Design Parameters for Graphite-Reflected Graphite-Foam-U Cores with Zero Burnup Reactivity Swing

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Research at the Materials Science Division of the Oak Ridge National Laboratory resulted in the development of a graphite foam[1] that, at low densities (ρ ~ 0.5 g/cm ^{3}), exhibits heat conductivities similar to the case of normal graphite (ρ ~1.6 g/cm^3). The foam conductivity is then, per unit mass, about 3 times larger than the one of normal graphite. Because of such reduction of the thermal inertia, uses of the foam in several technologies are being studied. This presentation describes potential applications of the foam to the innovative design of nuclear reactors that do not require refueling, have very low reactivity inventory and excellent thermal characteristics and that could develop, hopefully, into modular designs easy to operate as energy sources.

With ρ ~ 2 g/cm ^{3} for non-porous graphite, the foam (ρ ~ 0.5 g/cm ^{3}) has an available void fraction of 0.75 that can be filled with U metal (maximal ρ ~19 g/cm ^{3}). If the whole available volume could be filled with U metal we would have an upper limit for the uranium density in the mixture of 0.75*19=14.25g/cm ^{3}. Below it, the density of the foam in the mixture and its contribution to the thermal conductivity have their maximum values. For U densities above 14.25 g/cm ^{3} the foam density in the mixture is below 0.5 g/cm ^{3} and goes to zero at 19 g of U/cm ^{3}. Using the same argument for normal graphite of density 1.6 g/cm ^{3} (available void fraction 0.2) the reduction of the thermal conductivity of the mixture starts at much lower densities, 3.8 g/cm ^{3}. The heat conductivities (k) start to grow at very low U densities because the U occupies the available void fractions. But at the U densities of 3.8 g/cm ^{3} in graphite and 14.25 g/cm ^{3} in the foam, the U starts to displace C atoms with the corresponding decrease in k. Figure 1 shows the differences between the two materials.

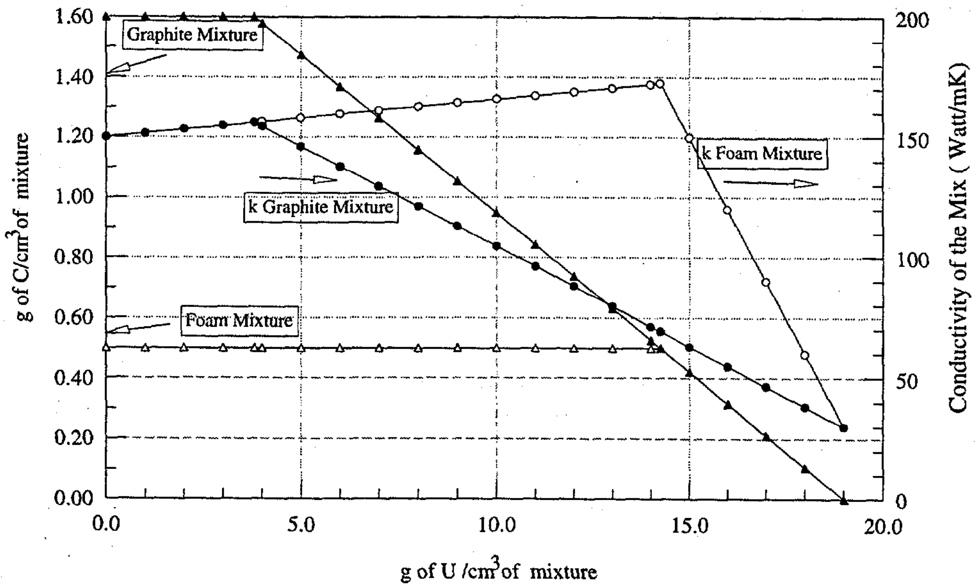

Figure 1: Carbon densities and heat conductivities for mixtures of U metal with the foam and normal graphite. Note: these are maximum effects under the hypothesis described in the text.

The possibility of having larger concentrations of U in C/U mixtures without the penalty of a considerable reduction in the heat conductivities opens the way for the design of fast C/U systems with zero burnup reactivity swing . The parameter C/^{235}U (ratio of atom densities) and the presence and the thickness of graphite reflectors (for the case of small core volumes) define the neutron spectra and then the average value of η (neutron production/absorption) for ^{235}U. Additionally, the presence of ^{238}U enhances, via fast fission effects, the average values of η for the whole core. Ultimately the three variables are going to define the possibility of a design with zero burnup reactivity swing but the most important variable is C/^{235}U.

The Helios[2] code was used to calculate the design parameters. Helios is a code that computes burnup histories that include a very detailed inventory of isotopes as function of burnup. With critical bucklings, migration lengths and reflector savings from Helios, estimations were made for the critical volume of finite cylindrical cores. Table 1 is a summary of the results corresponding to a carbon density of 0.5 g/cm^3 as function of $C/^{235}U$ and subject to the condition of zero reactivity swing up to a burnup of 40 GWd/ton.

Table 1
Design Parameters for Near Zero Burnup Reactivity Swing (Constant C Density Corresponding to the Graphite Foam, 0.5 g/cm^3)

Case	$C/^{235}U$	Enrichment (atom %)	U density (g/cm^3)	Reflector[b] Thickness (cm)	$\langle E_c \rangle$[c] (keV)	$\langle E_r \rangle$[c] (keV)	k_{eff} at 0 GWd/ton	k_{eff} at 40. GWd/ton
1	5	11.0	18.0[a]	20	107.	1.04	0.994	0.989
2	5	13.9	14.24	5	241.	140.	0.999	0.985
3	7	9.0	15.7	35	68.2	0.185	0.999	1.004
4	7	9.9	14.3	25	89.7	0.571	1.004	1.012
5	10	9.0	11.0	35	64.0	0.193	1.009	1.011
6	20	9.0	5.5	30	58.0	0.300	1.005	1.006
7	50	8.4	2.36	20	55.3	2.13	1.002	0.999
8	50	8.4	2.36	0	60.2	--------	0.992	0.991

a: Note that for this U density is not possible to have a C density of 0.5.
b: Graphite density 1.74.
c: Average neutron energy in core and reflector.

Table 1 (Continuation)

Case	Core Volume (m^3)	Reactor Volume (m^3)	Mass of U (Tons)	Mass of Reactor (Tons)	Density Fission Gases per Unit Energy (g/L GWd)	Damage in foam Per Unit Energy (dpa/GWd)[d]	Energy[e] Produced At 40. Gwd/ton (Gwdays)	Core Diameter (m)
1	0.101	0.584	1.827	2.72	1.28	1.77	73.	0.518
2	0.140	0.229	1.996	2.22	0.922	1.62	80.	0.578
3	0.219	1.947	3.438	6.55	0.592	0.971	138.	0.671
4	0.217	1.200	3.104	4.92	0.596	1.06	124.	0.669
5	0.455	2.834	5.003	9.37	0.285	0.623	201.	0.856
6	2.848	7.662	15. 670	25.47	0.0455	0.199	628.	1.577
7	141.260	173.501	333.172	459.90	0.00092	0.00618	13,323.	5.796
8	209.857	209.857	494.961	559.89	0.00062	0.00428	19,791.	6.582

d : Indeed this column includes the values of the average core fluence above approximately 100 keV in units of 1.0E+21. It was assumed then that 1.E+21 fluence produces 1 dpa (displacement per atom) in the foam.
e: A pure neutronics result without consideration any material degradation.

Table 1 shows that in general: 1) for small values of $C/^{235}U$ it is possible to build small cores with zero reactivity swing provided that the graphite reflector is not very thick. The cores are small, so the presence of a moderating reflector largely affects the neutron spectra in the core, reducing η and consequently requiring low enrichments and unrealisticly high values for the U density, and 2) it would be possible to build large cores with zero reactivity swing using values of $C/^{235}U$ between 20 and 50. From a neutronic point of view they would produce a huge amount of energy almost indefinitely. The reflector now only affects the criticality rather than the burnup.

The general tendencies shown in Table 1 can be used to find candidates for a modular design. For example a 1000 L core with a more relaxed U density, 6.9 g/cm^3, between cases 5 and 6, would have $C/^{235}U=12$, enrichment=12 %, reflector thickness = 15 cm, reactor mass=8.5 Tons. The total energy output at a discharge burnup of 40 GWd/ton, would be 250 GWd. At a steady operating power of 1 Mw and assuming conditions of heat conduction only (i.e. a completely solid core) the temperature at the center of the core would be 1150 C above the temperature at the boundary. A neutronic equivalent design with porous normal graphite (in order to have a carbon density=0.5) would exhibit an increase in temperature several thousand degree larger. The differences during transient conditions are also very large as the time constant of a thermal transient for a completely solid core, $\tau = \rho c R^2 / k\pi^2$ (c is the heat capacity and R the radius of the core), indicates. The factor ρ / k reduces the time constant of a thermal transient in the foam by a factor ~ 3 when compared with a neutronically equivalent design with normal graphite. In summary this analysis shows that the graphite foam developed at ORNL could be used to build modular energy sources in the Mw range that are small and long lasting, require no refueling and exhibit excellent thermal characteristics, hopefully a sort of "nuclear battery".

References

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