INTRODUCING THE LUNAR EVOLUTIONARY GROWTH-OPTIMIZED (LEGO) REACTOR CONCEPT

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ABSTRACT

The LEGO reactor is a fast-fission, heatpipe-cooled, lunar regolith clustered-reactor system promoting safety and reliability for lunar surface power applications. The reactor is divided into subcritical units that could be launched safely from the Earth's surface and then emplaced directly into the lunar regolith to generate critical reactor systems. The assembled reactor system would then use the regolith not just for shielding but as the reflector material to maintain the neutron economy of the system. The reactor units are manufactured using proven and tested materials in radiation environments such as UO_2 fuel, stainless-steel structure, and liquid-metal heatpipes. The LEGO reactor system promotes reliability, safety, and ease of manufacture and testing at the cost of a slight increase in launch mass per rated power level and a reduction in neutron economy when compared to a single-reactor system. Additional subunits may be launched with future missions to increase the cluster size and power according to desired lunar base power demand and lifetime. The impetus for current research involves the neutronics aspects of a lunar regolith clustered-reactor system as significant research, time, and effort have already been invested in the development and testing of heatpipe-reactor systems for use in space nuclear power applications.

Keywords: lunar power, nuclear reactor design, lunar regolith clustered-reactor system, MCNP

INTRODUCTION

The design and development of the Lunar Evolutionary Growth-Optimized (LEGO) Reactor is an ongoing project representing coordinated research efforts between the Center for Excellence in Nuclear Technology, Engineering, and Research at the University of Utah, the Center for Space Nuclear Research, and the Space Nuclear Systems and Technologies Division at the Idaho National Laboratory. The objective of this research is to develop a lunar regolith clustered-reactor system (LRCS) that is a safe and reliable fast-fission nuclear reactor, capable of satisfying the power demand of a growing lunar facility, as well as implemented, and later evolved, using *in situ* lunar-regolith resources. Additional factors regarding the development and some optimization parameters for an LRCS are available elsewhere.[1]

The provision of lunar surface power is a necessity for a sustained human or robotic presence, especially in the event of the actual construction and habitation of a lunar base facility. Power requirements are dictated by life-support, communications, transportation, scientific missions, space technology development, and *in situ* resource mining and manufacturing demands. The primary goals supported by the generation of a lunar facility focus upon the utilization of the lunar regolith resources and the satisfaction of mankind's inquisitive scientific nature. Nuclear power has been deemed the most appropriate candidate to satisfy the extensive power requirements of a surface base.[2] The purpose of the LEGO reactor is to enable both current and future lunar missions as an adaptable nuclear-powered system.

CURRENT DEVELOPMENT

Significant efforts over the past 50 years have gone into the development of space nuclear reactor systems for both power and propulsion. Many programs have been terminated due to inhibitive costs, lack of interest and support, or even the cancellation of the space missions for which the reactors were being developed. The quest to develop a “one-size-fits-all” reactor has also been detrimental to the promotion of space nuclear reactor activities.[3] Fast-fission; heatpipe-cooled reactors demonstrate the degree of safety and reliability necessary for space-nuclear applications. An excellent example of the abovementioned system is the Heatpipe-Oriented Moon Exploration Reactor (HOMER), [4] which is used as the fundamental design basis for LEGO reactor development. The heatpipe-reactor design promotes ease of operation,[5] manufacture,[6] and testing;[7] these are essential features for the ultimate construction and implementation of any nuclear power system.

The LEGO reactor design adheres to many of the basic requirements for a “one-size-fits-all” reactor at the cost of a slight increase in launch mass per rated power level and a reduction in neutron economy when compared to a single-reactor system. The reactor is also not currently designed to operate on any planetary or lunar surface or under the conditions of any environment. However, the adaptive nature in satisfying power demand and evolving the design while following the LRCS concept could make it a competitive power-production option for other non-lunar-surface, space-nuclear applications.

Reactor Design

The LEGO reactor is an LRCS comprised of subcritical nuclear-reactor subunits capable of generating approximately 25 kWe (100 kWth) apiece when combined into a single cluster. Power conversion using two Stirling engines (with two more in reserve) sets the power generation lifetime of a single subunit at about 10 years. Liquid-metal sodium heatpipes deliver the energy from the core to a potassium boiler/condenser connected to the Stirling engines. Stirling engines are used to generate the electric power which is to then be transmitted for use at the lunar facility. The reactor fuel is comprised of 93% enriched uranium dioxide, and the cladding and structural material is constructed from stainless steel 316. Extensive data libraries and practical reactor experience is readily available for UO_2 and SS-316 systems. Significant efforts have also been performed to evaluate and test the effectiveness of using heatpipes for heat transmittal in a nuclear reactor. The lunar regolith acts as both the neutron reflector and radiation shield for the reactor system to reduce the overall mass and dimensions of the reactor units. The subunits are emplaced into holes that are drilled into the lunar surface to create a reactor array that is coupled neutronically.

Coupling in heterogeneous reactor design had been studied extensively with the development of liquid-metal fast-breeder reactors. Renewed interest in coupled-reactor systems has more recently developed with the study of breeding or blanketed systems, accelerator or reactor-laser systems, sectioned reactors, and coupled pulsed reactors. Coupling or clustering effects for multiple reactors have been studied previously during the development of nuclear rocket engines.[8] Coupling effects are also evident in the design of the Advanced Test Reactor located at Idaho National Laboratory, which allows for variation in core power levels for different sections without completely decoupling the reactor system.[9]

Proper reactor coupling is an important aspect of the LRCS design and implementation. Multiple reactor sections, or subunits, are necessary to provide a critical system; additional units may be added in sequence to incrementally expand the power capabilities of the reactor system. The neutron economy of the complete system, compared to a single nuclear reactor operating at an equivalent power level, is reduced due to the increased neutron leakage probability. As additional subunits are coupled into the overall system, the leakage probability may be reduced per rated power generation.

Instrumentation and control are not part of the current study; however, they represent important key components that must be satisfactorily accounted for in the final design. Fast-fission reactors have much slower transient processes than conventional terrestrial thermal-neutron reactors. The compact size of space reactors is also a positive characteristic for ease in maintaining a stable reactor system. Simple control rods might only be necessary for the initial startup of the reactor system. Cruciform-like rods placed interstitially between subunits could be used for more significant reactor power manipulation as they would disrupt the coupling of the subunits. Ideally, an LRCS that is self-controlling would be the best option, whether using material or mechanical properties inherent in the reactor design itself.

Current computational analysis of the LEGO reactor neutronics is being performed using Monte Carlo n-Particle (MCNP5).[10] The reactor core is a monolithic, hexagonal structure with a 2.9445-cm pitch, 11.9-cm side length, and contains 43 heatpipes and 84 fuel pins (Figure 1). The core itself is just slightly smaller than a TRIGA (Training, Research, Isotopes, General Atomics) reactor core used in terrestrial research applications.[11] The heatpipes and fuel pellets have outer diameters of 1.6414 and 1.6150 cm, respectively. The fueled height of the core is 49 cm with heatpipes extending an additional 106 cm above the core. The overall subunit height is 160 cm within a regolith hole of approximately 200 cm in depth (Figure 2). Reactor control, power management and distribution, and heat rejection systems are not currently modeled.

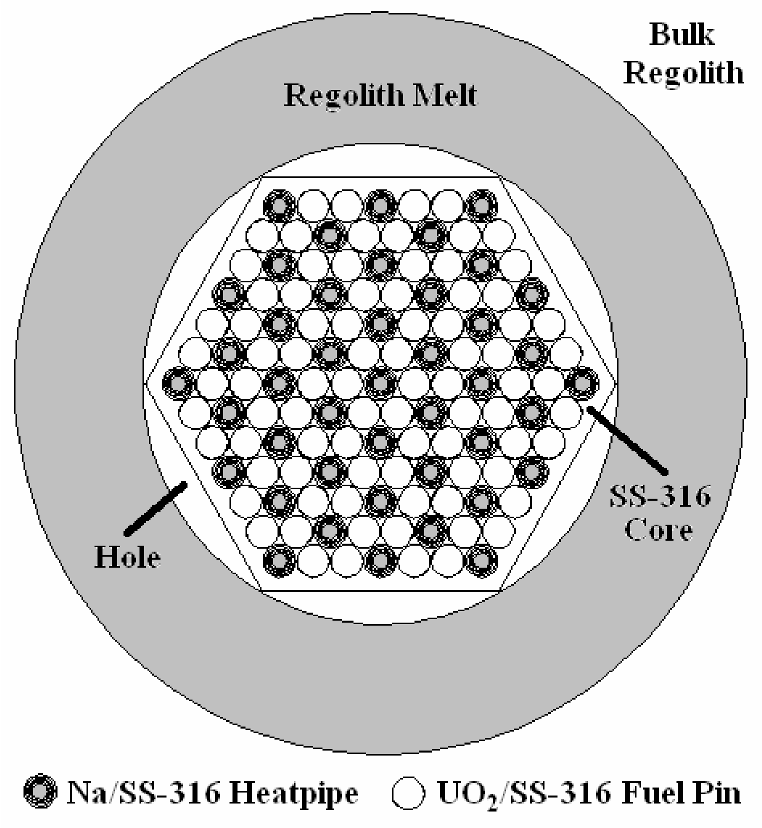

Figure 1. Horizontal cross-section of a single LEGO-reactor subunit core. The diagram also shows melted regolith regime generated during the rock-melt drilling process.

The mass of a single subunit was calculated using MCNP and supplemented with mass estimates for non-nuclear components provided for the HOMER.[4] Each unit is estimated to weigh slightly less than one metric ton apiece (~991 kg). The specific mass for the LEGO reactor is estimated to be approximately 40 kg/kWe. This result is within the same order of magnitude as specific mass estimates calculated for other contemporary space-reactor designs using their respective electrical power output and reactor mass without including the mass of additional radiation shielding. A competitive space reactor design should have a specific mass of less than or equal to 40 kg/kWe.[12] Therefore the preliminary LEGO reactor design just barely complies within this criteria, but does have a launch mass per rated power comparable to current space reactor designs.

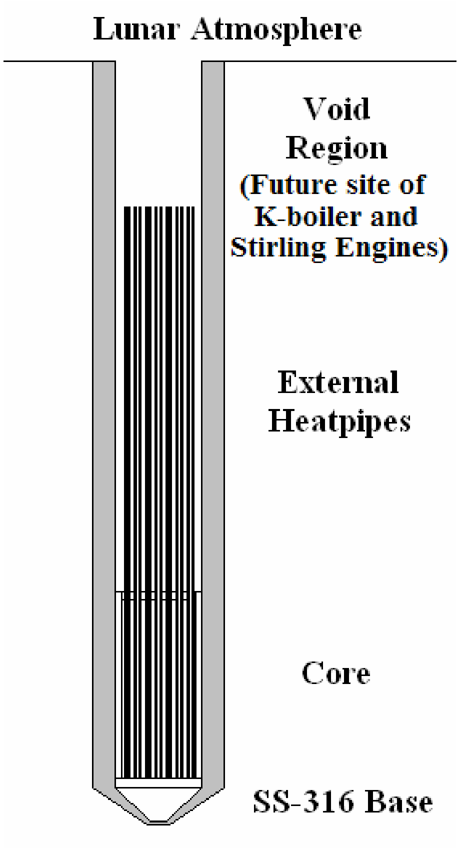

Figure 2. Vertical cross-section of the LEGO-reactor subunit emplaced within the lunar regolith. The figure depicts the comparative scale of major reactor components within a 200-cm deep hole.

Additional technological assumptions were made throughout research development. Lunar deployment will be available using current or proposed launch systems. Robotic- or human-controlled teleoperated systems will be available to assemble the reactor system. Rock-melt drilling will be utilized to generate the holes in the regolith, providing enhanced wall support and neutron reflectance. Microwave sintering will be available for dust-abatement surrounding the reactor site, especially to control the transport of activated indigenous material such as iron. Finally, control, power, radiator, and transmission systems that have already been developed could be included in the final design of a complete LEGO reactor system.

Unique Reactor Aspects

The LEGO reactor is unique in the fact that it employs existing lunar regolith as both radiation shielding and neutron reflector material. Reactor subunits are subcritical in design, promoting launch safety and reducing non-proliferation concerns in the event of a launch accident. Fast-fission reactor systems are capable of fissioning any additional actinides produced via neutron irradiation in the fuel and achieving deeper burn-up levels than conventional thermal reactors. The lower operational power per subunit provides reduced neutron damage and thermal loads compared to larger reactor systems, effectively increasing the longevity of the intrinsic properties of reactor materials. There is the capability to emplace additional reactor subunits as appendages to an existent cluster to increase power supply to an expanding lunar base, or to place new reactor systems anywhere on the lunar surface. Additional subunits could be launched as smaller fractions of the intended payload to be delivered to the lunar surface because the reactor subunits are smaller in design and mass. The failure of a single subunit does not imply the complete failure of the reactor system. The reactor subunit will still contribute neutronically to the coupled reactor system. As terrestrial and lunar technologies develop with the mining and manufacturing infrastructure on the lunar surface, the LEGO design can be improved and modified to incorporate *in situ* lunar resources.

CONCLUSIONS

Current progress with the LEGO reactor concept appears positive for the development of a competitive space nuclear reactor system using current technologies. This collaborative project is of benefit to the development of space nuclear activities in research and education. Primary objectives concerning the provision of safe and reliable nuclear power adaptive to the growing demand and available resources for a lunar base appear achievable with this design. Potential future benefits include the application of tungsten-cermet fuels or thorium breeding as lunar processing becomes more fully developed. Modifications of the LEGO design could be applied towards the promotion of reactors for use on other extraterrestrial surfaces such as Mars, other moons, or asteroids. Direct terrestrial benefit includes the application of the computational analyses of small, fast-fission reactors in support of developing research into Global Nuclear Energy Partnership or Advanced Fuel Cycle Initiative activities.

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