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Sectored Compact Space Reactor (SCoRe) concepts with a supplementary lunar regolith reflector

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Abstract

Design concepts of the Sectored Compact Space Reactor for Small power (SCoRe-S) have been developed for the avoidance of single-point failures in reactor cooling and energy conversion and a wide range of thermal powers. These modular, fast neutron spectrum, lithium cooled reactors with 16.0 cm thick BeO radial reflector are designed for at least +\$2.00 hot-clean excess reactivity, and with a sufficient reactivity shutdown margin. They employ ^{157}GdN additives in the UN fuel and a 0.10 mm thick coating of $^{157}Gd_2O_3$ on the outer surface of the reactor vessel to ensure that the bare reactors, when submerged in wet sand and flooded with seawater following a launch abort accident, remain at least −\$1.00 subcritical. In addition to identifying the smallest SCoRe-S concept that satisfies the design reactivity requirements, the benefit of using a lunar regolith as a supplementary reflector to decrease the thickness of the BeO radial reflector and hence, the launch mass of the SCoRe-S concepts for a lunar outpost is investigated. Calculations performed using MCNP5 confirmed that SCoRe-S_7 with a 16 cm thick BeO reflector is the smallest to satisfy the stated reactivity requirements. Results also show that a lunar regolith reflector alone is inadequate for this reactor to achieve a critical state at the beginning of life. However, when the regolith is used in conjunction with a BeO reflector of a reduced thickness, this reactor not only becomes critical, but also satisfies the reactivity design requirements at a significantly reduced launch mass. Using a supplementary reflector of regolith decreases the thickness of the BeO reflector for the SCoRe-S_7 from 16 cm to 8.0 cm, and to 5.7 cm for the SCoRe-S_{11} of the largest core. The resulting decreases in the launch mass of the SCoRe-S concepts are ∼34% or 150–200 kg.
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1. Introduction

The 2004 NASA Vision for Space Exploration (NASA, 2004) calls for the return to the moon by 2020. Initially, a lunar outpost will provide living quarters for 5–10 astronauts for up to 2 weeks to perform limited surface experiments. Such an outpost can later be expanded to support more personnel and comprehensive science experiments, as well as industrial activities, such as the recovery of minerals, indigenous resources and the production of propellant for subsequent travel to Mars. Robotic missions to the moon are planned by 2008, followed by the first human mission as early as 2015, but no later than 2020, to test new technologies for sustainable human and robotic missions to Mars and beyond. These activities would require electrical and thermal powers in the order of 10s–100s of kilowatts 24/7, which can be provided using compact and lightweight nuclear reactor power systems as the primary energy source, supplemented by photovoltaic arrays. Despite requiring regular cleaning from the deposited lunar soil, the solar option is certainly an important component of a balanced energy mix on the moon. For large power requirements, however, the solar option is massive, requiring large batteries and fuel cells for energy storage during the long nights on the moon, greatly increasing the launch cost, and requires frequent maintenance and replacements (Hickman and Bloomfield, 1989). Compact nuclear reactor systems for surface power represent a significant saving in the launch cost and operate continuously, independent of the sun, for

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Nomenclature

D	diameter (cm)
H	active core height (cm)
L	length (cm)
M	mass (kg)
NSM	natural seawater
MFI	multi-foils insulation
P	reactor power (kW)
X	core flat-to-flat distance (cm)
Greeks	
ΔP	pressure losses (Pa)
ΔT	temperature drop/rise (K)
$\Delta\rho$	reactivity margin ($)
δ	width of coolant annulus (cm)
γ	coefficient of thermal expansion (K^{-1})
ρ	excess reactivity ($) or density ($kg/m^3$)
Subscripts	
acc	accident
annulus	coolant annulus
cc	cold-clean
core	reactor core
ex	hot-clean or cold-clean excess
exit	reactor core exit
i	inner
lte	linear thermal expansion
o	initial condition
pin	UN fuel pin
refl	reflector
Rx	reactor
s	safety
sd	shutdown
th	thermal
vte	volumetric thermal expansion

more than 10 years without refueling and with no or little maintenance.

Fast spectrum space reactors are more compact than thermal spectrum reactors, particularly for high power requirements, and can be either gas, liquid metal, or heat pipes cooled (Houts et al., 1996; Hrbud et al., 2002; El-Genk et al., 2005; El-Genk and Tournier, 2004a; Hatton and El-Genk, 2006; King and El-Genk, 2007). Potential energy conversion technologies to use in conjunctions with these reactors include Closed Brayton Cycle (CBC) engines, Free Piston Stirling (FPS) engines, advanced thermoelectric, and alkali metal thermal-to-electric conversion (AMTEC), depending on the reactor coolant type and operating temperature (Wright et al., 2005; El-Genk, 2001, 2008; El-Genk and Tournier, 2004a, 2005, 2006; El-Genk and Saber, 2005; Mason et al., 2002). Liquid metal cooled reactors offer the advantage of operating at or near atmospheric pressure because of the low vapor pressures of typical working fluids of liquid sodium and lithium. They transfer thermal power at high heat fluxes that are compatible with energy conversion options such as the FPS engines and advanced thermoelectric (Wood and Lane, 2004; El-Genk and Saber, 2005; El-Genk, 2008). On the other hand, gas cooled space reactors are the best choice for coupling to a CBC in a space power system (Mason et al., 2002; El-Genk and Tournier, 2006; Mason et al., 2002; El-Genk, 2001).

For enhanced reliability, gas and liquid metal cooled space reactors may be designed for the avoidance of single-point failures in reactor cooling and energy conversion (El-Genk, 2001, 2008; El-Genk and Tournier, 2004a; Hatton and El-Genk, 2006; King and El-Genk, 2006). In addition, these reactors are expected to operate for up to 15 years without refueling, and satisfy stringent reactivity requirements. These include sufficient hot-clean excess reactivity at the beginning of life, acceptable shutdown reactivity margin and subcriticality when submerged in wet sand and flooded with seawater, following a lunch abort accident. To satisfy the latter, neutron absorbing poison materials, such as rhenium, europium or gadolinium, are added to the nuclear fuel and applied as a thin coating on the outer surface of the reactor core. These materials, referred to as Spectrum-Shift Absorbers (SSAs), insignificantly affect the nominal operation of fast spectrum space reactors, but are effective absorbers of the thermal neutrons generated in submerged and flooded bare reactors (Hawley, 1967; King and El-Genk, 2005a,b; Amiri and Poston, 2005).

At the University of New Mexico's Institute for Space and Nuclear Power Studies, three design concepts of the Sectored Compact Reactor (SCoRe) are developed for a wide range of power requirements: small (-S), medium (-M) and large (-L) thermal power levels. The details of these designs and the results of the thermal analysis and optimization are documented elsewhere (El-Genk et al., 2005). The SCoRe concepts are designed for the avoidance of single-point failures in reactor cooling and energy conversion (El-Genk et al., 2005). These fast neutron spectrum reactors use UN fuel pins and BeO radial and axial reflectors and are liquid metal cooled. The base SCoRe-S, -L, and -M concepts are originally designed for space exploration missions, thus the thickness of the BeO radial reflector is relatively thick ($\sim$16 cm). This reflector together with the radiation shadow shield to protect the payload from excessive exposure to the reactor's fast neutron and high-energy gammas add to the total mass of the reactor and the integrated power systems. For lunar outposts, however, a lunar regolith may be used as a supplementary neutron reflector, reducing the thickness of the radial BeO reflector and hence, the launch masses of the reactor and the power system. In this case, the SCoRe reactors will not startup until deployed on the lunar surface and a radiation shadow shield would not be required. The usefulness of the lunar regolith as a neutron shield (Johnson, 2005; Kang et al., 2006) has recently been investigated, but not as a supplementary reflector for compact nuclear reactors. The mass saving as a result of not having a radiation shadow shield and reducing the

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