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June 23, 1952

TO: W. C. Cooley
FROM: H. L. Sletten
SUBJECT: The Variation in Maximum Power Density and Maximum Heat Flux of the Core and Blanket Thorium Plates in the Converter Reactor with Irradiation Time

I. CONCLUSIONS

The time variation of the maximum heat flux from the thorium plates of the core and blanket of the converter reactor is determined by estimating the various factors which contribute to heat generation within the thorium. It is seen that the fissioning of U^{233} in the thorium is the only significant factor causing the transient. The steady state component of heat flux is 0.109×10^6 Btu/hr-ft² in the core and 0.0304×10^6 Btu/hr-ft² in the blanket. The maximum heat flux from the core thorium plates is increased to 0.319×10^6 Btu/hr-ft² after 100 days of irradiation. After 365 days of irradiation, the maximum heat flux in the blanket is 0.0794×10^6 Btu/hr-ft². These irradiation times correspond to about 0.3 per cent burn-up of thorium.

The spacing between the thorium boxes in the core is equal to the spacing between the fuel plates (0.117 inches). For the power level from which the maximum heat flux from the thorium plates was calculated, the maximum heat flux from the fuel plates is 1.09 times greater.

Since

$$\frac{q_f \max}{q_T \max} \approx \left(\frac{v_f}{v_T} \right)^{0.8} \frac{T_s \max - \frac{(T_{w2} + T_{w1})}{2}}{T_s \max - \frac{(T_{w2} + T_{w1})}{2}} \frac{f}{f \left(\frac{v_f}{v_T} \right) \left(\frac{q_T \max}{q_f \max} \right)}$$

for a full cosine axial flux distribution where subscripts f and T refer to the fuel and thorium cooling passages respectively and since

$$\frac{v_f}{v_T} \frac{q_{T \max}}{q_{f \max}} \cong 1 ,$$

$$\frac{q_{f \max}}{q_{T \max}} \cong \left(\frac{v_f}{v_T} \right)^{0.8} .$$

Therefore, the velocity of the water in the thorium cooling passage may be $\frac{1}{1.09}^{0.8} = 0.90$ times the water velocity in the fuel passage.

A water velocity of 3 to 5 ft/sec is sufficient to cool the blanket thorium plates to a temperature $T_{s \max} < 185^\circ \text{ F}$ for an inlet water temperature of 85° F .

II. HEAT PRODUCTION IN CORE THORIUM

It is assumed that the maximum power density with regard to space in the thorium assemblies in the core of the reactor will occur at the point of maximum neutron flux, viz., at the intersection of the centerline and mid-plane of the core for the hypothetical distribution on which all analyses have been based.

The best production is the sum of the following contributing factors:

- (1) Absorption of U^{235} fission gamma rays and U^{235} fission product decay gamma rays.
- (2) Absorption of gamma energy from neutron capture other than fission capture.
- (3) Absorption of beta particles from Th^{233} decay.
- (4) Absorption of beta particles and gamma rays from Pa^{233} decay.
- (5) Absorption of beta particles, gamma rays, and kinetic energy of fission fragments from U^{233} fission.
- (6) Absorption of beta particles and gamma rays from fission fragment decay.

1. U^{235} Fission (prompt) Gamma Rays and Fission Product (delayed) Gamma Rays -
Assuming that the reactor operates continuously at 312 megawatts, the heat production from this source is considered unvariant with time since the neutron

flux and U^{235} concentration are essentially constant, and the concentration of those fission products which are the major contributors to fission product decay gamma energy approaches the equilibrium concentration in a relatively short time. NAA-SR-Memo-351^{*} states that 40 per cent of the beta and gamma energy from the fission products in the fuel plates, amounting to $0.4 \times 13 = 5.2$ Mev per fission, escape from the fuel plates. Assuming that all of the prompt gamma rays, 4.6 Mev per fission, escape from the fuel plates and are captured in the thorium, the total energy per fission of the form belonging to this classification is $5.2 + 4.6 = 9.8$ Mev per fission.

All of this energy escaping the fuel plates is not captured in the core thorium, however. It is estimated by J. R. Wetch, using the method of Appendix F, NAA-SR-Memo-200, that the fraction of the core gamma rays which escape to the blanket is 0.111 for a peak/average flux ratio of 2.5. On this basis, the maximum energy which is absorbed by the thorium in the core from this source is

$$Q_1 = \frac{9.8}{198} (312 \times 10^6) (1 - 0.111) = 13,700 \text{ kilowatts}$$

The volume of the thorium in the core is

$$\begin{aligned} V_{Th,C} &= (185) \text{ boxes} \times (4) \frac{\text{plates}}{\text{box}} \times (0.320)(3.24)^{**} (58) \text{ thickness, width, length} \\ &= 44,500 \text{ in}^3 \\ &= (44,500)(2.54)^3 = 729,000 \text{ cm}^3 \end{aligned}$$

Then, the average power density is

$$q_1 \text{ avg} = \frac{13,700,000}{729,000} = 18.8 \text{ watts/cm}^3$$

Assuming that the gamma energy absorption in the thorium is distributed over the reactor volume in the same way as the neutron flux, the maximum power density is

$$q_1 = 18.8 \times 2.5 = 47 \text{ watts/cm}^3$$

^{*}Values of total fission energy and component energies of fission used here are taken from this memo.

^{**}The width has been decreased since this writing.

2. Absorption of Gamma Energy from Neutron Capture Other Than Fission Capture -

This contribution to the heat production in the thorium is the energy liberated in the neutron capture processes accompanying one fission, viz., non-productive capture in U^{235} , Th^{232} , Al and H_2O . Most of these gamma rays are the high energy (7.7 Mev) gamma rays which result from the $Th^{232} (n, \gamma) Th^{233}$ reaction. Assuming that all of the gamma rays from the neutron absorption processes are captured in the thorium, the energy per fission of U^{235} from this source is 7.7 Mev^2 .

If we assume that all of this gamma energy originates in and is distributed uniformly over the core volume (actually about 18 per cent of the $Th^{233} (n, \gamma) Th^{233}$ reactions occur in the blanket), the fraction which escapes to the blanket is 11.1 per cent and the amount which is absorbed in the core is $(1 - 0.111) 7.7 \text{ Mev}$ per fission. So that the contribution to the maximum power density from the neutron absorption processes is

$$q_2 = \frac{(1 - 0.111) 7.7}{198} \frac{312 \times 10^6}{0.729 \times 10^6} \cdot 2.5$$

$$= 36.8 \text{ watts/cm}^3$$

3. Absorption of Beta Particles from Th^{233} Decay - The equilibrium concentration of Th^{233} from the irradiation of Th^{232} by 1.25×10^{14} neutrons/cm²-sec is 1.75×10^{-3} grams/kg of Th^{232} . It can be shown that the heat production from it is insignificant compared to the other forms and, therefore, can be neglected.

4. Absorption of β -particles and γ -rays from Pa^{233} Decay - The time variation of heat production due to Pa^{233} decay (assuming that energy emitted per atom is 0.58 Mev and that all of it is absorbed in the thorium) is given on page 15 of Ref. 1, as a function of neutron flux. This table is reproduced below for a flux of 1.25×10^{14} neutrons/cm²-sec corresponding to the maximum in CR.

Irradiation Time, Days	15	30	60	100	150
q_4 , Heat Generation, watts/cm ³	0.597	1.01	1.48	1.73	1.83

It is seen that this, too, is a small contribution.

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56. Heat Production from U^{233} Fission and Fission Product Decay - The energy absorbed in the thorium per fission of U^{233} is assumed to be 183 Mev. This accounts for essentially all the energy released except that carried away by the neutrons¹ - a slight over-estimate of the heat generation since it includes all the energy from decay of the fission products. The heat production as a function of time at a thermal flux of 1.25×10^{14} is read directly from Fig. 3F of Ref. 1 (reproduced in Fig. 1 of this memo) as follows:

Irradiation Time, Days	15	30	60	80	100
$q_{5,6}$, Heat Generation, watts/cm ³	7.95	26.0	79.5	122	163

It is seen that the fissioning of the U^{233} is the only significant factor contributing to the time variation of heat production in the thorium plates. The steady state portion is $q_1 + q_2 + q_3 + q_4 = 47.0 + 36.8 + 0 + 1.2 = 85$ watts/cm³.

The total heat production as a function of time is

$$q = 85 + q_{5,6} \text{ watts/cm}^3.$$

For a thorium thickness, δ , of 0.320 inches, the maximum heat flux is

$$\frac{\delta q}{2} = \frac{(0.320)(2.54)}{2} (85 + q_{5,6}) \text{ watts/cm}^2$$

The maximum heat generation rate and heat flux are tabulated below and plotted in Fig. 2.

HEAT GENERATION IN CORE THORIUM

Irradiation Time	Days	0	15	30	60	80	100
Maximum Heat Prod.	watts/cm ³	85	93.0	111	165	207	248
	Btu/hr-ft ³ $\times 10^{-6}$	8.21	9.00	10.7	16.0	20.0	24.0
Maximum Heat Flux	watts/cm ²	34.6	37.8	45.1	66.8	84.1	100.7
	Btu/hr-ft ² $\times 10^{-6}$	0.109	0.120	0.143	0.212	0.267	0.319

II. HEAT PRODUCTION IN BLANKET

The factors which contribute to heat production in the blanket will be the same as for the core. The difference will be in the magnitude of the steady state component and a lower production rate and fission rate of U^{233} for a region of lower neutron flux. Obviously, the maximum power density in the blanket will be in thorium plates adjacent to the core since they will receive high intensity radiation from the core and will be in a region of highest neutron flux of the blanket.

1. From Parts 1, and 2, of Section I, the amount of gamma energy incident on the blanket is

$$\frac{(0.111)(9.8 + 7.7)}{198} \times 312 \times 10^6 \text{ watts}$$

$$= 3.06 \times 10^6 \text{ watts}$$

The differential equation for the attenuation of this gamma ray energy is given by

$$\frac{dI}{dx} = -\mu I$$

where

$$\mu = \text{attenuation coefficient}$$

and

$$I = \text{intensity of radiation}$$

The particular solution is

$$\frac{I}{I_0} = e^{-\mu x}$$

where I_0 is the incident intensity.

If we choose a conservative attenuation coefficient of 1.0 cm^{-1} for thorium (0.51 for 2 Mev gammas in lead³), the fraction of the incident radiation which is absorbed by a plate 0.320 inches thick is

$$1 - \frac{I}{I_0} = 1 - e^{-(1.0)(0.320)(2.54)}$$

$$= 1 - \frac{1}{2.255}$$

$$= 0.557$$

If it is assumed that the radiation equal to 3.06×10^6 watts is emitted uniformly in all directions from the core, the power which is incident on a unit area of thorium plate at the midplane of the reactor at a distance of 84 centimeters (approximate core radius) from the center is

$$\frac{3.06 \times 10^6 \text{ watts}}{4 \pi (84)^2 \text{ cm}^2}$$

The volume of thorium in the plate per cm^2 of incident surface is $(0.32 \times 2.54) \text{ cm}^3$, and 55.7 per cent of the incident power is absorbed. Therefore, the average absorption density in a thorium plate next to the core is

$$\begin{aligned} \frac{3.06 \times 10^6}{4 (84)^2} \times \frac{0.557}{(0.320)(2.54)} \text{ watts/cm}^3 \\ = 23.6 \text{ watts/cm}^3 \end{aligned}$$

2. A value of the heat production in the blanket thorium due to beta and gamma decay of Pa^{233} is estimated on the same basis as the core. If the neutron flux falls to 20 per cent of the maximum flux ($0.20 \times 1.25 \times 10^{14} = 2.5 \times 10^{13}$) at the interface between the core and blanket, the time variation of heat generation, from page 15 of Ref. 1, is as follows:

Irradiation Time	Days	15	30	60	100	150	200	250	300	365
Heat Prod.	$\text{cal/sec-cm}^3 \times 10^2$	1.79	3.04	4.46	5.23	5.57	5.66	5.71	5.68	5.67
	watts/cm^3	0.075	0.127	0.187	0.219	0.234	0.237	0.239	0.238	0.238

It is seen that the heat production from Pa^{233} decay reaches a steady-state value of about 0.238 watts/cm^3 after 150 days irradiation time. In other words, the Pa^{233} in the thorium has reached an equilibrium concentration.

3. The heat production from U^{233} fission and fission product decay may again be read from Fig. 3F of Ref. 1 (see Fig. 1) for a neutron flux of $2.5 \times 10^{13} \text{ neutrons/cm}^2\text{-sec}$ over the whole irradiation period.

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HEAT PRODUCTION IN BLANKET THORIUM BY U^{233} FISSION

Irradiation Time	Days	15	30	60	100	150	200	250	300	365
Heat Prod.	cal/sec-cm ³	0.093	0.330	1.07	2.25	3.75	5.20	6.40	7.60	9.00
	watts/cm ³	0.390	1.38	4.48	9.43	15.7	21.8	26.8	31.8	37.7

HEAT GENERATION IN BLANKET THORIUM

Irradiation Time	Days	0	15	30	60	100	150	200	250	300	365
Maximum Heat Production	watts/cm ³	23.6	24.1	25.1	28.3	33.2	39.5	45.6	50.6	55.6	61.5
	Btu/hr-ft ³ x 10 ⁻⁶	2.23	2.33	2.43	2.74	3.21	3.82	4.41	4.89	5.37	5.95
Maximum Heat Flux	watts/cm ²	9.99	9.79	10.2	11.5	13.5	16.1	18.5	20.6	22.6	25.0
	Btu/hr-ft ² x 10 ⁻⁶	0.0304	0.0311	0.0324	0.0366	0.0428	0.0509	0.0587	0.0653	0.0717	0.0794

The time variations in maximum power density and heat flux for the core and blanket are plotted in Fig. 2.

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FIG. 1

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FIG. 2 333-10

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