A Comparison of Fission Power System Options for Lunar and Mars Surface Applications

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Abstract

This paper presents a comparison of reactor and power conversion design options for 50 kWe class lunar and Mars surface power applications with scaling from 25 to 200 kWe. Design concepts and integration approaches are provided for three reactor-converter combinations: gas-cooled Brayton, liquid-metal Stirling, and liquid-metal thermoelectric. The study examines the mass and performance of low temperature, stainless steel based reactors and higher temperature refractory reactors. The preferred system implementation approach uses crew-assisted assembly and in-situ radiation shielding via installation of the reactor in an excavated hole. As an alternative, self-deployable system concepts that use earth-delivered, on-board radiation shielding are evaluated. The analyses indicate that among the 50 kWe stainless steel reactor options, the liquid-metal Stirling system provides the lowest mass at about 5300 kg followed by the gas-cooled Brayton at 5700 kg and the liquid-metal thermoelectric at 8400 kg. The use of a higher temperature, refractory reactor favors the gas-cooled Brayton option with a system mass of about 4200 kg as compared to the Stirling and thermoelectric options at 4700 and 5600 kg, respectively. The self-deployed concepts with on-board shielding result in a factor of two system mass increase as compared to the in-situ shielded concepts.

Introduction

NASA has studied the use of nuclear power for lunar and Mars surface applications for many decades, and some example papers by the author are referenced (Mason, Bloomfield, and Hainley, 1989; Mason, et al., 1992; Mason and Cataldo, 1993; Mason, 1999, 2001). The recent Vision for Space Exploration expressed by President Bush has renewed the interest in establishing a sustained human presence on the moon and initiating human missions to Mars. Under the President's Vision, lunar surface missions would occur in the early 2020's while Mars surface missions would follow in the 2030's. Power requirements for human-tended surface outposts and bases are expected to range from 25 to 100 kWe during the early build-up phases. As the base becomes fully operational with in-situ resource production and closed-loop life support, power requirements could approach 1 MW. Figure 1 shows a representative power profile for the early phases of a potential lunar surface mission that result in a total power requirement of about 70 kWe within two years of establishing the outpost. The most mass-efficient means of providing high power for surface missions is through the use of nuclear fission systems.

In the months following NASA's cancellation of the Jupiter Icy Moons Orbiter (JIMO) mission, several study groups explored the application of fission power systems for lunar and Mars surface missions. The first group, under the direction of the Exploration Systems Architecture Study (ESAS), developed a lunar fission surface power system derived from the JIMO concept (Elliott, 2005). It used a gas-cooled reactor and direct Brayton power conversion at 1150 K turbine inlet temperature. Like JIMO, this concept required advanced reactor fuel and refractory cladding materials due to the high operating temperatures. A second study team, consisting of NASA and DOE personnel, conducted a 60-day study that recommended a low temperature, liquid-metal cooled reactor using more conventional UO_2 fuel and stainless steel cladding. The low temperature reactor was proposed in order to reduce development risk and cost. The 60-day study team also recommended continued evaluation of three different power conversion technologies: Brayton, Stirling, and thermoelectric.
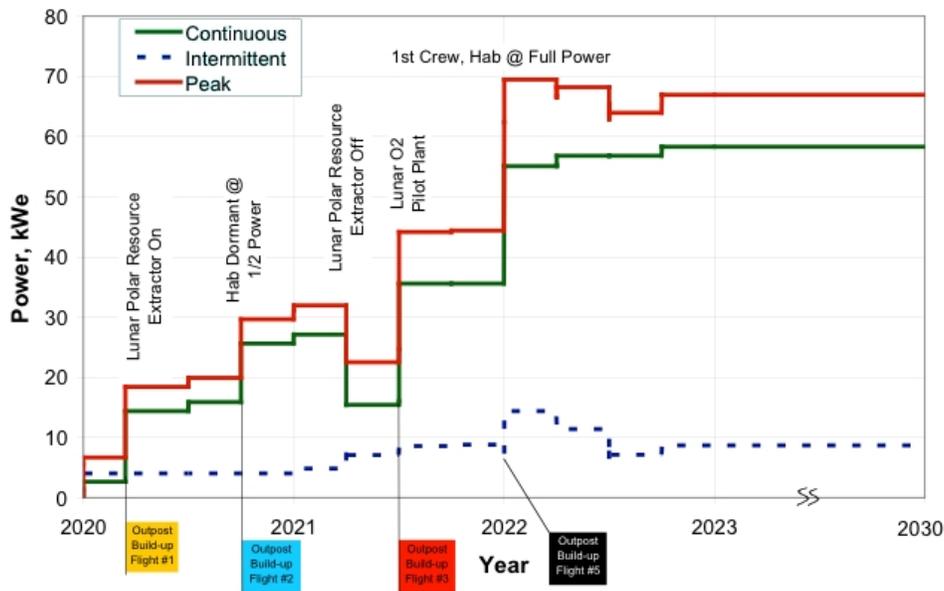
Figure 1.—Notional lunar outpost power requirements.

This paper provides mass and performance estimates for the three different power conversion options with a low temperature, stainless steel reactor. In addition, the three power conversion technologies are evaluated with a high temperature refractory reactor. Since reactor shielding has a pronounced effect on system mass, two different shielding approaches are considered: in-situ shielding with the reactor located in an excavated hole, and on-board shielding using earth-delivered materials. The study assumes a reference system power level of 50 kWe, but provides scaling between 25 and 200 kWe. The reactor power system technologies discussed are readily applicable to both the lunar and Mars surface missions. The lunar mission presents a more difficult thermal environment for waste heat radiators, given the higher solar insolation levels and longer daylight periods. The carbon-dioxide atmosphere at Mars introduces potential material issues, especially for refractory based reactor concepts. However, this might be managed through the use of a containment structure surrounding the exposed refractory components and an inert cover gas.

Fission Power Technology Options

There are three leading reactor options for space fission power applications such as the lunar and Mars surface mission: liquid-metal cooled, gas cooled, and heat pipe cooled. The reactor could be fast-spectrum or moderated. The fuel and core construction material would dictate operating temperature. A predominantly stainless steel construction would limit coolant temperatures to about 900 K. Possible fuel options for the low temperature reactor include UO_2 and UZrH. If refractory alloys, such as niobium, tantalum, or molybdenum, could be used for the fuel cladding and primary coolant boundary, operating temperatures up to about 1300 K could be considered. At the higher temperature, UO_2 and UN are the likely fuel choices. The refractory reactor introduces additional risk given the greater uncertainty for long-term material performance, but also the potential for greater power conversion efficiency, smaller waste heat radiators, and reduced system mass. This study assumes the low temperature, stainless steel reactor as a baseline with either liquid-metal or gas primary coolant. These systems are assumed to be at a more mature stage of development using "off-the-shelf" technology. Additional results quantify the performance benefits of increased operating temperature with the refractory reactor option. The heat pipe reactor was not evaluated in this study.

There are also three leading power conversion options for the fission power system: Brayton, Stirling, and thermoelectric. Figure 2 shows potential design configurations for the three converter options. The Brayton converter is a closed-cycle, recuperated gas turbine that uses a single-stage radial turbo-compressor and a permanent-magnet alternator supported on gas-foil bearings similar to designs built and tested during the 1970's (Davis, 1972; Dobler, 1978). The hot-end and turbine wheel are constructed of nickel-based superalloys and the working fluid is a mixture of helium and xenon (HeXe). Brayton conversion can be combined with the liquid-metal cooled reactor through a hot-side heat exchanger. The Brayton option also provides the potential for direct integration with a gas-cooled reactor eliminating the need for a primary coolant pump and heat exchanger. The Stirling converter is a dual-opposed, free-piston design with a linear alternator that uses high-pressure helium working fluid similar to designs built and tested during the 1980's (Dochet, 1993; Dhar, 1999). The opposed-piston configuration balances the linear motion, and essentially eliminates mechanical vibration. Reactor thermal energy is introduced at the Stirling heater head through a sodium heat pipe heat exchanger that interfaces directly to the pumped liquid-metal reactor coolant. The heater head and heat exchanger would be fabricated using nickel-based superalloys. The thermoelectric converter consists of multiple conductively-coupled thermocouple arrays configured in a compact, sandwich heat exchanger similar to designs developed during the SP-100 Program (Truscello and Rutger, 1992). The low temperature, stainless steel reactor would use n-leg lead-telluride (PbTe) and p-leg TAGS (a solid solution of tellurium, antimony, germanium, and silver) thermoelectric devices while the high temperature, refractory reactor would use silicon-germanium (SiGe) thermoelectrics. The use of advanced, segmented thermoelectrics with skutterudite materials for the low temperature reactor was excluded based on their relative immaturity compared to PbTe/TAGS.
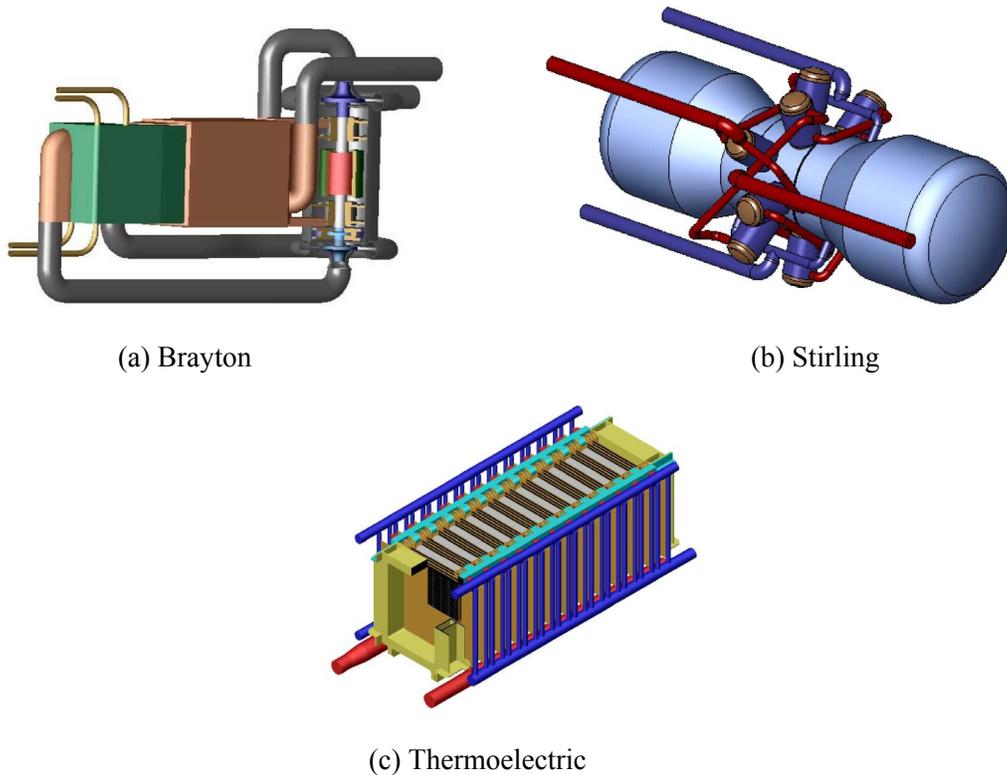

(a) Brayton   (b) Stirling

(c) Thermoelectric

Figure 2.—Power converter design configurations.

Power System Architectures

The proposed power system architectures for the three reactor-converter options are presented in figure 3. The schematics show the number of converters, the reactor coolant flow arrangement, and the radiator coolant flow arrangement. The dashed lines indicate redundant converters, fluid loops, or pumps. All systems include two vertical heat pipe radiator wings coupled to a pumped-loop heat transport system. The gas-cooled direct Brayton (DBR) concept uses two converters, one of which is required for full power operation. The HeXe working fluid (molecular weight 40, maximum cycle pressure 1380 kPa) is heated directly in the reactor core, and exits at 900 K for the stainless reactor option. The reactor exit temperature is increased to 1150 K for the refractory reactor, considered to be the maximum operating temperature for a superalloy-based Brayton. The Brayton concepts assume two converters that are nominally operated at 50 percent of rated power, with each converter using one of two radiator cooling loops. If a Brayton unit malfunctions, the remaining unit can be brought to full power via a speed and/or inventory change and the startup of the second cooling loop. This Brayton architecture can tolerate a failure of a power converter or a radiator coolant loop and still deliver full power. Both the stainless steel and refractory-based reactor options use pumped water cooling loops and water heat pipe radiators.

The liquid-metal Stirling (ST) concept uses four converters in serial pairs with two converters required for full power operation. The serial pair configuration results in lower operating temperatures for the second converter, providing greater creep life should that be a limiting factor. Similar to the Brayton concept, the Stirling converters would be nominally operated at 50 percent of rated power using piston stroke and/or frequency control. The reactor coolant loop uses redundant annular linear induction pumps(ALIP). For the low temperature stainless steel case, the reactor coolant is sodium-potassium (NaK). The

(a) Gas-cooled direct Brayton   (b) Liquid-metal Stirling

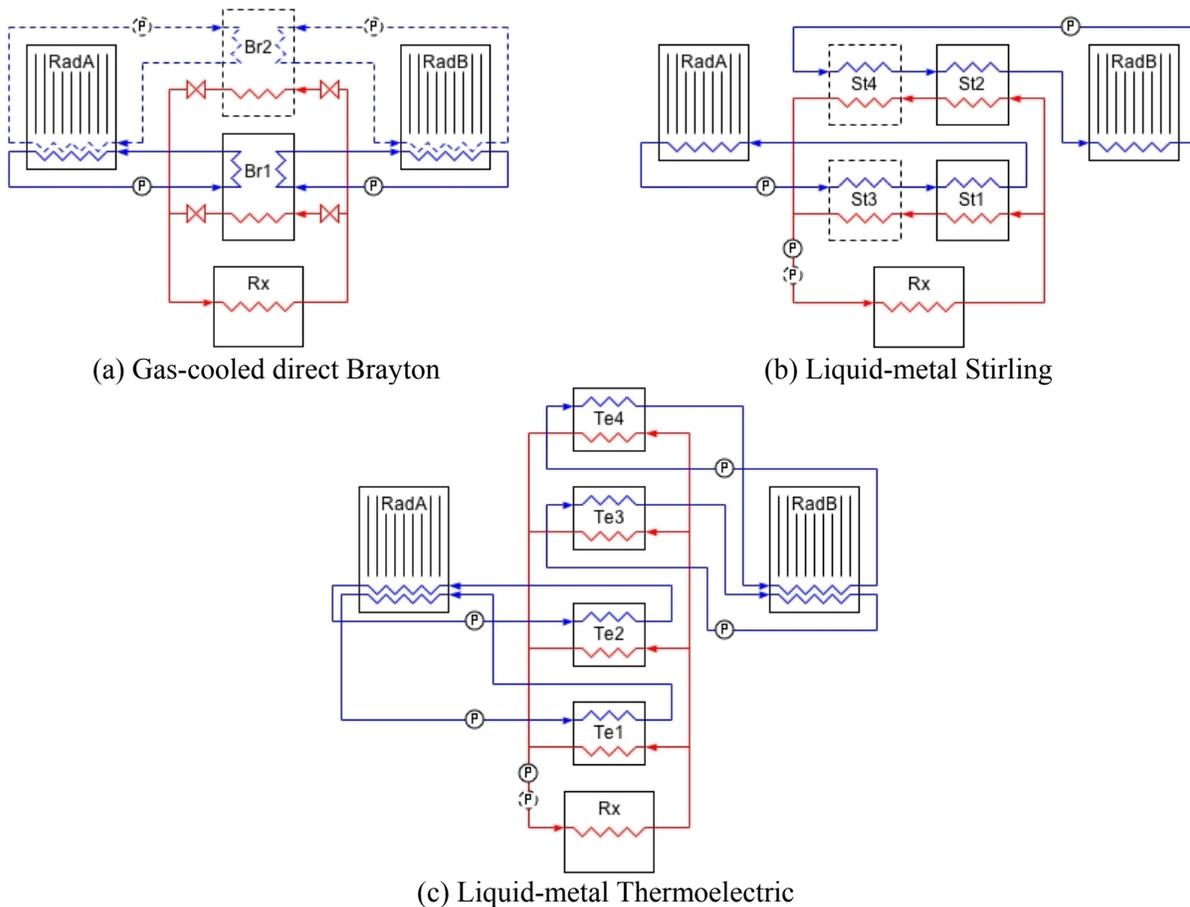(c) Liquid-metal Thermoelectric

Figure 3.—Power system architectures.

reactor coolant exit temperature is 900 K and the average heater head temperature is 850 K. The refractory reactor uses lithium coolant, a reactor exit temperature of 1100 K, and an average heater head temperature of 1050 K. The 1050 K heater head temperature is considered the maximum allowable for the superalloy-based Stirling converter design in this power class. The Stirling architecture can tolerate a maximum of two converter failures without impacting power production. A failure in a radiator loop would result in a 50 percent loss of power. Both the low and high temperature Stirling systems use water heat pipe radiators. The pumped radiator coolant fluid is water for the low temperature system and NaK for the high temperature system.

The liquid-metal thermoelectric (TE) system includes four converters with parallel reactor coolant flow and redundant ALIPs. The reactor coolant is NaK at 900 K exit temperature for the stainless steel reactor option and lithium at 1300 K exit temperature for the refractory reactor option. The corresponding thermoelectric hot-shoe temperatures are 850 and 1250 K, respectively. Since it is impractical to operate the thermoelectric modules in off-design mode, there are no redundant heat exchangers. However, the large number of thermoelectric couples and the series-parallel arrangement of the arrays provide inherent fault protection. Two TE converters are dedicated to each radiator wing, utilizing independent coolant loops. The higher cold-end temperatures for the TE systems preclude the use of water as the radiator coolant. The stainless/NaK TE system uses NaK radiator coolant and cesium heat pipes; the refractory/lithium system uses lithium radiator coolant and potassium heat pipes.

Reactor Shielding Options

Two different reactor shielding approaches were considered as shown in figure 4. The preferred approach places the reactor in an excavated hole to provide crew-rated radiation protection. This approach would likely require crew assistance and construction equipment for the system installation. The availability of regolith-moving equipment is anticipated based on plans to mine resources from the local terrain. The reactor would be installed in a vertical excavation approximately 2 meters in diameter and 4 meters tall. An upper conical shadow shield, comprised of tungsten and lithium hydride reduces radiation to acceptable levels for the power conversion and heat rejection equipment located above the excavation. A 2 cm thick, boron-aluminum (Boral) liner would enclose the reactor and shadow shield, providing neutron absorption and regolith contamination protection. This shielding approach reduces the reactor radiation dose to less than 5 rem/yr at a radial distance of about 6 meters from the reactor centerline.

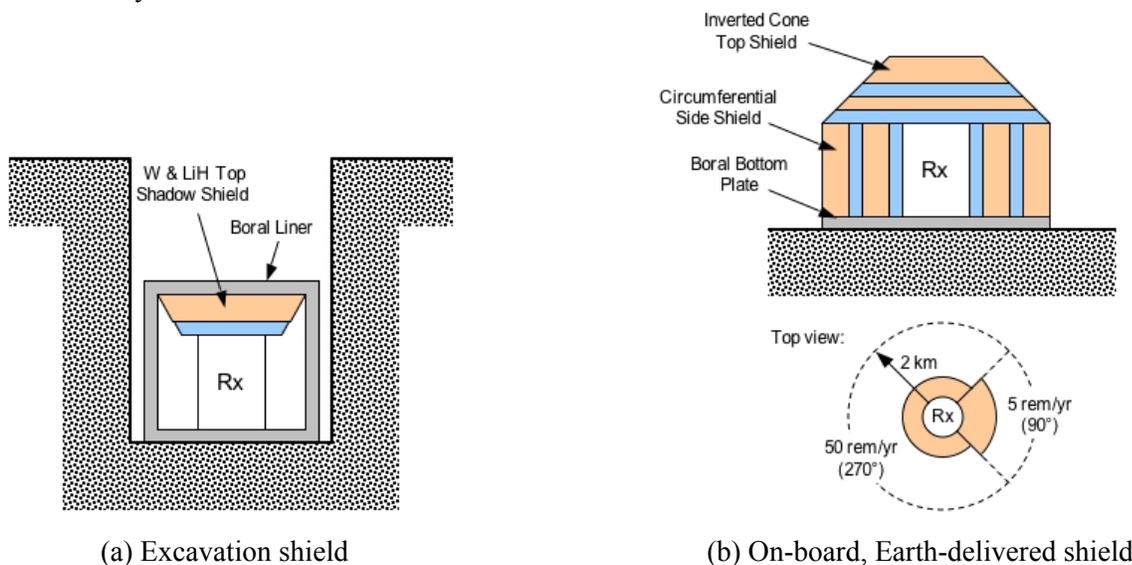(a) Excavation shield   (b) On-board, Earth-delivered shield

Figure 4.—Reactor shielding approaches.

As an alternative, the reactor could be fully shielded using earth-delivered materials as shown in figure 4(b). This shield consists of a circumferential side shield and inverted cone top shield, both constructed with alternating layers of tungsten and lithium hydride. The reactor is placed directly on the regolith surface and a Boral bottom plate limits neutron back-scatter. To reduce mass, the circumferential side shield is sectored with a 90° segment sized to limit radiation to 5 rem/yr at 2 km in the direction of the crew habitat area. The remaining 270° portion, as well as the top shield, is sized for 50 rem/yr at 2 km permitting safe short term operations by crew members and acceptable radiation levels for the power conversion equipment. The 2 km separation distance was determined based on an optimization of shield mass versus power cabling mass.

The primary benefit of the on-board shield approach is the potential for the power system to be self-deployed without crew assistance or equipment. Under this scenario, the system is landed remotely from the crew habitat area. A motorized cart containing the power management and distribution (PMAD) equipment is driven from the landing site to the crew habitat area, while simultaneously deploying the power transmission and data cables. This mobile PMAD concept is assumed for the self-deployed concepts presented in this paper; the PMAD deployment cart is included in the system mass estimates based on a 50 percent cart mass fraction. A hybrid shielding approach that uses a partial on-board shield combined with selective siting of the system behind natural surface features (e.g., hills, crater rims, etc.) could also be considered.

Heat Rejection Concept

The waste heat from the power converters must be removed and transported to radiator panels where it can be rejected to the space environment. A pumped-loop heat transport system coupled to a heat pipe radiator, similar to the JIMO concept (Siamidis, et al., 2005), is proposed for all three power conversion options. The heat pipe radiator approach permits efficient heat spreading to the panel surface and reduces the vulnerability to micrometeoroid damage as compared to an all pumped-loop system. The radiator coolant would transfer the waste heat to the heat pipe evaporator sections which are bent at 90° relative to the condensers and thermally integrated with the coolant ducting as shown in figure 5. This coolant duct concept uses split piping and high conductivity graphite saddle materials to maximize heat transfer. A thin-wall composite sleeve surrounding the piping provides micrometeoroid bumper protection. The heat pipe spacing is determined based on a compromise of radiator fin effectiveness and panel mass: closer spacing provides greater effectiveness and reduced area at the expense of greater mass per unit area. The heat pipe condenser sections are also supported in graphite saddles and sandwiched between two high conductivity, composite facesheets. A lightweight, porous carbon filler material is included between the heat pipes for structural considerations. The coolant loop and heat pipe envelopes are titanium. A common radiator geometry was developed that was suitable to both the low and high temperature reactors and all three converter options. This radiator geometry uses 2 cm diameter by 2 m length heat pipes with 10 cm spacing and 0.048 cm thick facesheets.

The surface thermal environment has a significant effect on radiator performance, especially during daylight conditions. Analytical methods developed previously and available in the literature can be applied for the lunar mission (Dallas, Diaguila, and Saltsman, 1971). Horizontal radiators with one-sided heat rejection view deep space and absorb direct solar radiation during the day. Using high emissivity, low absorptivity coatings would result in equivalent radiator sink temperatures of about 262 K at solar noon. Vertical radiators would absorb both direct solar radiation and reflected surface radiation resulting in an equivalent sink temperature of 317 K at solar noon. However, the vertical radiator would have a smaller planform area given its ability to reject heat from two sides. The radiator systems assumed in this study use vertical, two-sided radiators having an emissivity of 0.86 and absorptivity of 0.17, representative of several commercial thermal control paints. All heat rejection systems are sized for worst-case thermal conditions: lunar noon on the equator. Depending on the converter choice and cold-end operating temperature, these systems could produce as much as 25 percent excess power during nighttime operations.
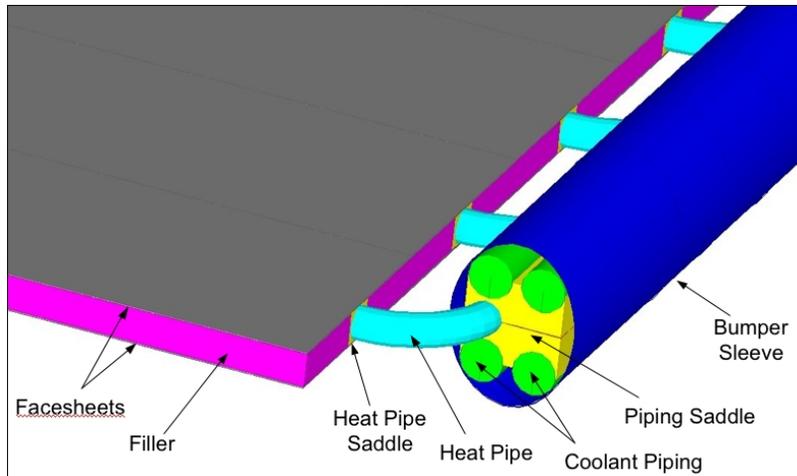
Figure 5.—Coolant loop interface with heat pipe radiator panel

Power Management and Distribution Concept

The large separation distances between the fission power system and the crew habitat area dictate the use of high voltage power transmission cabling to achieve reasonable mass. The generalized PMAD concept proposed for these systems is shown in figure 6. It consists of a Local Control Module located about 25 meters from the fission power system, a power transmission and data cable set, and a remote Power Distribution Module at the crew habitat area. The anticipated output characteristics of the three converter options are 440 Vrms (line-to-line) at 2250 Hz, 3-phase for the Brayton, 300 Vrms at 100 Hz, single-phase for the Stirling, and 200 Vdc for the thermoelectrics. The main power cable is a 5000 Vac, 3-phase cable with copper conductors and kapton insulation. Each power conversion unit has a dedicated power conditioning stage and transmission cable in order to preserve the desired redundancy throughout the system. The transmission voltage level was selected based on the desire for low cable mass while maintaining appropriate safety. The use of high voltage DC transmission (rather than AC) for the three conversion options was also considered and found to not significantly effect PMAD mass.

The Local Control Module accepts the power conversion output and modifies it accordingly for the 5000 V transmission. For the Brayton system, this is accomplished with a simple boost transformer, estimated at 98 percent efficiency. The preferred PMAD approach for the low frequency Stirling unit is to convert to DC and then to high frequency AC to avoid excessive transformer mass penalties. Consequently, the Stirling option requires an active rectifier and DC-AC inverter prior to the boost transformer. The DC thermoelectric system requires a DC-AC inverter in front of the boost transformer. The total control module efficiencies for the Stiring and thermoelectric systems are 92 and 95 percent, respectively. At the opposite end of the transmission cable, the Power Distribution Module is assumed to include a buck transformer to provide 120 Vac service for the various user loads, and all the PMAD control electronics. All of the power conversion options would use a shunt regulator and parasitic load radiator to dissipate excess electrical power not required by the user loads. The Power Distribution Module has an efficiency of 97 percent and an estimated control power requirement of 500 W. A solar array and battery are included for startup and emergency power. The Power Distribution Module also processes the electrical power for the reactor and radiator pumps and delivers it back to the fission power system via a 120 V power cable. Thermal radiators are provided for both the Local Control Module and Power Distribution Module to dissipate waste heat and maintain electronics temperatures at 333 K.

The main power cable efficiency is dependent on the transmission distance and cable size. The cable size is based on the conductor current, minimum insulation thickness to prevent voltage breakdown, and temperature. The cable temperature is determined from a thermal heat balance between resistive losses, solar insolation, and surface radiation. This study assumes the power cable is laid-out on the surface
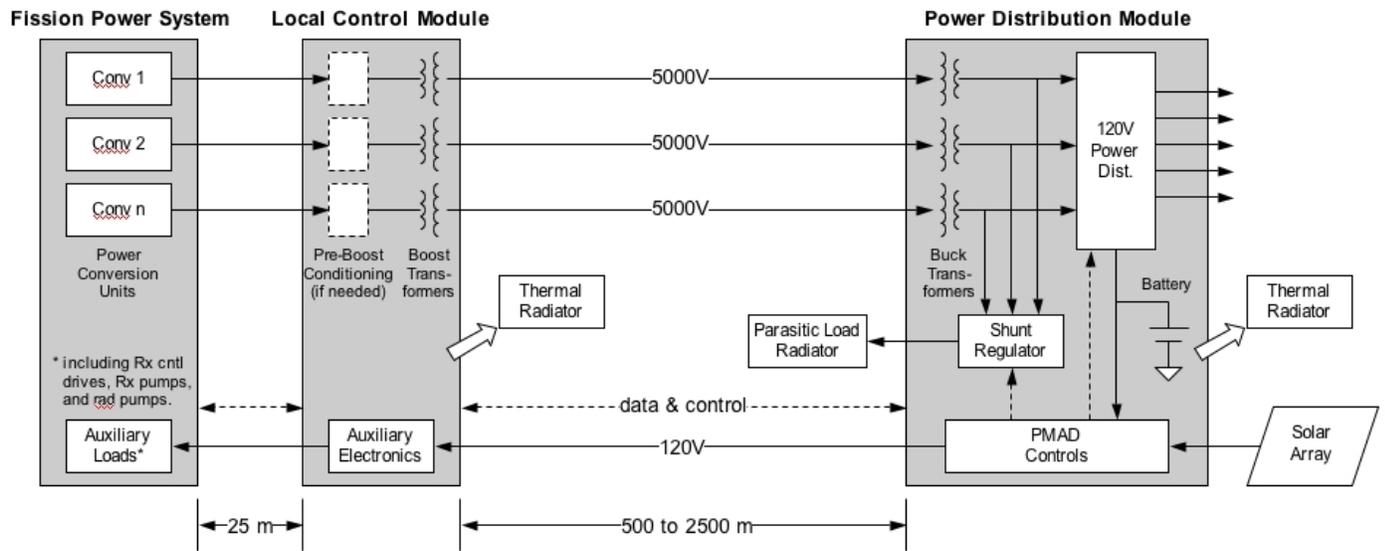
Figure 6.—PMAD architecture.

with a 50 percent view factor to space. For the crew-deployed system with in-situ shielding, the transmission distance is set at 500 m and the cable is sized for 98 percent efficiency. For the self-deployed system with on-board shielding, the transmission distance is 2500 m (providing margin relative to the 2 km required separation distance) and the cable is sized for 95 percent efficiency. The resulting maximum cable operating temperature for the both the 500 m cable and the 2500 m cable is less than 373 K.

System Model Description

The analytical results presented in this paper were generated from Glenn Research Center's Space Reactor Power System Optimization (SRPS-Opt) model. SRPS-Opt is a spreadsheet-based, parametric design tool that evaluates the end-to-end power system including reactor, shield, power conversion, heat rejection, and PMAD. The model includes reactor scaling relationships derived from previous and on-going space reactor design studies. Reactor coolant options include lithium, sodium, potassium, NaK, and HeXe. The reactor interface is addressed through available models for the reactor coolant pump and hot-side heat exchanger. Shield sizing routines are provided for both robotic and human mission applications, with a wide range of configurations and geometries. Power conversion modules are included for Brayton, Stirling and thermoelectric. The power conversion modules contain detailed thermodynamic calculations, empirical-based component performance algorithms, and mass scaling relationships that are anchored to previous hardware and designs. The heat rejection subsystem is addressed through models for coolant flow, piping layout, pump power, radiator fin effectiveness, and radiation heat transfer. Radiator coolant options include water, NaK, and lithium. The PMAD portion of the model accounts for power conditioning electrical losses, electronics thermal control, and transmission cabling.

The SRPS-Opt model is not a detailed design code. Its primary limitations arise when designs are projected beyond the reasonable range of the scaling relationships and the designs on which they are based, which varies from subsystem to subsystem. The power levels in this study are considered within the applicable range. The primary advantage of the model is the ability to provide consistent "apples-to-apples" system comparisons between various design architectures, as well as sensitivity studies on key design parameters. SRPS-Opt has served as the principle government design tool for comparing reactor power system options under NASA's Project Prometheus.

Mass and Performance Results

SRPS-Opt provides the means to optimize the power system design based on various independent design parameters. A key system trade involves the variation in cold-end temperature for a fixed hot-end temperature. This results in a trade-off of reactor mass versus radiator mass. Figure 7 presents the power system optimization trends for the three converter options with the low temperature reactor and the excavation shield for 50 kWe system output power. Generally, lower cold-end temperatures result in smaller heat sources, but larger radiators due to the lower rejection temperatures. Higher cold-end temperatures generally result in smaller radiators, but larger heat sources due to the lower efficiency. The Brayton radiator curve in figure 7(b) shows that a minimum area design results when the benefits of high heat rejection temperatures are overcome by low efficiency. The minimum system mass design points occur at 380, 460, and 530 K respectively, for the Brayton, Stirling, and thermoelectric systems. The radiator area estimates include 10 percent margin; the system mass estimates include 20 percent margin.
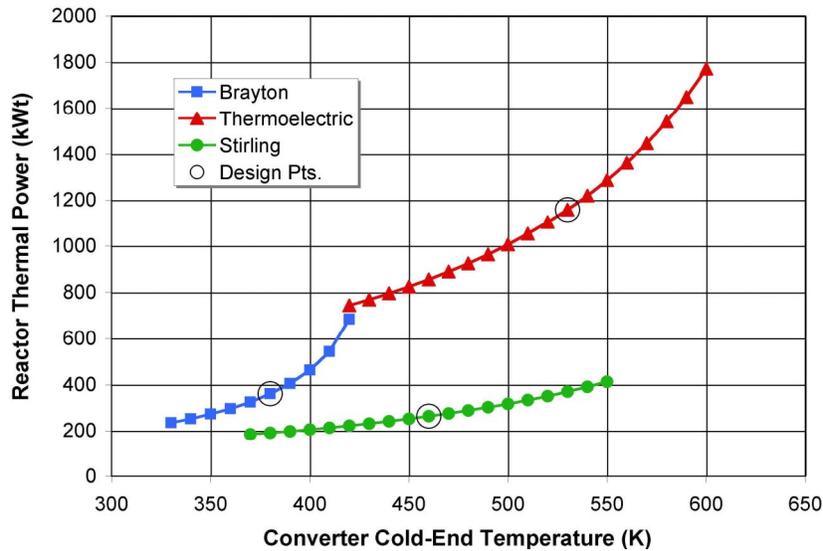
(a) Reactor power versus cold-end temperature
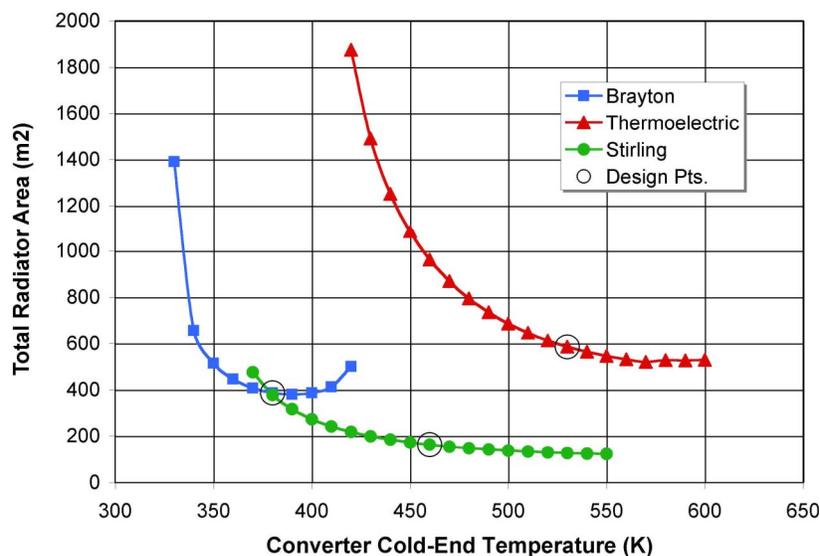
(b) Radiator area versus cold-end temperature
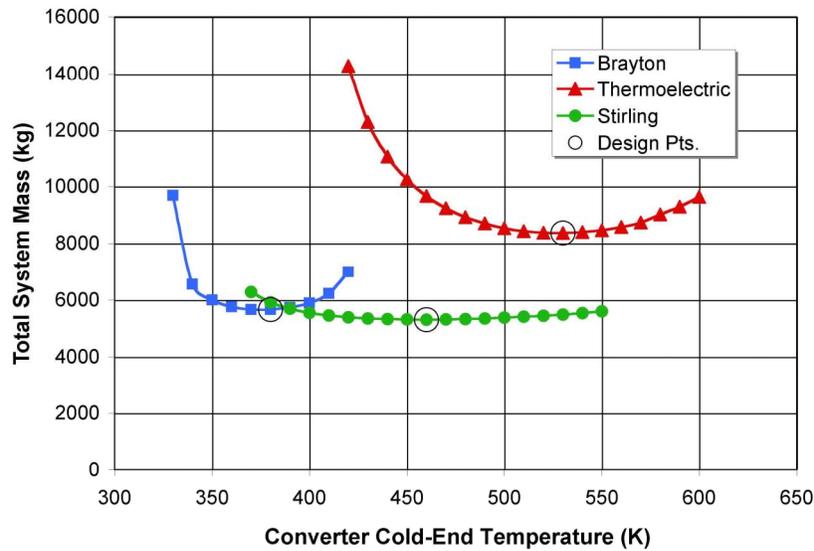
(c) System mass versus cold-end temperature

Figure 7.—Power system optimization.

The system design points are presented in table 1 for both the low temperature, stainless steel reactor and the higher temperature, refractory reactor with the excavation shield. The power conversion output power levels reflect the total power that must be generated to account for PMAD losses and auxiliary power loads, including the reactor and radiator pumps. The Stirling system design provides the lowest mass among the low temperature reactor options. The NaK Stirling system combines the highest system efficiency (19 percent) with the lowest radiator area (163 m^2). The 30.8 kWe converter unit size is within the range of Stirling designs that were designed and built by Mechanical Technology Inc. during the 1980's (Dochet, 1993; Dhar, 1999). The low temperature Brayton system is only 7 percent greater mass, but requires more than twice the radiator area. The similarity in overall mass results from the larger radiator mass for the Brayton system being offset by greater power conversion and PMAD masses for the Stirling system. The NaK/TE system is 58 percent greater mass than the Stirling option with about four-times more radiator area.

TABLE 1.—50 kWe SYSTEM DESIGN POINTS WITH EXCAVATION SHIELD

System concept	Stainless steel reactor			Refractory reactor		
	Low-Temp direct Brayton	NaK PbTe/TAGS	NaK Stirling	High-temp direct Brayton	Lithium SiGe	Lithium Stirling
Reactor thermal power (kWt)	360	1159	263	213	1232	214
Reactor exit temperature (K)	900	900	900	1150	1300	1100
Converter hot-end temperature (K)	900	850	850	1150	1250	1050
Converter cold-end temperature (K)	380	530	460	400	750	500
Power conversion output (kWe)	54.6	77.5	61.7	54.4	63.7	62.4
Converter unit power (kWe)	54.6	19.4	30.8	54.4	15.9	31.2
Auxiliary power loads (kWe)	0.3	19.3	3.4	0.2	7.0	4.0
Converter efficiency	15.6%	7.5%	25.9%	26.3%	5.8%	32.1%
System efficiency	13.9%	4.3%	19.0%	23.5%	4.1%	23.4%
Main radiator area (m^2)[a]	387	586	163	154	156	82
Total system mass (kg)[b]	5657	8364	5309	4193	5556	4674

[a]includes 10 percent area margin
[b]includes 20 percent mass margin

The higher temperature, refractory reactor concepts show the direct Brayton system to have the lowest system mass. The Stirling and thermoelectric systems have 11 and 33 percent greater mass, respectively. The Brayton radiator is still larger than the Stirling, but within the range of feasibility for reasonable packaging and deployment. Compared to their stainless steel reactor counterparts, the Brayton system is 26 percent less mass, the thermoelectric system is 34 percent less mass, and the Stirling system is 12 percent less mass. The 54.4 kWe Brayton converter size is comparable to commonly used open cycle, micro-turbine generators used for terrestrial grid power augmentation (Winters, 2000). The gas-cooled, refractory reactor option could use a superalloy external pressure boundary by nesting the high temperature HeXe piping within the low temperature piping (Wright and Lipinski, 2003). This approach would confine the use of refractory alloys to the fuel cladding and internal structure only making it more attractive for use is oxidizing environments. The combination of a pumped-lithium reactor with indirect Brayton power conversion was also considered and found to have similar overall mass and performance as the high temperature, direct Brayton. In this case, the gas reactor mass was comparable to the combined mass of the lithium reactor, primary coolant pumps, and hot-side heat exchanger.

Figure 8 shows the mass breakdowns for the all of the design variants including the three converter options, the two reactor options, and the two different shielding approaches. The differences between the stainless and refractory reactor options are most evident in the heat rejection subsystem masses; the low temperature systems have as much as three times the heat rejection mass as the high temperature systems. The self-deployed concepts with on-board shielding are dominated by shielding and PMAD mass. The crew-rated, circumferential side shield and inverted cone top shield for the self-deployed systems results in a factor of four shield mass increase as compared to the excavation shadow shield and Boral liner assumed for the crew-deployed systems. The mobile deployment cart that delivers the power distribution module to the crew habitat area combined with the 2500 m transmission cable results in a factor of three greater PMAD mass for the self-deployed concepts. Overall, the self-deployed systems are approximately a factor of two greater mass than the crew-deployed counterparts. The higher mass of the self-deployed systems must be weighed against the ability to land, deploy, and operate the system without relying on crew assembly or special construction equipment.
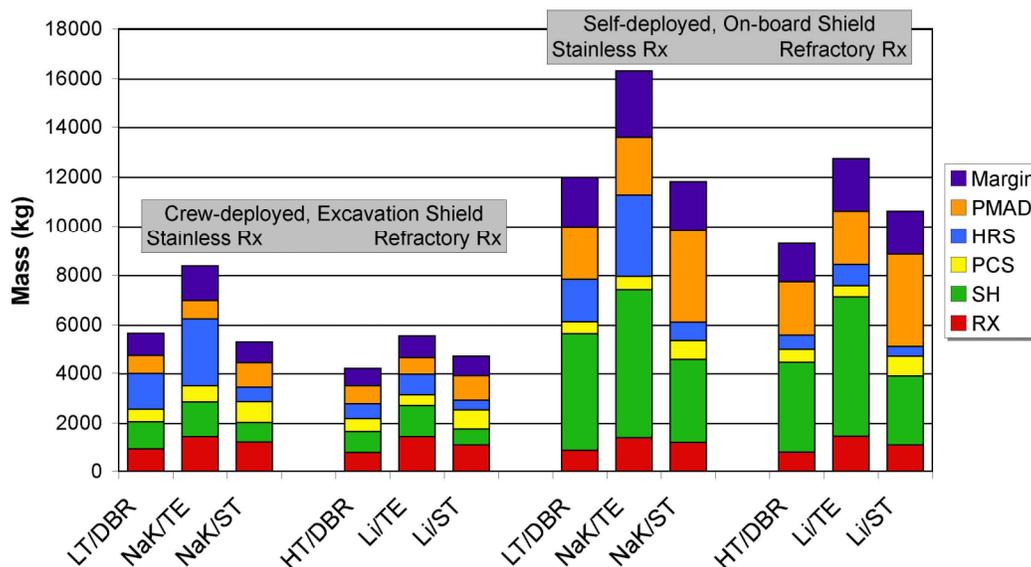

Figure 8.—50 kWe system mass comparisons.

Figure 9 presents the system mass versus power level trends for both the stainless and refractory reactor options with excavation shielding. The power level that can be delivered to the surface is dependent on the lander payload capability. Notional lunar surface mission landers have been projected with payload capabilities between 6000 and 15000 kg. For the low temperature reactor systems, the maximum power that could be deployed with a 6000 kg lander capability would be around 50 kWe for the Brayton and Stirling concepts and 25 kWe for the thermoelectric concept. If a 15000 kg lander were available, power levels increase to over 200 kWe for Brayton and Stirling and 100 kWe for thermoelectric. The refractory reactor options permit significantly greater power levels for the same lander capability. A 100 kWe Brayton system could be accommodated with a 6000 kg lander. Power levels in excess of 200 kWe could be delivered via the 15000 kg lander with a large payload fraction remaining for other surface assets. A potential nuclear power system buildup approach could utilize a 6000 kg lander to deliver an initial 50 kWe stainless reactor system followed by a 200 kWe refractory system delivered as part of the payload of a 15000 kg lander. This approach provides system-level redundancy and considerable growth margin for in-situ resource production and closed-loop life support.
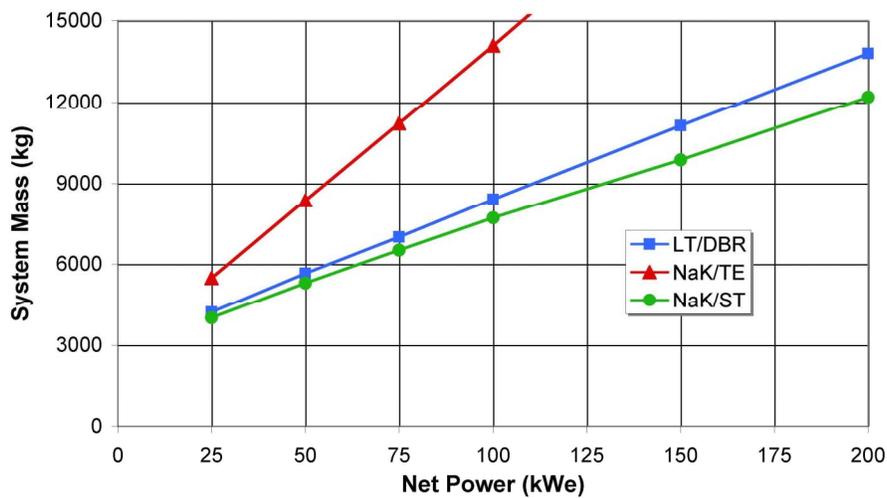
(a) Stainless steel reactor and excavation shielding
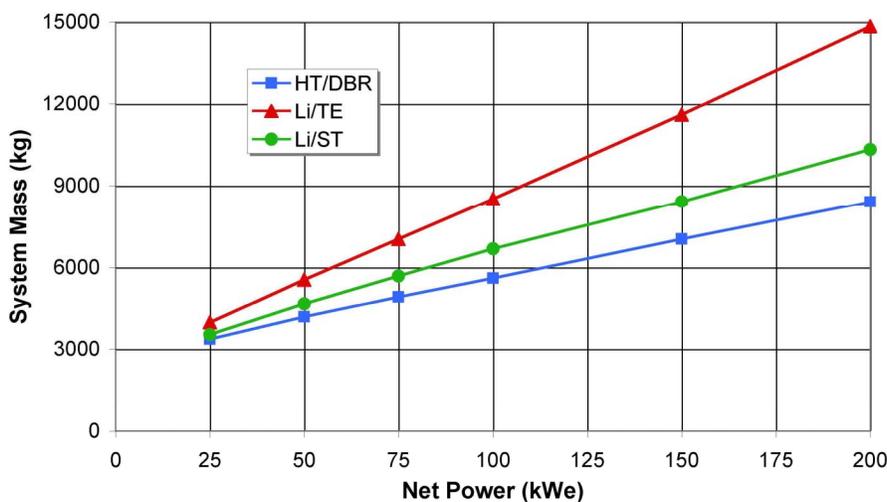
(b) Refractory reactor and excavation shielding

Figure 9.—Mass sensitivity with power output.

Conclusion

A study was performed to compare reactor and power conversion design options for lunar and Mars surface power applications for power levels from 25 to 200 kWe. The study explored both low and high temperature reactors, three different power conversion technologies, and two different shielding approaches. A 50 kWe power level was chosen for reference, representing the class of system that would be needed for the initial emplacement phase. The lowest mass option is the high temperature, gas-cooled Brayton concept with in-situ shielding at about 4200 kg. If the fission reactor was constrained to use stainless steel construction, the liquid-metal Stirling concept provided the lowest mass with a 27 percent penalty relative to the high temperature, gas-cooled Brayton system. If the fission power system has to be deployed without crew assistance or construction equipment, it might require on-board shielding and a teleoperated PMAD cart to deploy the transmission cable and provide the electrical interface at the crew habitat area. The mass of a self-deployed, self-shielded fission system including the mobile PMAD cart was approximately twice that of the in-situ shielded system.

References

Elliott, J., *Prometheus Project—Lunar Fission Surface Power System Study Report*, JPL 982-R66153, Jet Propulsion Laboratory, Pasadena, CA, 2005.

Dallas, T., Diaguila, A.J., and Saltsman, J.F., *Design Studies on the Effects of Orientation, Lunation, and Location on the Performance of Lunar Radiators*, NASA TM X-1846, NASA Lewis Research Center, Cleveland, OH, 1971.

Davis, J.E., *Design and Fabrication of the Brayton Rotating Unit*, NASA CR–1870, National Aeronautics and Space Administration, Washington D.C., 1972.

Dhar, M., *Stirling Space Engine Program, Volume 1—Final Report*, NASA/CR—1999-209164/VOL1, Mechanical Technology Incorporated, Latham, NY, 1999.

Dobler, F.X., et al., *Analysis, Design, Fabrication and Testing of the Mini-Brayton Rotating Unit (Mini-BRU)*, NASA CR–159441, NASA Lewis Research Center, Cleveland, OH, 1978.

Dochet, G., *SPDE/SPRE Final Summary Report*, NASA Contractor Report 187086, Mechanical Technology Incorporated, Latham, NY, 1993.

Mason, L.S., Bloomfield, H.S., and Hainley, D.C., *SP-100 Power System Conceptual Design for Lunar Base Applications*, NASA TM-102090, NASA Lewis Research Center, Cleveland, OH, 1989.

Mason, L.S., Rodriguez, C.D., McKissock, B.I., Hanlon, J.C., and Mansfield, B.C, *SP-100 Reactor With Brayton Conversion for Lunar Surface Applications*, NASA TM-105637, NASA Lewis Research Center, Cleveland, OH, 1992.

Mason, L.S., and Cataldo, R.L., "Nuclear Power Systems for the First Lunar Outpost," in *Proceedings of the 10th Symposium on Space Nuclear Power and Propulsion*, edited by M. El Genk and M. Hoover, AIP Conference Proceedings 271, New York, NY, 1993, pp. 351–358.

Mason, L.S., *Surface Nuclear Power for Human Mars Missions*, NASA/TM—1999-208894, NASA Lewis Research Center, Cleveland, OH, 1999.

Mason, L.S., *A Comparison of Brayton and Stirling Space Nuclear Power Systems for Power Levels from 1 Kilowatt to 10 Megawatts*, NASA/TM—2001-210593, NASA Glenn Research Center, Cleveland, OH, 2001.

Truscello, V.C., and Rutger, L.L, "The SP-100 Power System," in *Proceedings of the 9th Symposium on Space Nuclear Power Systems*, edited by M. El Genk and M. Hoover, AIP Conference Proceedings 246, New York, NY, 1992, pp. 1–23.

Siamidis, J., Mason, L., Beach, D., and Yuko, J., *Heat Rejection Concepts for Brayton Power Conversion Systems*, NASA/TM—2005-213337, NASA Lewis Research Center, Cleveland, OH, 2005.

Winters, R.K., *Distributed Energy Services—The World's Power and Transportation Industries: Set for a Revolution, Part II*, Bear, Stearns & Co. Incorporated, Equity Research Report, November 2000.

Wright, S.A, and Lipinski, R.J., "Pin-Type Gas Cooled Reactor for Nuclear Electric Propulsion," in proceeding of the *Space Technology and Applications International Forum (STAIF 2003)*, edited by M.S. El Genk, AIP Conference Proceedings 654, Melville, New York, 2003, pp. 408–419.

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13. ABSTRACT (Maximum 200 words)

This paper presents a comparison of reactor and power conversion design options for 50 kWe class lunar and Mars surface power applications with scaling from 25 to 200 kWe. Design concepts and integration approaches are provided for three reactor-converter combinations: gas-cooled Brayton, liquid-metal Stirling, and liquid-metal thermoelectric. The study examines the mass and performance of low temperature, stainless steel based reactors and higher temperature refractory reactors. The preferred system implementation approach uses crew-assisted assembly and in-situ radiation shielding via installation of the reactor in an excavated hole. As an alternative, self-deployable system concepts that use earth-delivered, on-board radiation shielding are evaluated. The analyses indicate that among the 50 kWe stainless steel reactor options, the liquid-metal Stirling system provides the lowest mass at about 5300 kg followed by the gas-cooled Brayton at 5700 kg and the liquid-metal thermoelectric at 8400 kg. The use of a higher temperature, refractory reactor favors the gas-cooled Brayton option with a system mass of about 4200 kg as compared to the Stirling and thermoelectric options at 4700 and 5600 kg, respectively. The self-deployed concepts with on-board shielding result in a factor of two system mass increase as compared to the in-situ shielded concepts.

14. SUBJECT TERMS

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