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PRELIMINARY DESIGN DATA FOR A
CIRCULATING FLUORIDE-FUEL HIGH-FLUX REACTOR

ABSTRACT

A rough calculation shows that a flux of 10^{16} n/cm² sec can be obtained in the internal thermal column (island) of a reflector-moderated circulating fluoride-fuel reactor. Existing NaZrF₅-base fuels and a graphite moderator are used. The average power density in the reactor is 1 kw/cc, and the total power is 444 Mw. Inner radius of the fuel region is 50 cm.

In a reflector-moderated fluoride-fuel reactor, fluxes of the order of 10^{15} n/cm² sec are obtained in the "island" even at a power below 100 Mw. The following is a preliminary attempt to investigate the feasibility of obtaining a flux of 10^{16} n/cm² sec by means of a reactor of this type, using graphite as a moderator, limiting the average power density of the fuel in the reactor to 1 kw/cc, and the overall power to less than 500 Mw. The theory used is admittedly very crude, and no attempt has been made at optimization. Refinements are believed to lead to more optimistic results.

In the calculation the reactor is described as a spherical shell embedded in an infinite moderator. For the purpose of computing the behavior of the neutrons in the moderator, the fuel region is collapsed into an infinitely thin spherical shell, being black for thermal neutrons, and emitting 2.7 fission neutron for each thermal neutron absorbed. The absorptions at epithermal energies, both in the fuel and the moderator, are neglected, which is probably pessimistic, as the thermal neutron flux peak in the moderator will most likely be higher for a given power, if the epithermal absorptions are considered.

In the model used the fission neutrons emitted from the shell slow down according to the age-kernels*, and then diffuse according to diffusion theory with the boundary condition created by the black shell. Graphite of density 2, age to thermal 256 cm², thermal diffusion length 43.5 cm was used. The computation yields, for a 50 cm radius sphere, that per fission neutron emitted, 0.633 thermal neutrons return to the shell, and the flux at the center of the sphere is 3×10^{-4} n/cm².

* A. M. Weinberg and L. C. Noderer, Theory of Neutron Chain Reactions: Diffusion and Slowing Down of Neutrons, Vol. I, ORNL CF-51-5-98, p. III-38 (May 15, 1951).

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From this the required reactor power is found as follows:

$$10^{16} \text{ n/cm}^2 \text{ sec} = 3 \times 10^{-4} (\text{n/cm}^2)/\text{fission neutron} \times 2.5 \text{ fission neutron/fission} \\ \times 3 \times 10^{10} \text{ fission/watt sec} \times P \text{ watts}$$

$$P = 444 \times 10^6 \text{ watts.}$$

With 1 kw/cm^3 , this requires $444,000 \text{ cm}^3$, or if the inner radius of the spherical shell is 50 cm , its thickness t has to be given by:

$$\frac{4}{3} \pi \left[(t + 50)^3 - 50^3 \right] = 444,000 ,$$

$$t = 11.4 \text{ cm.}$$

If 0.633 neutrons return to the shell and there are $n \text{ U}^{235}$ atoms per NaZrF_5 molecule then

$$\frac{n \times 687 \times 0.633}{0.73 + n \times 687}$$

neutrons will be absorbed in U^{235} . The thermal absorption cross section of a NaZrF_5 molecule is 0.73 , and 687 is the same for a U^{235} atom. This number of neutron absorptions in U^{235} times 2.08 (the number of fission neutrons per neutron absorbed in U^{235}) should be one, to keep the chain reaction going. From this n can be computed to be, $n = 0.00335$. (Usually, NaZrF_5 is counted as two molecules, NaF and ZrF_4 . The above n value hence corresponds to $0.167 \text{ mol } \% \text{ of } \text{U}^{235} \text{ F}_4$.)

With a density of the NaZrF_5 of 3 g/cm^3 , there would be

$$3 \times \frac{0.00335 \times 235}{209} = 0.0113 \text{ g } \text{U}^{235}/\text{cm}^3.$$

Since the burnout at 1 kw/cc would be $0.0013 \text{ g/cm}^3/\text{day}$, all uranium would burn out in 8.7 days. (not counting the uranium in the external circuit). Obviously that is too rapid a burnout, and we somewhat arbitrarily specify a uranium density 5 times as great, or $0.0565 \text{ g } \text{U}^{235}/\text{cm}^3$, or $0.8 \text{ mole } \% \text{ in the usual terminology}$. The uranium in the reactor would then be $0.0565 \text{ g/cm}^3 \times 444,000 \text{ cm}^3 = 25 \text{ kg}$. The excess reactivity would have to be taken care of by prepoisoning or control rods.

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The macroscopic scattering cross section of the NaZrF_5 is

$$\frac{32 \times 10^{-24} \text{ cm}^2/\text{molecule NaZrF}_5 \times 0.6 \times 10^{24} \text{ molecules/mole} \times 3 \text{ g/cm}^3}{209 \text{ g/mol}} = 0.276 \text{ cm}^{-1}.$$

The macroscopic absorption cross section of the fuel is

$$\frac{(0.730 + 687 \times 0.0565) \times 10^{-24} \times 0.6 \times 10^{24}}{209} = 0.344 \text{ cm}^{-1}.$$

The diffusion length in the fuel is thus

$$L = \frac{1}{\sqrt{3 \times 0.276 \times 0.344}} = 1.87 \text{ cm},$$

which is indeed short compared to the thickness of the fuel layer so that the layer would be black to thermal neutrons as assumed in the calculation. This would be true even for somewhat higher neutron temperatures.

It is clear that realistic features such as non-spherical geometry will make the result somewhat less optimistic. On the other hand, the results would be improved if the epithermal fissions were taken into account, and if optimization were attempted. Furthermore, it appears that an improvement could be obtained by "bismuth dam", a layer of bismuth between the internal thermal column and the fuel layer. This dam would offer a resistance to the flow of thermal neutrons from the graphite (where they are created) to the shell, where they are absorbed. This resistance has to be overcome by an increase in the potential, the thermal flux. The bismuth also would serve as a gamma shield protecting the internal thermal column and the apparatus therein.

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