Irradiation Studies of Graphite Foams and Effects on Properties for Use in a Solid State Self-regulating Nuclear Heat Source for Small Modular Power Units

James Klett , Nidia Gallego, Tim Burchell, Jeff Bailey

Oak Ridge National Laboratory
Oak Ridge, TN 37831-6087

Introduction

The Solid State Reactor (SSR) is an advanced reactor concept that would take advantage of newly developed materials with enhanced heat transfer characteristics and superb high temperature mechanical properties to provide an inherently safe, self-regulated heat source. The concept achieves demand-driven heat generation without the need of moving parts or working fluids. The nature of the reactor design makes the concept inherently safe, proliferation resistant, and ideal as a long-term, reliable source of power for harsh, remote, and/or inaccessible environments on Earth and space. Low-cost power generation is envisioned on a wide variety of temperature and power ranges.

The SSR is currently being developed with funding provided by the DOE NERI program as the Demand-Driven Nuclear Energizer Module project.

Concept Technology

This concept adapts the mechanisms of inherent-safety with auto-shutdown in the event of loss of heat removal, demonstrated at EBR-II and the pebble-bed reactors, to be the normal operating mode of the reactor.

Each basic heat source module consists of a cylindrical reactor core surrounded by an externally sealed neutron reflector. The core contains nuclear fuel embedded inside a matrix of high-conductivity graphitized carbon foam. This carbon foam, originally developed at ORNL, has a bulk apparent density of 0.5 g/cm^3 and an approximate thermal conductivity of nearly 150 W/m·K (1-5). Heat generated by the nuclear fuel embedded in the pores of the foam is transferred to the reactor boundaries by conduction, i.e., without working fluids. Heat will be removed from the module's external boundary in whichever form is most suitable to the balance of plant.

The enrichment of the nuclear fuel, density of the graphitized foam, and dimensions of the reflector will be designed to provide automatic power regulation and long life without refueling. The solid-state nuclear module will provide power on an as-needed basis and shut down automatically when there is no demand (i.e., as the heat extraction is decreased the reactor will heat up causing geometric expansion and an increase in parasitic neutron absorption in the fuel - Doppler effect). This will, in turn, bring the reactor to a new, safe, power level at the boundary of sub-criticality and the reactor will remain there in hot stand-by mode. When the demand is increased, the heat extracted from the hot core will cause a reduction in temperature that will increase reactivity and bring the reactor to a production state whose output level matches the new rate of heat extraction.

The graphite foam will act mainly as structural support and heat conduction material. The main moderating contribution will come from the reflector and the energy of the dominant neutron population will be in the fast-epithermal region. The low density of the foam will result in a low carbon-uranium ratio. This is the key to attain a zero burn-up reactivity swing for long time periods.

Inherent self-shutdown and load following traits minimize nuclear safety concerns and operator training and educational requirements. Once in place, the nuclear heat source will require no maintenance or human intervention for a lifetime. Any operational or maintenance requirements will be imposed by the heat utilization system (i.e., the balance of plant.)

The fuel, enriched ^{235}U, will be embedded in the pores of the foam and itself will be coated with a thin layer of cladding material to provide containment of fission products. The uranium enrichment required for this reactor is well below the 20% limit for proliferation concerns. This design allows for operating temperatures of the order of 800-1000°C and standby temperatures approximately 1200°C. Thermal efficiency up to 40%, depending on the energy conversion technology used in the balance of plant, can be achieved.

The concept appears to be realizable on a wide range of scales and temperature levels. Matching specific requirements of any target process seems a matter of finding the appropriate fuel and foam density combination.

Low-cost is inherent, and design for low as well as high temperature operation and/or low/high output levels that are inherently safe and proliferation resistant seems feasible.

Experimental

To demonstrate that this concept is feasible, a mock-up reactor core was built from the graphite foam. A 12-cm-dia. by 16-cm-high cylinder of graphite foam was fabricated to mock the reactor core of our solid state reactor (See Figure 1). A hole was drilled in the center of the foam cylinder and a heater rod inserted in the hole, simulating the heat generated from the fission. To emulate the self-regulating characteristics of this concept a thermistor (an electronic component whose electrical resistance decreases as temperature increases) was placed near the outer edge of the cylinder that provides feedback to the power electronics driving the heater rod. As a result, the heating rod delivers less power as the temperature increases and shuts off at a pre-established standby temperature. When power is removed from the heater rod the temperature decreases and the thermistor signals the power electronics controlling the heater rod to supply more power to compensate. This first stage of physical modeling will continue with the objective to debug the electronics and build safety enclosures for both the electronics and graphite foam block. Figure 2 is a graph of the simulated reaction time of the full-scale reactor.

A simulation code, Helios, was used to calculate burn-up histories with a detailed inventory of isotopes. Initial results from the nuclear physics for this concept indicate that a reactor core could be built that is roughly 1000 liters in volume, contains roughly 8.5 tons enriched ^{235}U, and would supply 1MW electric power for several decades and be completely self contained. For example, the core could be buried in the ground and heat extracted to power the desired application. No refueling for the life of the reactor would be required and the core would be proliferation resistant and protected from sabotage.

Irradiation studies at ORNL's High Flux Isotope Reactor (HFIR) facility are underway to determine the effects of neutron flux on the thermal properties of the graphite foam as a function of dose rates up to 2.6 displacements per atom (dpa), see Table I. The graphite samples are machined into cylinders and placed in an aluminum capsule, which is sent to the HFIR reactor through a hydraulic tube. Silicon Carbide (CVD deposited) temperature monitors are placed in the capsules to monitor the irradiation temperature. The dimensional changes of the CVD silicon carbide as a function of irradiation and temperature are well known, and therefore, by the dimensional changes observed, it can be deduced what temperature the samples actually attained during the irradiation. It is anticipated that the graphite foam will behave similar to standard nuclear graphite and carbon/carbon composite materials, see Figure 3. Typical graphites exhibit a reduced thermal conductivity (about 75% reduction) after irradiation at high dose levels. However, most of this can be recovered after annealing at elevated temperatures up to 1200°C (similar to the standby temperature of the current reactor design). The samples (base-line and irradiated) will be characterized by dimensional changes, mechanical properties, and thermal properties as a function of dose. Following the initial effects of the irradiation, the samples will be annealed at temperatures ranging from 500°C to 1200°C and the thermal properties as a function of annealing temperature will be reported. Also, x-ray and SEM characterization will be performed to determine what structural damage is occurring to the foam during the irradiation and to determine if it is reparable under annealing conditions. It is anticipated that these annealing conditions will occur during standby operation of the reactor as the temperature increases when heat removal is ceased.

References

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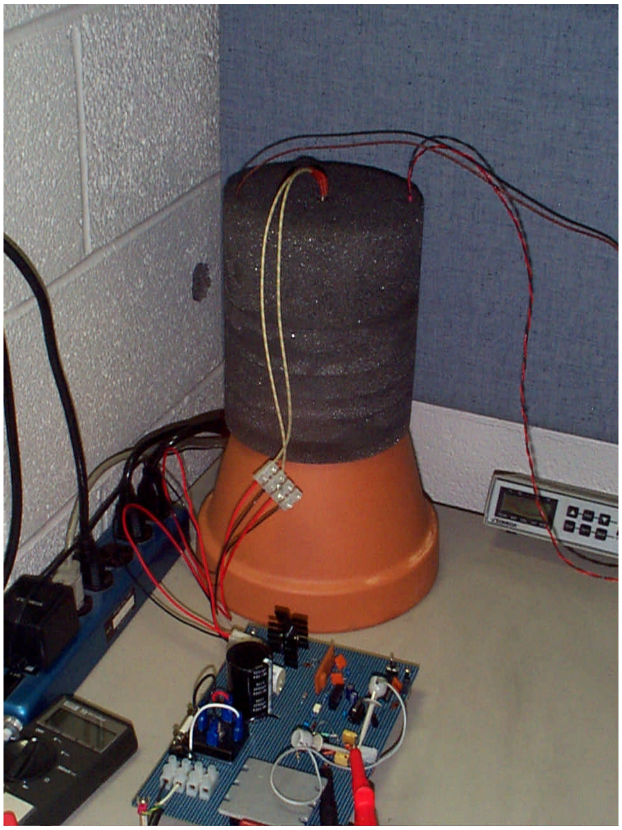

Figure 1. Physical model of the solid state reactor core with feed-back controllers and thermistor sensors.

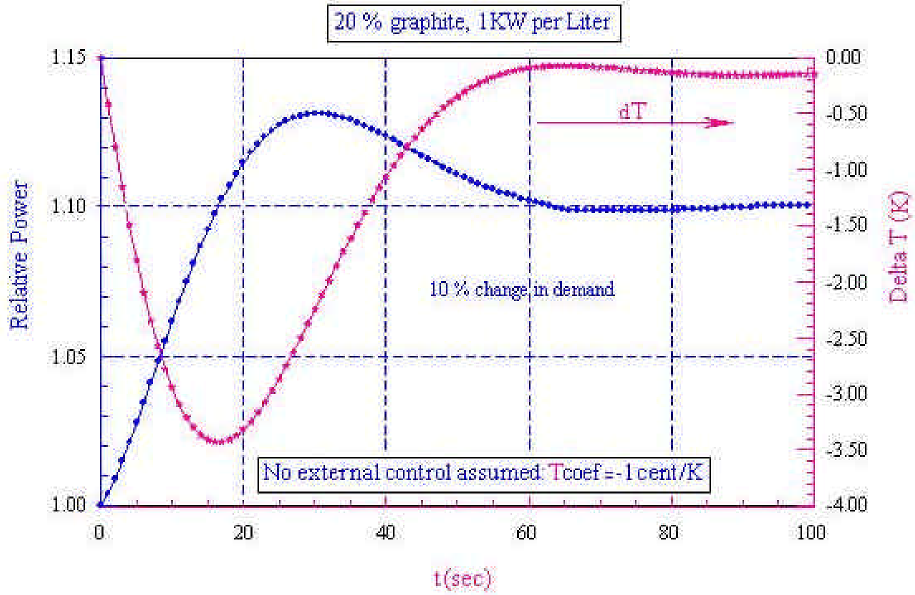

Figure 2. Simulated response of expected behavior to a 10% increase in Heat Flux out of the reactor core.

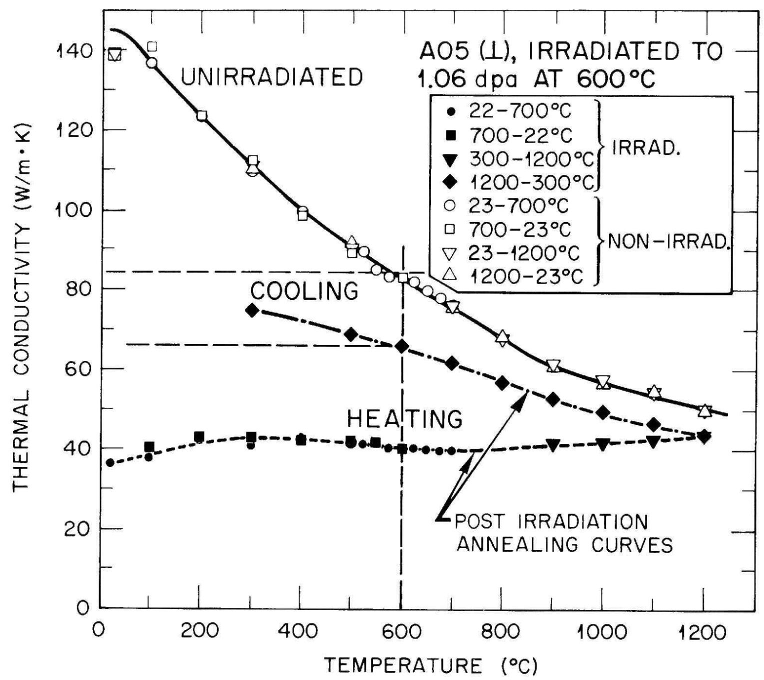

Figure 3. Thermal conductivity of graphite (un-irradiated and irradiated at 1 dpa at 600°C) before and after annealing at 1200°C.

Table I. Samples of graphite foam for irradiation studies.

Sample ID	Diameter	Length	Mass	Density	Capsule ID	Expected Dose	Planned Temperature
	[cm]	[cm]	[g]	[g/cm^3]		[dpa]	[°C]
IP-1	0.5931	1.0147	0.250	0.535	NERI-1	0.3	600
IP-3	0.5931	1.0160	0.156	0.556	NERI-1	0.3	600
IP-4	0.5956	1.0160	0.142	0.502	NERI-1	0.3	600
IP-7	0.5956	1.0135	0.150	0.531	NERI-3	2.6	600
IP-14	0.5918	1.0147	0.145	0.519	NERI-3	2.6	600
IP-15	0.5906	1.0135	0.152	0.548	NERI-3	2.6	600
IP-9	0.5639	1.0109	0.120	0.475	Base Line	n.a.	n.a.
IP-16	0.5918	1.0173	0.144	0.515	Base Line	n.a.	n.a.
IP-17	0.5334	1.0071	0.080	0.355	Base Line	n.a.	n.a.
IP-18	0.5994	1.0147	0.159	0.555	Base Line	n.a.	n.a.
IP-19	0.5956	1.0122	0.141	0.500	Base Line	n.a.	n.a.
OP-2	0.5956	1.0122	0.126	0.447	NERI-2	0.3	600
OP-3	0.5918	1.0109	0.129	0.464	NERI-2	0.3	600
OP-9	0.5931	1.0109	0.125	0.448	NERI-2	0.3	600
OP-15	0.5969	1.0122	0.129	0.455	NERI-4	2.6	600
OP-16	0.5906	1.0147	0.128	0.461	NERI-4	2.6	600
OP-17	0.5956	1.0122	0.134	0.482	NERI-4	2.6	600
OP-1	0.5918	1.0147	0.142	0.509	Base Line	n.a.	n.a.
OP-4	0.5969	1.0109	0.122	0.431	Base Line	n.a.	n.a.
OP-10	0.5982	1.0135	0.146	0.513	Base Line	n.a.	n.a.
OP-14	0.5918	1.0122	0.121	0.435	Base Line	n.a.	n.a.
OP-18	0.5969	1.0097	0.120	0.425	Base Line	n.a.	n.a.