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Abstract – *A final design has been established for a basic Lunar Evolutionary Growth-Optimized (LEGO) Reactor using current and near-term technologies. The LEGO Reactor is a modular, fast-fission, heatpipe-cooled, clustered-reactor system for lunar-surface power generation. The reactor is divided into subcritical units that can be safely launched with lunar shipments from Earth, and then emplaced directly into holes drilled into the lunar regolith to form a critical reactor assembly. The regolith would not just provide radiation shielding, but serve as neutron-reflector material as well. The reactor subunits are to be manufactured using proven and tested materials for use in radiation environments, such as uranium-dioxide fuel, stainless-steel cladding and structural support, and liquid-sodium heatpipes. The LEGO Reactor system promotes reliability, safety, and ease of manufacture and testing at the cost of an increase in launch mass per overall rated power level and a reduction in neutron economy when compared to a single-reactor system. A single unshielded LEGO Reactor subunit has an estimated mass of approximately 448 kg and provides approximately 5 kWe. The overall envelope for a single subunit with fully extended radiator panels has a height of 8.77 m and a diameter of 0.50 m. Six subunits could provide sufficient power generation throughout the initial stages of establishing a lunar outpost. Portions of the reactor may be neutronically decoupled to allow for reduced power production during unmanned periods of base operations. During later stages of lunar-base development, additional subunits may be emplaced and coupled into the existing LEGO Reactor network, subject to lunar base power demand. Improvements in reactor control methods, fuel form and matrix, shielding, as well as power conversion and heat rejection techniques can help generate an even more competitive LEGO Reactor design. Further modifications in the design could provide power generative opportunities for use on other extraterrestrial surfaces.*

I. INTRODUCTION

President George W. Bush reinitiated American interest in space exploration with his speech, "A Renewed Spirit of Discovery". The National Aeronautics and Space Administration (NASA) has similarly expressed its "U.S. Space Exploration Policy" to include missions to the moon, Mars, and beyond. The ultimate goal of the proposed vision is to advance U.S. science, security, and economic interests through a robust space exploration program. Specific objectives include the implementation of sustained and affordable human and robotic exploration missions, extended human and robotic presence on the moon, the development of innovative technologies, knowledge and infrastructure to support space exploration, and the promotion of international and commercial participation. NASA plans to return humans to the moon by 2020 in preparation for human exploration of Mars.[1] Most likely an international base camp will be established at one of the lunar poles with a permanent manned presence by 2024.[2] The moon's southern pole is currently favored due to the increased duration of solar coverage and potential availability of mining resources and water although much of the lunar surface presents opportunities for exploration, research, and mining.[3] A permanent base anywhere on the lunar surface would require power for habitation and operations through the lunar night, a period of up to 354 hours.

"The availability of sufficient amounts of electrical power is critical to the safe operation of a lunar base."[3] Extended human or robotic habitation on extraterrestrial surfaces will require power generation to support exploration and mission activities, communications systems, technological development, *in situ* resource mining and manufacturing project, transportation, and life-sustainment. 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 fission power reactors have been deemed the most reliable and cost effective source of sustained energy generation for a lunar surface base.[4] Development of a nuclear power reactor suitable for multiple missions and applications is vital in sustaining America's space interests.

Current NASA research efforts highlight the development of a safe and affordable fission reactor capable of generating approximately 40 kWe using Stirling power conversion.[5] Basic lunar outpost construction and development requires a proposed minimum of 30 kWe for the initial 5 years with approximately 80 kWe for the next 15 years[1] with variations in power demand typically ranging from 5-10 kWe during the early stages of base construction and manned operations.[6]

Any power-production system placed onto the lunar surface will be limited by mass and volume limitations set by existing and proposed launch vehicles. Commercial viability increases proportional to the reduction in upmass to the lunar surface. Significant mass reduction of any lunar nuclear reactor system is available *in situ* as lunar regolith, or the "blanket rock" scattered across the lunar surface, to provide the biological shielding between the reactor and manned space activities, especially as it allows manned lunar operation and habitation within 10 to 100 meters of the nuclear reactor site.[7] Further reduction in the reactor mass may be possible by emplacing components into the regolith material itself, utilizing the debris material not only as shielding, but as reflector material in a fast-fission system. A piecemeal approach to the construction of a reactor will allow for power production appropriate to the growing energy demand of the lunar facility or the installation of remote power systems of similar design.

The potential of an accident occurring during the failed launch of a nuclear reactor into space has resulted in the requirement of numerous studies to address the reduction or otherwise elimination of such concerns.[8] Measures incorporating spectral shift absorbers such as rhenium, B_4C, and Gd_2O_3 are being developed such that fast-spectrum reactors can achieve criticality during normal operation but not inadvertently during thermalized accident conditions.[9] Means for assembling or fueling the reactor after launch have also been analyzed[10] but would require increased complexity beyond the design of a space nuclear system. The launching of subcritical reactor units avoids any extensive measures needed to maintain mechanical integrity while minimizing the capability of inadvertent criticality. While most criticality accidents would result in minimal exposure to the general public and only high prompt dose within the immediate vicinity of the reactor,[11] confirmation of a subcritical configuration during most credible accident scenarios would allow for post-accident recovery and positive public image.

A Lunar Regolith Clustered-Reactor System (LRCS) is a distributed-core reactor design that can be optimized for lunar-base power demand and implemented using *in situ* lunar-regolith resources.[12] A LRCS also promotes safety and reliability not just with the reactor design itself, but for a lunar mission as a whole. With the capability to launch portions of a core per launch, the loss of a single spacecraft would not result in the complete loss of the lunar power system, only a portion of its power-production capabilities. A modular reactor of this type would also comply well with NASA's incremental build approach to developing a lunar base,[1] and would allow for power adjustments proportional to developmental stages of construction and expansion.

Modularity aspects are vital to the growth and development of space exploration efforts. Modular systems that can be launched with existing technology and later assembled in space or on extraterrestrial surfaces will promote the incorporation of current space infrastructure with increased functionality of multiple launches.[13] The prefabrication of LRCS modules to create an integral fission and power unit supports ease of transport and a means to build up a larger power systems subject to demand. Modular units that can be developed as non-mission specific can be used for a variety of missions and effectively reduces mission risk, or consequences of payload loss, because spares and replacements can be more rapidly developed at reduced costs, allowing for more affordability in sustainable space exploration.[14] As newer modules are developed with increased functionality and upgradability, they can be incorporated into the existing LRCS environment.

II. THEORETICAL DEVELOPMENT

II.A. Current Space Reactor Concepts

Significant efforts over the past 50 years have invested 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.[15] Unfortunately, the United States has only launched a single demonstration reactor into orbit, the SNAP-10A; Russia has launched over 30 reactors with mixed results.[16] Various reactor design concepts for the provision of nuclear-electric power for in-space and surface applications have been presented since the development of early SNAP reactor technology in the 1960s.[15] Some of the more recent designs for providing extraterrestrial power include the SP-100,[17] the Martian Surface Reactor (MSR),[18] the Heatpipe Operated Mars (or Moon) Exploration Reactor (HOMER),[19] the Safe Affordable Fission Engine (SAFE),[20] the Space Nuclear Steam Electric Energy (SUSEE) Reactor,[21] the Sectored

Compact Reactor (SCoRe),[22] the Submersion-Subcritical Safe Space (S^4) reactor,[23] the Space Power Annular Reactor System (SPARS),[24] and the Affordable Fission Surface Power System (AFSPS) Study.[25] All of these reactor concepts present diverse alternatives for power generation using different components, materials, and concepts. No single reactor design will provide the ideal solution for electric power generation in space.[15] It is important to develop the technology and applications needed to allow for further adaptation and evolution of proven reactor designs as they are presented.

II.B. The LEGO Reactor Design

The basic Lunar Evolutionary Growth-Optimized (LEGO) Reactor is a LRCS comprised of self-subcritical (i.e. inherently subcritical without additional means) nuclear-reactor subunits capable of generating up to approximately 5-6 kWe (~20-24 kWth) each when combined into a cluster. A fundamental cluster comprised of six subunits could provide approximately 30 kWe to a lunar base. Power conversion using a single free-piston Stirling engine, with potential for addition of reserve units, sets the power generation lifetime of a single subunit at a minimum of at least 5 years based upon information available for a Stirling engine currently being developed for near-term space-nuclear systems.[5]

Liquid-metal sodium heatpipes deliver the energy produced in the core to a secondary heat exchange system, a potassium boiler. The transferred heat will produce potassium vapors in the boiler that will condense on the Stirling head, providing the uniform heat source needed to generate electric power. The power can then be transmitted to the lunar facility via cables, lasers, or microwaves. Waste heat is disposed of by using carbon-coated heatpipe-radiator panels which radiate into the cooler environment of the lunar surface.[26]

The reactor fuel is comprised of enriched UO_2, and the cladding and structural support material is constructed from SS-316. Extensive data libraries and practical reactor experience is readily available for UO_2 and SS-316 in fast fission systems.[25] Oxide fuel fabrication is well entrenched in today's nuclear industry and ceramic fuels can withstand irradiation, high temperatures, and coolant penetration. Significant efforts have also been performed to evaluate and test the effectiveness of using heatpipes coupled with a nuclear reactor.

The LEGO Reactor is unique in the fact that it employs existing lunar regolith as both radiation shielding and neutron reflector material. The subunits are emplaced into holes that are drilled into the lunar surface to create a reactor array that is coupled neutronically and capable of achieving criticality to generate power. Reactor subunits are subcritical in design, promoting safety in the event of a launch accident. Fast-fission reactor systems are capable of fissioning any additional actinides produced in the fuel and can achieve deeper burn-up levels than conventional thermal reactors. The lower operational power per subunit reduces neutron damage and thermal loads, compared to larger reactor systems, effectively increasing the longevity of the intrinsic properties of the 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 within resupply payloads 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.

The capabilities and requirements of a "one-size-fits-all" reactor has been previously outlined.[15] The LEGO Reactor design adheres to many of the basic requirements for an ideal reactor at the cost of a potential 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 nonlunar-surface applications.

The LEGO Reactor subunit (Figs. 1 and 2) is modeled with similarities to the basic HOMER-25 design[19] using only 127 core positions comprised of 84 fuel rods and 43

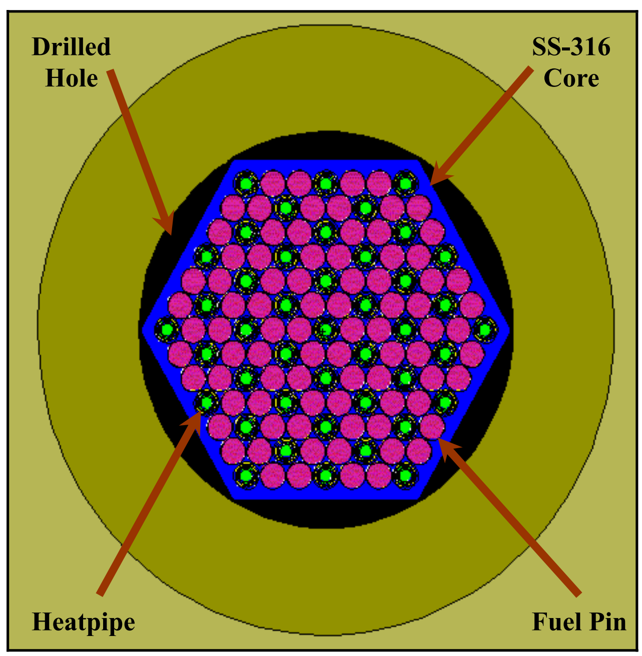

Fig. 1. Cross-sectional view of a LEGO Reactor subunit core.

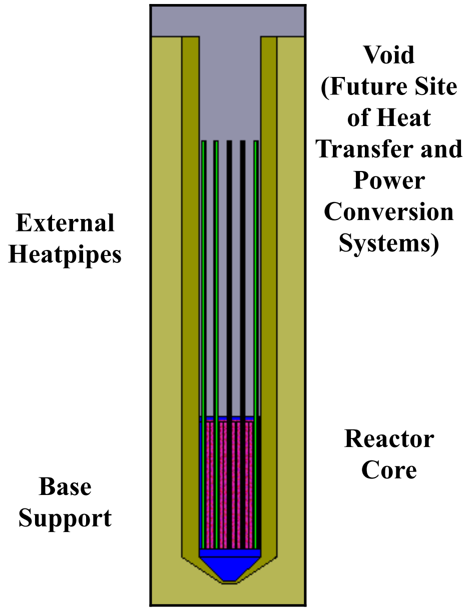

Fig. 2. Reactor subunit emplaced within the lunar regolith.

heatpipes. The selection of this hexagonal packed system allows for a high heat transfer to fuel surface ratio at the cost of greater critical mass dimensions. The fuel and heatpipe placement has a hexagonal pitch of 1.70 cm. Fuel pellets with a diameter of 1.6160 cm are contained within 1.6414-cm ID SS-316 pipes with helium filled gaps. The heatpipes are modeled identical to those described in the HOMER-25 design except with liquid sodium as the coolant; they have a 1.1254-cm ID SS-316 shell with a 0.7878-cm ID, 0.0844-cm thick SS-316 wick. Heat transfer through the adiabatic section of the heatpipes is restrained using a 1.6414-cm OD, 0.1-cm thick SS-316 pipe. The fuel is 93% enriched in ^{235}U at 95% of the theoretical density. The fuel rods are 49-cm long with an overall core height of 54 cm; the heatpipes extend an additional 106 cm above the core. The monolithic, SS-316 hexagonal core design has a circumscribed corner-to-corner diameter of 23.80 cm. A tapered stainless-steel base extends 9 cm below the core to provide support, stability, and alignment within the drilled hole.

A final reactor design is selected for analysis using six reactor subunits placed in a hexagonal formation with centerline distances of 60-cm (Fig. 3). The regolith is modeled as JSC-1 simulant[28] containing the average concentration of trace elements found in lunar regolith material[29] with the dimensions and parameters of the previously defined lunar environ.[12] Secondary heat-transfer, power-conversion, and heat-rejection systems were not included in the final KENO-VI[30] (ENDF/B-VI) model. In essence an annular reactor system is developed with a central neutron reflector similar to the concept of the SPARS reactor.[24] Emplacement and regolith sensitivity studies for a LRCS have been previously performed.[12]

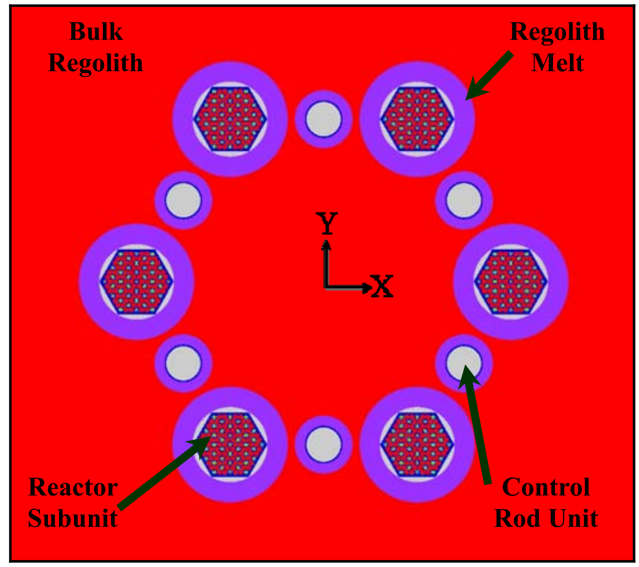

Fig. 3. 30 kWe LEGO Reactor Cluster in the Lunar Surface.

A simplified reactor control system is modeled to effectively demonstrate control of the coupled-reactor system using boron-carbide control rods placed midway between adjacent subunits. A rock-melt-drilled hole (assuming implementation of subterrene/subselene technology[12]) of 6-cm radius (9.266 cm melt radius) has a hollow stainless-steel 316 case with an inner radius of 5.5 cm placed within it. The case contains a 5-cm radius, 49-cm in length, B_4C control rod with a density of 2.52 g/cm^3. The case is modeled as hollow , except for the control rod, although in reality a control-rod drive system would be included such that excessive temperatures or radiation damage would cause the rod to fail into the hole and significantly reduce coupling between adjacent reactors.

III. RESULTS AND DISCUSSION

III.A. Final System Design

A breakdown of the component masses for a single reactor subunit and control shaft is compiled in Table I. The mass of the radiator is estimated from the specific power of 0.688 kW/kg provided for a carbon-carbon composite, heatpipe-finned radiator.[26] The mass of the Stirling power conversion unit is determined using a specific power of 140 W/kg.[5] The reactor core, steel support structure, nuclear fuel, and heatpipe masses are determined using results generated with MCNP5.[31] The remaining masses for non-nuclear components such as the power management and distribution, cabling, and secondary heat exchanger (potassium boiler) are scaled from the HOMER-25 reactor.[19] The mass of the control shaft with boron-carbide control rod is also determined using MCNP5. A 20% mass contingency is added to the

TABLE I

Mass Estimate for a Single LEGO Reactor Subunit

Mass (kg)	Component
207.16	Reactor Core, Fuel, and Heatpipes
10.15	Secondary Heat Exchanger
35.71	Free-Piston Stirling Convertor
29.07	Waste-Heat Rejection (Heatpipe Radiator)
12.50	Power Management and Distribution
6.25	Cabling
72.53	Control Rod and Shaft
373.37	Subtotal
74.67	20% Mass Contingency
448.04	Total without Shielding

estimated mass to provide a total LEGO Reactor subunit mass of 448 kg. Each subunit contains 88 kg of highly enriched UO_2 fuel (78 kg uranium).

The total mass of the system does not include an axial reflector or radiation shielding. Typically the radiation shielding for a space nuclear reactor has a mass up to approximately one-third to one-half of the total mass of the system. A radiation shield for the HOMER-25 has a mass of approximately 569 kg.[19] Even if a shield of this mass was included, the total mass per LEGO Reactor subunit would be less than one metric ton.

The average surface temperature of the lunar surface is approximately 255 K.[3] A radiator panel area of about 15 m^2 would reject 20 kW with an average radiator temperature of 420 K. If a frustum-like radiator paneling system composed of multiple finned heatpipes is implemented, it would have a minimum radius of approximately 12 cm, a maximum radius of 25 cm, and a total overall height of 6.45 m. The radiator paneling could be packed during shipment to the lunar surface and then later unfolded to full height. The redundancy in design would allow for reliable heat transfer in spite of damaged or dusted heatpipe surfaces. Interaction between the radiators of the subunits would add an additional means of heat rejection. A study of the heat rejection characteristics would be necessary to determine the exact interactions and ultimate rejection temperatures for the system. The means for heat rejection from the LRCS will limit the maximum total operational power and specific mass of the system.

The estimated specific mass (and specific power) for the unshielded LEGO Reactor subunit is 89.6 kg/kWe (11.2 We/kg). A solar array with regenerative fuel cell system is estimated to have a down mass of 5880 kg to provide 20 kWe, a specific power of 3.4 We/kg.[32] The LEGO Reactor demonstrates favorably compared to solar power. Even should excessive shielding be incorporated into the design, the specific mass would be greater than 5 We/kg. Nuclear power scales better than solar power with rechargeable batteries; as the power demand for the base increases, nuclear units will remain the better option.

The specific mass for the basic LEGO Reactor design is greater than many of the other space reactor designs previously mentioned, yet remains within the same order of magnitude as many of the designs and only 23% greater than the current design of interest from NASA, the AFSPS.[25] A comparative summary of the various reactors is provided in Table II; radiation shielding mass is excluded from the comparison because shielding can be very specific to the application and design of the reactor system. Some reactors incorporate regolith material as shielding material; others implement an all-encompassing shield or a shadow shield that encompasses only a portion of the reactor, typically a 120º arc between the reactor and lunar base operations. A competitive space reactor design should have a specific mass of less than or equal to 40 kg/kWe.[33] It is expected that the LEGO Reactor could easily achieve this goal as the technologies for fuel form, clad materials, reactor control, and heat-rejection techniques are improved.

The overall volume of the subunit reactor with all non-nuclear components will fit within a cylinder 8.77 m high and 0.50 m in diameter. While the radiator panels may be stowed during shipment and later extended for use on the lunar surface, the complete reactor subunit can easily fit within the proposed payload faring for future flights to the lunar surface. The proposed faring limitations in the current NASA architecture for payload length and diameter are 10.5 m and 7.5 m, respectively,[25] with a mass limit of approximately 20 metric tons.[1] Therefore a single reactor subunit could be easily stowed with additional materials, tools, and consumables within a single payload for delivery to the lunar surface.

III.B. LEGO Evolution

Incorporation of various technological and materials developments in fuels, reactor control, shielding, cladding, and heat transfer capabilities can potentially increase the competitive nature of the LEGO Reactor design. Furthermore, various potential applications are enabled through the utility of a LRCS design such as the LEGO Reactor and its evolution.

III.B.1 Nuclear Fuels Development

Uranium nitride represents a possible alternative fuel. Nitride fuel does not react with sodium metal, has a higher fuel density and higher thermal conductivity than oxide fuel, and lower fission gas release. Nitrides might react with steel to cause embrittlement, therefore alternative clad material may become necessary. Use of uranium nitride fuel would decrease the overall mass and volume of the reactor system.

TABLE II

Specific Mass Comparison of Various Space Reactor Designs.

Reactor	Power (kWe)	Mass (kg)	Specific Mass (kg/kWe)
SCoRe[22]	450[a]	~480	~1.1
S^4[23]	138[a]	418	3
SAFE-400[20]	100	541	5.4
SUSEE[21]	200	3000	15
SPARS[24]	100	2374	23.7
SP-100[17]	100	--	40-45
MSR[18]	100	4525	45.3
HOMER-25[19]	25	1564	62.6
AFSPS[25]	40	2916	72.9
LEGO Reactor	5/subunit	448/subunit	89.6

[a] The electric power is estimated from the reference thermal power multiplied by a conversion efficiency of 25%.

Incorporation of fissile fuels other than highly enriched uranium could further reduce the mass and volume of the reactor. Plutonium-239, uranium-233 or even Cm-235/-244 are expected to provide alternative fuel options for a space reactor system.[34] The smallest nuclear reactor that has been proposed uses Am-242m fuel and has been lauded as a potential portable neutron source or space power reactor.[35]

III.B.2 Reactor Control Development

Reactor control dynamics will be another issue to be further examined and optimized. Placement of control methods external to the core are currently accepted because it requires less development, works well in fast reactors, and would be ideal to develop a successful, first-generation space reactor.[36] However, control in a coupled-reactor system, especially a loosely-coupled one, should have poisons placed between the fissile zones so as to provide tighter control and prevent flux tilting in the core. To reduce sensitivity to perturbations in the system, it is ideal to develop systems that closely characterize point kinetics and maintain stable static characteristics throughout the life-cycle of the reactor.

Typically a single space reactor would incorporate moveable reflectors, or sliders, that could be used to control the neutron leakage from the core, or control drums containing reflector and absorber material. Sliders result in a lower mass system while control drums provide integration and operation advantages.[36] The control drum approach may not function well within a coupled-reactor.

It is proposed that vertical "shades" be developed that would surround each reactor subunit. Each shade could be placed around a section of the subunit core, presenting absorber material to neutrons interacting between the core and the nearest facing subunit core. The shade would be lifted to achieve criticality and allow adjacent cores to interact neutronically.

III.B.3 Axial Reflector and Shielding

While loose regolith material may provide a cheap *in situ* resource for an axial reflector, challenges may exist in implementing it efficiently. Beryllium and beryllium oxide represent low density materials with high moderation and reflection capabilities that could be incorporated into the reactor subunit design. Disadvantages of toxicity and limited industrial infrastructure are a concern and less information is available for beryllium oxide material than for pure beryllium metal. While beryllium would represent the lower technical risk, beryllium oxide could provide a lower mass system.[36] The mass penalty of including an axial reflector may be quite small as fuels development might allow for a much smaller reactor core design. Furthermore, addition of an axial reflector will reduce the amount of shielding needed for the non-nuclear components of the reactor system.

Electronic systems, such as those necessary for power management and distribution and reactor control, are potentially vulnerable to radiation, which can cause mild performance degradation or catastrophic failure. Radiation susceptibility of the materials, lubrication, and alternator of the Stirling convertor should be addressed. Past studies propose limits of 2 Mrad and $1 \cdot 10^{14}$ neutrons/cm^2, but actual limits might be higher and a study is currently in progress.[37] The current shielding needs for a LEGO Reactor has not been addressed as much of the information needed to optimize shielding for the non-nuclear components is currently under investigation.

III.B.4 Cladding Development

Cladding development is another ongoing task to develop materials capable of withstanding higher temperatures of operation, thus improving power production efficiency, increasing waste-heat rejection capabilities, and generating lower overall system mass and volume. Refractory metals such as niobium, tantalum, and molybdenum-rhenium alloys are being investigated. However, hardening and embrittlement at low temperatures might be a concern, as well as chemical compatibility. Additional experimental data is necessary to develop these materials.[38] Oxide dispersion steels have been recommended over refractory metals and conventional steels because they are stronger, lighter, and perform better in a radiation environment. However, testing with alkali metals is a necessary concern that must be addressed prior to incorporation of these steels with any space reactor system.[39]

Tungsten-cermet reactors have also been investigated for their ruggedness and high temperatures. Tungsten-cermet represents an ideal material as it might be able to retain all fuel, fission products, and fission gases within its matrix material and are more resistant to physical changes induced by radiation.[40] Additionally, it is a strong deterrent against proliferation attempts due to the processing capabilities necessary to deconstruct tungsten-cermet material. It is assumed that tungsten-cermet materials maintain high retention of internal ceramic materials even at elevated temperatures.

III.B.5 Heat Transfer Development

As better structural and cladding material are deemed effective for use in high-temperature space-reactor systems, liquid metals such as lithium could then be used to increase the heat transfer capabilities of the reactor to the power conversion and waste-heat rejection systems. High temperature gas systems using Brayton engines would also become viable options for power production. The hexagonal prismatic core assembly would then implement an offset design, reducing the effective surface area for heat transfer to accommodate the higher system temperatures. The fuel mass needed for criticality would be further reduced, significantly reducing the overall mass of the nuclear system.

Liquid droplet radiators have been investigated as lightweight means for rejecting large amounts of waste heat from a system.[41] Less volume is needed for these radiators, allowing for a more compact clustering of LEGO Reactor components, providing better clustering capabilities and potential for further reduction in critical mass needed per subunit assembly. Concern as to what effect lunar dust might play upon the dynamics of a liquid droplet radiator, or some variant, will have to be addressed.

Another means for waste-heat rejection may rely upon using the lunar regolith, and perhaps bedrock, as a heat sink. Heatpipe extensions through the regolith to bedrock material or a thermal sink at another location might functionally reduce the volume of the heat rejection system. Additional material might need to be added to the regolith material to improve thermal conductivity. Most rocks are multicomponent chemical systems with low average temperature ranges; high-pressure injection of fluxing or mineralizing agents can lower these melting temperatures, effectively reducing power requirements for rock-melt drilling.[42] An agent that would improve the thermal properties of the surrounding regolith melt would thus provide benefit beyond just the reactor emplacement.

An additional means for combined heat rejection and power conversion could involve thermophotovoltaics. The reactor could be operated at temperatures high enough to emit low-wavelength, photon energy that can be captured by thermophotovoltaic cells.[43] A reactor capable of operating at such high temperatures would need to be developed, probably utilizing tungsten-cermet materials. The simplification in design would eliminate many technological concerns for heat transfer, power production, and waste-heat rejection. Shielding and control of this reactor design would require further investigational measures. The development of carbon nanotubes as infrared detectors presents an opportunity to possibly utilize them for electricity production whether as a primary means of power conversion or a parasitic secondary power conversion method using rejected waste heat.[44]

III.C. Potential Applications

Many other rocky bodies in exist in our solar system on which a clustered-reactor system could be employed: Mercury, Mars, Phobos, Deimos, Io, Europa, Titan, and innumerable asteroids. As with any extraterrestrial surface, characterization of the environment will be important, such that an LRCS could be properly adapted to function and survive. Mass savings incurred by modular design become even more relevant for the exploration of planets, moons, and asteroids with increasing distances from our Earth-Moon system.

In situ resource utilization strategies and activities are mandatory for the support of both near- and far-term missions. While power provision is mandatory to perform mining and manufacturing activities on the lunar surface, these activities can also be developed to provide materials, resources, and industry for the lunar fabrication of reactor subunits for use on the lunar surface. A self-sufficient lunar base could eventually generate LEGO Reactor subunits that could expand upon the initial cluster sent up from the Earth's surface. Industry for the lunar fabrication of components for spacecraft and propellant to explore the solar system could also construct reactor components for nuclear power provision on the surface of Mars or for tri-cluster shipments to various asteroids to empower observatories and extended scientific missions.

Lunar power autonomy could also be enabled through thorium breeding. Thorium quantities have been characterized on the moon, and would be a byproduct obtained during other mining procedures. A thorium-fueled subunit could be placed in proximity to a LRCS and converted to an operational core as neutrons leaked from the system are absorbed to generate fissile U-233 material. A similar concept has been presented for a terrestrial reactor design, the CANDLE reactor. This type of reactor is expected to need little control yet demonstrate excellent performance, with inherent simplicity and safety, especially when explicit operation and maintenance routines are unnecessary.[45]

A lunar reactor facility also provides opportunity for extended research capabilities not available by using other power provision methods. The reactor could be used as a neutron irradiation facility, especially as later evolutions of the reactor design operate at higher power levels. Development of a lattice-like system composed of many subunits allows for holes to be dug within the lattice gaps into which experiments may be inserted without significantly affecting the reactivity of the system. Development of a neutron flux-trap facility could aid in the isotopic analysis of lunar regolith material as well as benefit lunar fabrication techniques with a materials testing facility. A target irradiation facility could be designed to test the neutron hardening and radiation damage effects of electronics developed on the lunar surface; especially should silicon photovoltaic cell fabrication facilities be implemented on the lunar surface.

The coproduction of electrical energy and radionuclides is another option when using a fast reactor because the high energy neutron flux would have fewer parasitic neutron captures. Radioisotope fabrication could generate isotopes for space power and heat, the detection of defects in parts, sterilization, food preservation, treatment of sewage and waste, and use as a photon source in lighting applications.[46]

Earth's material composition is much like the moon's. Therefore, potential exists for adaptation of coupled reactor research for nuclear power efforts closer to home. First-generation space reactors could not compete with the power demand typical for terrestrial activities; however, materials and fuel development activities combined with technological development could provide small-scale, megawatt-class reactors sufficient for generating power in isolated and remote areas.

There is technical and economical potential for fast-spectrum small, modular reactors. They demonstrate reliability and safety, economic efficiency, and are burners of plutonium and other actinides. Terrestrial reactors can benefit from the advances in fuel developments and alternative means of power conversion for space nuclear reactor systems. Ultimately, clustered-reactor systems must be competitive with alternative nuclear and non-nuclear energy sources to gain public acceptance and become commercially viable.

IV. CONCLUSIONS

A hexagonal cluster of LEGO Reactor subunits can provide the 30 kWe necessary for preliminary lunar base construction and operations. Means for waste-heat rejection may represent the limiting factor for implementation of tighter coupling within the reactor system and maximum operational power per subunit. A thorough thermodynamic and heat transfer analysis will be necessary to complete the characterization of the LEGO Reactor system prior to design refinement and eventual construction of a prototype model for further testing. Each subunit has an estimated unshielded mass of approximately 448 kg. Even with full-scale shielding, the total expected subunit mass would be less than one metric ton. The overall envelope for a single unit with fully extended radiator panels has a height of 8.77 m and a diameter of 0.50 m. A single reactor subunit could easily be stowed as a small portion of a payload delivery to the lunar surface.

Current progress with the LEGO Reactor concept appears positive for the development of a competitive space nuclear reactor system using current and near-term technologies. 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. Future improvements include advances in reactor control methods, fuel form and matrix, determination of shielding requirements, as well as power conversion and heat rejection techniques to generate an even more competitive LEGO Reactor design. Potential future benefits include the application of tungsten-cermet fuels for advanced reactor concepts or thorium breeding as lunar processing becomes more fully developed. Implementation of a neutron flux-trap might allow for investigational research using excess neutrons normally lost from a LRCS. Modifications of the LEGO Reactor 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 may include application of small, fast-fission reactors in support of providing power-grid-compatible reactors for developing countries and isolated industrial projects.

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