 for the case of "4 shim rods in".⁽⁴⁾ Table III lists the main thermal and hydraulic characteristics of the representative fuel elements at conditions of maximum peak to average power ratio.

Hot channel axial temperature profiles for the coolant, outside cladding surface, and inside cladding surface are illustrated in Figures 3 through 7. The cladding temperature values represent the average of the fuel rod circumferential temperature distribution, affected by the nonuniformity in power distribution within the fuel rod. Maximum fuel temperatures as reported in Table III make allowance for the actual power distribution within the fuel rods.

The nominal coolant outlet temperatures of the special test, standard test, and highest power driver elements are limited to values less than 1200°F because of the design temperature limitation of the cladding. The remaining driver elements may operate with coolant outlet temperatures of 1200°F because of the lower heat flux and correspondingly lower surface to coolant temperature difference.

II. Method of Analysis

The steady state thermal analysis for the core at the specified operating conditions was almost entirely conducted by means of the SORTD code.⁽²⁾ Input data, corresponding to the cases reported, is presented in Table I. This code has been written primarily to perform the heat transfer analysis of SGR calandria type cores in which all the heat generated within the graphite moderator is removed by the main coolant flowing through the process tube. In the SRE-PEP, the moderator elements are canned with a separate moderator cooling system. A portion of the heat deposited in the moderator is removed by the moderator coolant while the remainder is removed by the process tube main coolant. To use the SORTD code for this design, it was necessary to adjust the input variables, P (reactor power) and b (moderator heat fraction), as follows:

$$P_{\text{input}} = P_{\text{actual}} (1 - xy)$$

$$b = 1 - \frac{1 - y}{1 - xy}$$

where x = fraction of the heat deposited in the moderator removed by the moderator coolant

y = fraction of total power generated in the moderator

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For the SRE-PEP, $y = .0585$ and $x = 2/3$ (Ref. 5), hence input values are:

$$P_{\text{input}} = P_{\text{actual}} \left[1 - \frac{2}{3} (0.0585) \right]$$
$$= 0.961 P_{\text{actual}}$$

$$b = 1 - \frac{1 - 0.0585}{0.961} = 0.0203$$

By these adjustments to the input variables, the code correctly determined the temperature rise of the coolant on the basis of $0.961 P_{\text{actual}}$ and the temperature rise in the fuel, clad, thermal bond and film on the basis of:

$$P_{\text{input}} (1 - b) = 0.961 P_{\text{actual}} (1 - 0.0203) = 0.9415 P_{\text{actual}}$$

This is in agreement with the 5.85% value of the heat being deposited in the moderator. The only correction to the code results because of these adjusted input values was to the value of "average core specific power". To obtain specific power based on total fission power the code output values were divided by 0.961, corresponding to 1 minus the fraction of heat generated in the moderator and removed by the moderator coolant.

The fuel elements performance was determined with the code by individual analysis of the representative elements. This was accomplished by specifying the particular element geometry together with the element input power based on the actual element power, P_{actual} , determined as follows:

$$P_{\text{actual}} = P_{\text{average}} \times \phi_e$$

where P_{average} is the average element power, $\frac{\text{Total Core Power}}{\text{Number of Elements}}$,

and ϕ_e is the element power peaking factor, $\frac{\text{Element Power}}{\text{Avg Element Power}}$.

The element power peaking factor was obtained from the distribution of power in the core shown in Figures 1 and 2. Maximum values of peaking factors were used for the particular elements. For the cases considered, maximum values occurred for the "all control rods out" condition with the exception of the highest powered standard driver elements. These have a higher value when the shim rods are fully inserted.

Other input data for the individual cases were: coolant inlet temperature, coolant temperature rise, and the element hot channel factors. The determination of the hot channel factors of the SRE Core III (5) is illustrated in Table IV. This method consists of combining the individual contributing factors in the manner of normal distribution deviations, taking the square root of the sum of the squares. The

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coolant inlet temperature of 650°F was a fixed value and the coolant temperature rise in each element was limited by either or both of the following: a maximum average temperature on the cladding of 1275°F and of 1200°F for the coolant outlet temperature of the nominal channel.

The coolant heat transfer coefficients computed by the code were obtained by means of the Lubarsky-Kaufman correlation,

$$h = 0.625 \left(\frac{k_{\text{cool}}}{D_e} \right)^{0.6} (C_p \rho)^{0.4} (3600 V)^{0.4}$$

where,

h = heat transfer coefficient, Btu/hr-ft²-°F

k = thermal conductivity of the coolant, Btu/hr-ft-°F

C_p = specific heat of the coolant, Btu/lb-°F

ρ = density of the coolant, lb/ft³

V = velocity of the coolant, ft/sec

D_e = equivalent diameter, ft

This equation tends to yield conservative values for the coefficient for rod bundles, hence high values of the corresponding surface temperatures.

The code determination of the nominal and hot channel temperatures of the coolant, cladding and fuel are based upon a cosine axial power distribution and uniform power distribution within the fuel rods. Since a non-uniform heat generation exists within the fuel rod, the values of maximum fuel temperature calculated by the code had to be corrected to allow for this condition. For this purpose a detailed two dimensional analysis was performed with the Heating code (3) to evaluate the effect of non-uniformity in power density on the temperature distribution in the fuel rod. (7) The analysis was made for the special fuel rod in the core center element (15% enriched). The axial midplane of the hot channel fuel rod was considered. For the 15% enriched fuel rod the transverse power distribution is given by the relation:

$$q''' = q_0''' (1 + 38 r \cos \theta + 1394 r^2)$$

where

q''' = local volumetric heat generation, Btu/hr-ft³

q_0''' = volumetric heat generation at centerline, Btu/hr-ft³

r = radial distance from fuel slug centerline, ft

θ = angle measured from point of maximum heat generation

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For the case considered, the centerline heat generation, q_o'' , was found to be 76.8% of the mean heat generation rate. With the above power distribution relation, the fuel temperatures of the special center element were determined as a function of θ and r . The maximum hot-channel fuel temperature obtained was 67°F less than the corresponding value calculated by the SORTD code, based on uniform power distribution. Since this represented a significant difference, all values of maximum fuel temperature of the various elements were corrected to the non-uniform power distribution basis.⁽⁸⁾ For the 15% enriched special elements this was done by adjusting the 67°F temperature correction of the case analyzed by the ratio of the corresponding heat generation rates. For the 6.5% enrichment standard test and driver elements, in addition to the heat generation rate adjustment, the temperature difference was also adjusted to reflect the change in power distribution within the fuel rods.

The inside cladding temperatures, calculated by the SORTD code on the basis of uniform power distribution within the fuel rods, represent the average circumferential value. An actual circumferential temperature distribution for the inner surface of the cladding was determined as part of the two dimensional analysis for the special center element fuel rod conducted with the Heating code.⁽⁷⁾ This indicated a difference between the hottest and the coldest spot on the circumference of 111°F at the axial midplane where the rod power per unit length (kw/ft) is a maximum. At the cladding hot spot location, near the active length outlet (see Figure 3), this difference reduces to 68°F for the hot-channel and 60°F for the nominal channel.

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TABLE I
INPUT DATA TO SORTD CODE

<u>Data Identification</u>	<u>Special Test Center</u>	<u>Special Test First Row</u>	<u>Std. Test First Row</u>	<u>Std. Driver Highest Powered</u>	<u>Std. Driver Average Powered</u>
Number of elements	1	1	1	1	1
Coolant velocity, ft/sec	0.	0.	0.	0.	0.
Conductivity of fuel, Btu/hr-ft-°F	13.3	13.3	13.3	13.3	13.3
Mass of fuel slug/ft, KgU/ft	0.4925	0.4925	0.70927	0.70927	0.70927
Fraction heat in moderator	0.0203	0.0203	0.0203	0.0203	0.0203
Reactor thermal power, Kw	14,913.0	14,519.8	11,794.0	11,724.5	8736.4
Core temperature rise, °F	493	495	536	541	550
Number of fuel rods per element	8	8	8	8	8
Length of core, ft	5.833	5.833	5.50	6.00	6.00
Length/Extrapolated length	0.72	0.72	0.72	0.72	0.72
Coolant inlet temp., °F	650	650	650	650	650
Number of control rods	0.	0.	0.	0.	0.
Number of sources	0.	0.	0.	0.	0.
Average core burnup, Mwd/MTU	25,000	25,000	25,000	25,000	25,000
Plant Factor	0.80	0.80	0.80	0.80	0.80
Coolant density, lb/ft ³	52.1	52.1	52.1	52.1	52.1
Conductivity of coolant, Btu/hr-ft-°F	38.8	38.8	38.8	38.8	38.8
Viscosity of coolant, lb/hr-ft	0.59	0.59	0.59	0.59	0.59
Specific heat of coolant, Btu/lb-°F	0.303	0.303	0.303	0.303	0.303
Radial flux peaking factor	1.0	1.0	1.0	1.0	1.0
Axial flux peaking factor	1.25	1.25	1.25	1.25	1.25
Element peaking factor	1.0	1.0	1.0	1.0	1.0
Fuel hot channel factor	1.15	1.15	1.15	1.15	1.15
Coolant hot channel factor	1.039	1.039	1.039	1.039	1.039
Process tube I.D., inches	3.0	3.0	3.0	3.0	3.0
Central tube O.D., inches	0.874	0.874	0.857	0.857	0.857
Clad O.D., inches	0.57	0.57	0.68	0.68	0.68
Fuel diameter, inches	0.50	0.50	0.60	0.60	0.60
Clad I.D., inches	0.55	0.55	0.66	0.66	0.66
Element triangular pitch, inches	11.0	11.0	11.0	11.0	11.0
Pitch weighting factor	0.866	0.866	0.866	0.866	0.866
Conductivity of clad, Btu/hr-ft-°F	13.5	13.5	13.5	13.5	13.5
Conductivity of bond, Btu/hr-ft-°F	33.4	33.4	33.4	33.4	33.4
Added wetted perimeter, inches	4.71	4.71	2.262	2.262	2.262
Frontal area, inches ²	0.2209	0.2209	0.0509	0.0509	0.0509

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NO. NAA-SR-TDR 9431DATE 2-27-64PAGE 9 OF 17TABLE IIOVERALL REACTOR THERMAL PERFORMANCE DATA

Reactor thermal power (Mw)	30
Heat generated outside fuel (%)	5.85
Heat removed by fuel channel coolant (% of reactor power)	96.1
Mixed-mean core outlet coolant temperature (°F)	1185
Inlet coolant temperature (°F)	650
Number of fuel elements	33
Axial maximum-to-average power ratio	1.25
Process tube ID (in.)	3.00
Coolant temperature rise hot-channel factor	1.04
Hot channel factor applied to local temperature differences (clad surface to bulk coolant, across clad and bond, and fuel surface to centerline)	1.15
Total reactor coolant flow (lb/hr)	6.32×10^5

TABLE III
FUEL ELEMENT PERFORMANCE DATA

Parameter	Special Test Element (Center)	Special Test Element (first row)	Standard Test Element (first row)	Standard Driver Element (highest powered)*	Standard Driver Element (average powered)
Element power/avg element power	1.707	1.662	1.350	1.342	1.000
Active fuel length (in.)	70	70	66	72	72
Element flow (lb/sec)	9.45	9.18	6.88	6.79	4.97
Coolant velocity (ft/sec)	6.21	6.04	5.39	5.31	3.89
Heat transfer coefficient (Btu/hr-ft ² -°F)	5979	5911	6295	6266	5530
Max linear heat rate (kw/ft)	39.1	38.1	32.8	29.9	22.3
Avg specific power (kw/kgU) ✕	67.5	65.7	39.3	35.8	26.7
Max specific power (kw/kgU)	84.4	82.1	49.1	44.8	33.4
Max nominal heat flux (Btu/hr-ft ² x 10 ⁻⁵)	8.95	8.71	6.30	5.73	4.27
Nominal coolant outlet temp (°F)	1143	1145	1186	1191	1200
Max hot-channel clad temp (°F)	1275	1275	1275	1275	1272
Max nominal clad temp (°F)	1238	1238	1245	1245	1244
Max hot-channel fuel temp (°F) #	2097	2071	1940	1863	1671
Max nominal fuel temp (°F) #	1938	1915	1806	1740	1577
Avg burnup rate (Mwd/MTU-mo) ✕	2054	2000	1197	1090	812
Max burnup rate (Mwd/MTU-mo)	2568	2500	1496	1363	1015

* This element has been recently designated as "standard test element - (second row)".

✕ Initial values only.

Includes correction for self shielding.

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TABLE IV
DETERMINATION OF HOT CHANNEL FACTORS⁽⁶⁾

Variable	Variation	Variation in θ , %	$(\Delta \theta)^2$	Variation in θ_c , %	$(\Delta \theta_c)^2$	Variation in θ_b , %	$(\Delta \theta_b)^2$	Variation in θ_f , %	$(\Delta \theta_f)^2$	Variation in ΔT , %	$[\Delta(\Delta T)]^2$
1. Fuel Enrichment	$\pm 1\%$	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	--	--
2. Fuel Slug Diameter	$\pm 1\%$	2.00	4.00	2.00	4.00	2.00	4.00	2.00	4.00	--	--
3. Cladding Thickness	$\pm 10\%$	-	-	10.00	100.00	-	-	-	-	--	--
4. Thermal Conductivity											
a) Fuel (UC)	$\pm 10\%$	-	-	-	-	-	-	10.00	100.00	--	--
b) Sodium Bond	$\pm 10\%$	-	-	-	-	10.00	100.00	-	-	--	--
c) Clad (304 SS)	$\pm 5\%$	-	-	5.00	25.00	-	-	-	-	--	--
5. Coolant Heat	+ 40%	-	-	-	-	-	-	-	-	--	--
Transfer Coefficient	- 0%	-	-	-	-	-	-	-	-	--	--
6. Clad Diameter	± 3 mils	0.50	0.25	0.50	0.25	*	-	-	-	--	--
7. Coolant Outlet Temperature	$\pm 15^\circ\text{F}$	-	-	-	-	-	-	-	-	2.50	6.25
8. Coolant Inlet Temperature	$\pm 5^\circ\text{F}$	-	-	-	-	-	-	-	-	0.83	0.69
9. Coolant Flow Distribution	$\pm 2\%$	-	-	-	-	-	-	-	-	2.00	4.00
10. Power Distribution											
a) Radial	$\pm 10\%$	10.00	100.00	10.0	100.0	10.00	100.00	10.00	100.00	--	--
b) Axial	$\pm 10\%$	2.00	4.00	2.00	4.00	2.00	4.00	5.00	25.00	2.00	4.00
		$\Sigma = 109.3$		$\Sigma = 235.3$		$\Sigma = 209.0$		$\Sigma = 230.0$		$\Sigma = 14.94$	
		$\sqrt{\Sigma} = 10.5$		$\sqrt{\Sigma} = 15.2$		$\sqrt{\Sigma} = 14.5$		$\sqrt{\Sigma} = 15.2$		$\sqrt{\Sigma} = 3.87$	
		$F_\theta = 1.11$		$F_c = 1.15$		$F_b = 1.15$		$F_f = 1.15$		$F_{\Delta T} = 1.039$	

* Neglected because both θ_c and θ_b cannot apply concurrently.

θ = Temperature difference, $^\circ\text{F}$

F = Hot Channel Factor, dimensionless

ΔT = Coolant temperature rise, $^\circ\text{F}$

Subscripts:

b = Sodium bond

c = Cladding

f = Fuel

FIGURE 3
Axial Temperature Distribution
For Central Special Test Element

FIGURE 4

Axial Temperature Distribution
For Special Test Element - First Row

FIGURE 6

Axial Temperature Distribution
For Standard Driver Element - Highest Powered

FIGURE 7

Axial Temperature Distribution
For Standard Drive Element - Average Powered