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Submersion-Subcritical Safe Space (S^4) reactor

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Abstract

The Submersion-Subcritical Safe Space (S^4) reactor, developed for future space power applications and avoidance of single point failures, is presented. The S^4 reactor has a Mo–14% Re solid core, loaded with uranium nitride fuel, cooled by He–30% Xe and sized to provide 550 kWth for 7 years of equivalent full power operation. The beryllium oxide reflector of the S^4 reactor is designed to completely disassemble upon impact on water or soil. The potential of using Spectral Shift Absorber (SSA) materials in different forms to ensure that the reactor remains subcritical in the worst-case submersion accident is investigated. Nine potential SSAs are considered in terms of their effect on the thickness of the radial reflector and on the combined mass of the reactor and the radiation shadow shield. The SSA materials are incorporated as a thin (0.1 mm) coating on the outside surface of the reactor core and as core additions in three possible forms: 2.0 mm diameter pins in the interstices of the core block, 0.25 mm thick sleeves around the fuel stacks and/or additions to the uranium nitride fuel. Results show that with a boron carbide coating and 0.25 mm iridium sleeves around the fuel stacks the S^4 reactor has a reflector outer diameter of 43.5 cm with a combined reactor and shadow shield mass of 935.1 kg. The S^4 reactor with 12.5 at.% gadolinium-155 added to the fuel, 2.0 mm diameter gadolinium-155 sesquioxide interstitial pins, and a 0.1 mm thick gadolinium-155 sesquioxide coating has a slightly smaller reflector outer diameter of 43.0 cm, resulting in a smaller total reactor and shield mass of 901.7 kg. With 8.0 at.% europium-151 added to the fuel, along with europium-151 sesquioxide for the pins and coating, the reflector's outer diameter and the total reactor and shield mass are further reduced to 41.5 cm and 869.2 kg, respectively.

1. Introduction

In the last few years, there has been renewed interest in Space Reactor Power Systems (SRPSs) to enable a variety of future NASA missions. In addition to returning to the moon to establishing a permanent human presence, these missions include deep space exploration of planets such as Mars, Jupiter and Pluto, along with many of the promising outer solar system satellites (Europa, Titan, Triton, etc.). For these missions, SRPSs could provide ample and reliable power (100s to 1000s of kW_e) for 7–15 year mission lifetimes.

Potential combinations of nuclear reactors and power conversion technologies for SRPSs may be arranged in a $3 \times N$ matrix. The three main types of reactors are heat pipe cooled, liquid metal cooled, and gas cooled (Merrigan, 1985; Hoffman and Yoder, 1984; Fraas and Michel, 1966; Harper and Shaltens, 1993; El-Genk and Tournier, 2004a,b; El-Genk et al., 2005). Potential energy conversion technologies are thermoelectric, free-piston Stirling cycle, potassium Rankine cycle, and Closed Brayton Cycle (Mondt et al., 2004; Schreiber, 2001; Fraas and Michel, 1966; Bevard and Yoder, 2004; Harper and Shaltens, 1993). Other conversion technologies, which are at an earlier stage of development, include Alkali-Metal Thermal-to-Electric Conversion (AMTEC) and thermophotovoltaic (Tournier and El-Genk, 2003; Christopher et al., 2005). Each of these reactor types and power conversion technologies has unique characteristics and limitations that should be considered individually and in combination with the integrated space reactor power system.

Heat pipe reactors offer cooling redundancy and can be restarted easily from a frozen state without complications (Poston et al., 2002; El-Genk and Tournier, 2004a,b). However, the large number of heat pipes exiting the reactor and that must be routed around the shadow shield makes system integration relatively complex and can inflate the size and mass of the reactor and the shadow shield (El-Genk and Tournier, 2004a,b). Conversely, the startup of a liquid metal cooled reactor from the frozen state is an operational and design challenge, requiring

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an auxiliary system to thaw the working fluid before the reactor can be started (Hoffman and Yoder, 1984). The startup of a gas-cooled reactor is simpler, since the coolant does not need to be thawed; however, the working pressure of a gas-cooled reactor is higher (0.3–10 MPa compared to ≤0.1 MPa in liquid metal cooled reactors), which increases the size and mass of the reactor vessel and piping. Liquid metal coolant circulation is accomplished using electromagnetic or thermoelectric electromagnetic pumps, while a compressor that is an integral part of the Closed Brayton Cycle provides coolant circulation in a gas-cooled reactor system.

All space reactor types are designed to a specific set of operational and launch safety requirements. A space reactor is launched in a non-critical state and contains almost no radioactive material until it is brought to critical once in a safe trajectory (Poston et al., 2002). Ensuring that space reactors stay subcritical when submerged in seawater or wet sand and subsequently flooded with seawater, following a launch abort accident, is an overriding safety concern. This requirement must be fulfilled while having sufficient excess reactivity at the beginning of mission to operate the nuclear reactor at full power for 7–15 years without refueling. In addition, space reactors should be compact for lower mass and smaller and lighter radiation shadow shields (see Fig. 1). As a result, these reactors typically use high enrichment fuel (50–95 wt.%) with a high metal atom ratio (e.g. uranium nitride or uranium carbide) and have high neutron leakage. Space reactors can be designed with either a thermal or a fast neutron spectrum, the latter being preferred for reducing the mass of the reactor system at higher fission powers. Thermal spectrum reactors use low-density, low-atomic-number moderators that typically increase the size of these reactors, particularly at higher power levels (>a few hundred kW_{th}).

For all space reactor types, seawater or wet sand submersion, with subsequent flooding of the reactor core by seawater, increases the number of thermalized neutrons returning to the core from the surrounding medium and thermalizes the neutron spectrum in the core. The resulting spectrum shift towards lower neutron energies increases the effective fission cross-section. The higher fission cross-section increases the reactor's reactivity, potentially making it supercritical. These effects are typically more significant for fast spectrum space reactors.

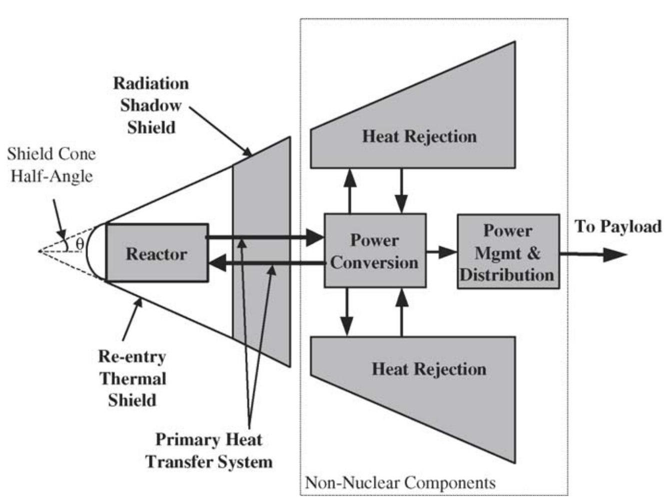

Fig. 1. Generic layout of a space nuclear reactor power system.

Another consideration that is generally unique to space nuclear reactors is a long operational lifetime (7–15 years) without refueling. This means that these reactors must have sufficient excess reactivity at the beginning of mission to overcome the negative temperature reactivity feedback when operating at full or partial power and the loss of reactivity from 7+ years of fuel burnup and fission product accumulation. Therefore, the reactor control subsystem must be designed to exert enough reactivity control that the reactor is sufficiently subcritical at launch and has sufficient excess reactivity to operate through the end of the mission.

To alleviate the submersion criticality concern, particularly with fast spectrum space reactors, thermal neutron absorber materials (known as "Spectral Shift Absorbers", or SSAs) could be added to the reactor core (Hawley, 1967; Poston, 2002; King and El-Genk, 2006). When a space reactor core containing SSAs is submerged in wet sand or seawater, the thermalized neutron spectrum in the core increases the parasitic neutron absorption by the SSA materials, thus counteracting the effect of a higher effective fission cross-section. This approach was thoroughly investigated for thermal spectrum reactors in the SNAP Aerospace Nuclear Safety program in the 1960s (Otter et al., 1973). The SNAP reactors, fueled with uranium–zirconium hydride (UZrH), were compact, under-moderated, and had high neutron leakage. During normal operation, ∼1/3 of the fission neutrons leaked from the reactor core, 90% with energies in excess of 100 keV (Hawley, 1967). The SNAP-8 reactors were designed with a beginning of mission cold excess reactivity of ∼$8.8 to accommodate a 1 year operational life (Hawley, 1967). A large portion (∼$5.35) of this reactivity requirement was to compensate for the loss and redistribution of the hydrogen moderator, which is not a concern in fast spectrum space reactors.

Recently, King and El-Genk (2006) screened the available nuclear database for potential spectral shift absorbers and seven SSAs (cadmium-113, samarium-149, europium-151, gadolinium, gadolinium-155, gadolinium-157, and iridium) were recommended for further examination as core additives and as coatings on the outside surface of space reactor cores. Boron-10 and cadmium were only recommended as core coatings. However, to quantify the usefulness of these SSA materials in space reactors, their application to an actual reactor design is needed. This paper presents the gas cooled, Submersion-Subcritical Safe Space (S^4) reactor design and assesses the worth of the different SSA materials. In addition, a space reactor design methodology using SSAs is presented, which balances three competing design requirements: having sufficient excess reactivity for an extended operational lifetime without refueling, having sufficient reactivity control over of the reactor, and remaining subcritical in a submersion accident. This design methodology is applied to the design and performance analysis of the S^4 reactor. In addition to rhenium as the base-case spectral shift absorber, the SSAs recommended by King and El-Genk (2006) are examined and their utility considered in terms of reducing the size and mass of the S^4 reactor and its shadow shield. The S^4 reactor is described in the next section.