Chapter 2

SPACE POWER REACTORS

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2.1 INTRODUCTION

Fission reactors are expected to play a critical role in upcoming human planetary missions. The primary sources of electrical power for the Apollo spacecraft were fuel cells, but nuclear power was utilized during these missions to the moon to operate surface science experiments.

A lunar base is contemplated by NASA's Constellation (Cx) Program spacecraft which consist of the Aries I and Aries V launch vehicles, the Orion crew capsule, the Earth Departure Stage and the Lunar Surface Access Module. These spacecraft will be capable of performing a variety of tasks, from Space Station resupply to lunar landings with the goal of full operational capability no later than 2014 and returning USA astronauts to the moon by 2020.

Radioisotope Thermo-electric Generators (RTGs) convert thermal power from the alpha decay of Pu^{238} to electrical power by way of solid state thermoelectric elements.

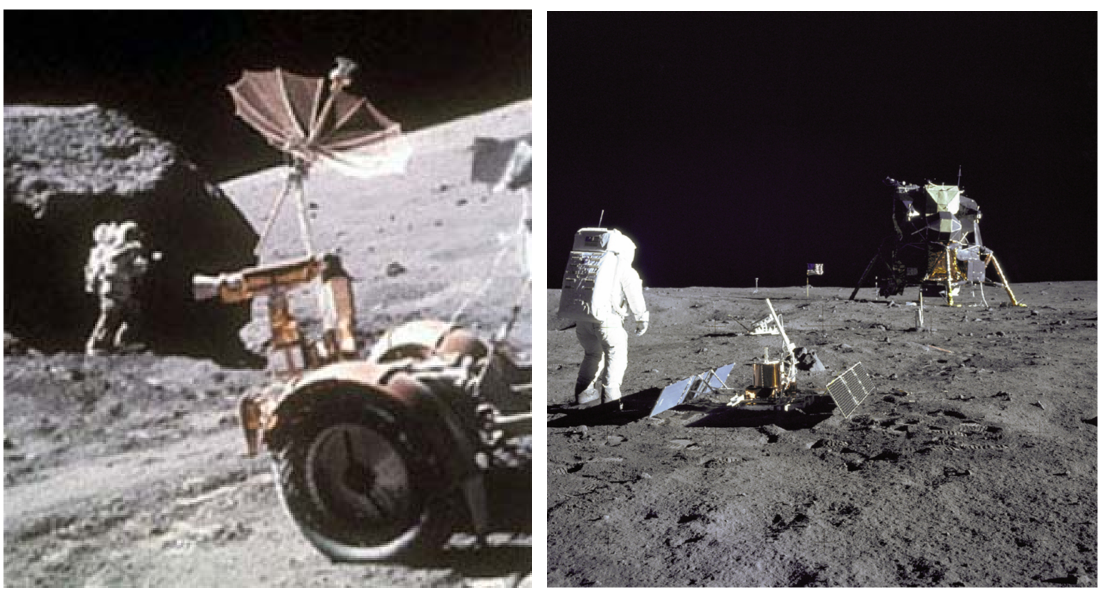

Figure 1. Astronaut Harrisson H. Schmitt on the Apollo 17 lunar mission, 1972, left. Solar array and thermoelectric generator power systems on the moon, right. NASA Photographs.

RTGs have also been used on the surface of Mars on the two Viking landers. The Mars Exploration Rovers relied on radioactive heater units for internal thermal control keeping the electronics and charged batteries from freezing during the Martian nights.

Electrical power on the surface of Mars was generated by solar panels in spite of atmospheric dust conditions that limit the amount of solar radiation that reaches the surface.

For power requirements in space, USA missions have relied almost solely on fuel cells, RTGs, and solar cells for energy. The single exception is the SNAP-10A 45 kWth fission reactor, launched in 1965. Russia has utilized fission reactors on more than 30 satellite surveillance missions. These power sources offer distinct advantages for extended missions on the moon or Mars. RTGs become prohibitively massive at high electrical powers.

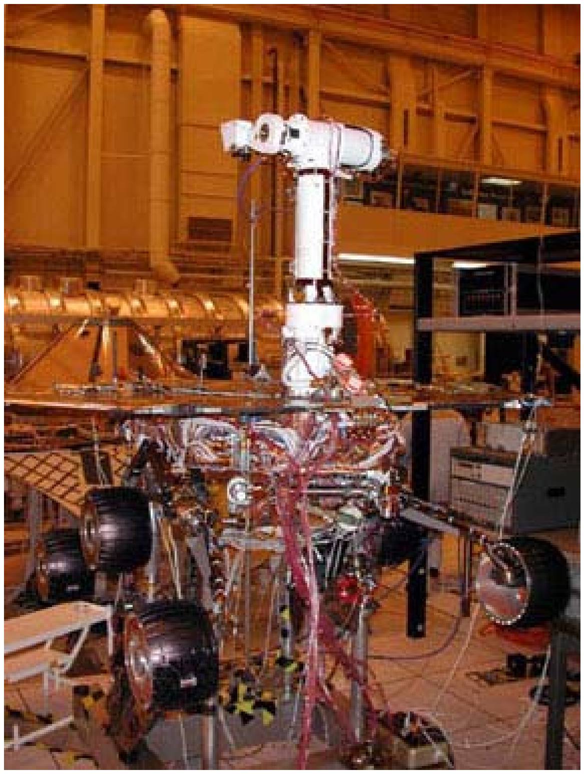

Figure 2. Spirit Rover used on Mars during assembly and testing. NASA Photograph.

The Cassini spacecraft mission to Saturn and its moons like Titan, carries three RTGs and 32.8 kg of Pu^{238} fuel that provide a total electrical power of 0.870 kWe. High-efficiency thin film silicon solar cell arrays can produce 0.676 kWe/kg and triple-junction InGaAs solar cell arrays can produce 0.360 kWe/kg at geosynchronous orbit [1]. Fuel cells on the Space Shuttle produced electricity at 0.130 kWe/kg at a continuous output of 7 kWe. For an estimated power budget of 100 kWe for surface missions, electricity produced exclusively by these technologies becomes impractical. However, a combination of these technologies and nuclear fission reactors with Stirling Cycle engines may provide a more practical solution to electrical power needs and thermal control for surface exploration.

2.2 NUCLEAR TECHNOLOGY FOR PLANETARY ENGINEERING

The largest application of nuclear technology in space would be to “terra forming” Mars, and make it possible for the kind of life that exists on Earth. Currently the Mars atmosphere is much thinner than Earth’s and is composed primarily of carbon dioxide as shown in Table 1.

Earth and Mars are very different worlds. Mars is inhospitable and harsh for life. Without topographical variations, water on Earth can cover the whole surface to a depth of 3 kms. Mars does not contain liquid water, even though there are indications that it is present as permafrost.

Table 1. Comparison of the Martian and Terrestrial atmospheres, volume percent.

Characteristics	Mars	Earth
N_2	2.70	78.08
O_2	0.13	20.95
Ar	1.60	0.93
H_2O		<1-4
CO_2	95.32	0.035
O_3(Ozone, ppbv)		10-100
Surface temperature, ^oC	-53	+15
Surface pressure, mbars	6.36	1,013

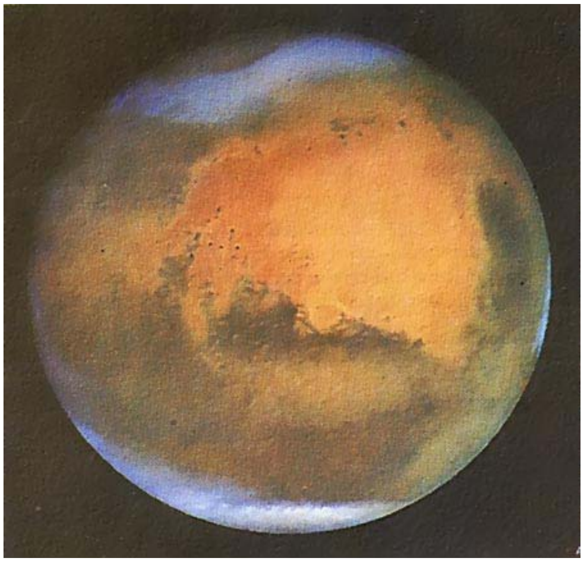

Figure 3. Mars photographed by the Hubble Space Telescope showing frozen fields of carbon dioxide at the poles.

The average temperature of the Earth is about 15 degrees Celsius, whereas Mars is at a frigid –53 degrees Celsius temperature. The thin atmosphere of Mars has a surface pressure of 6.36 mbars, compared with Earth's atmosphere of 1,013 mbars. Mars' atmosphere is primarily carbon dioxide with a small amount of nitrogen and trace amounts of oxygen, whereas the atmosphere of Earth is primarily nitrogen and oxygen with small amounts of argon, water vapor and carbon dioxide. Earth is full of plant and animal life forms both microscopic and macroscopic, whereas Mars is devoid of life on its surface. It is possible that some forms of life exist under its surface in localized areas of volcanic heat generation.

Nature may have already started the process of terra forming Mars. The photograph of Fig. 3 displays vast fields of frozen carbon dioxide at its poles. These fields are eroding suggesting that the atmosphere of Mars is getting denser and that the climate of Mars could undergo a greenhouse effect leading to its warming. This warming could release vast amounts of frozen water from its permafrost.

The process can be encouraged by humans by exploding thermonuclear devices at the poles releasing more carbon dioxide to its atmosphere, followed by the insertion of bacterial life from Earth that would use solar photosynthesis to generate oxygen in the Mars' atmosphere eventually leading to the spread of life on the now dead planet.

The generation of oxygen would result as a byproduct from the photosynthesis process acting on H_2O and CO_2 in the presence of light and chlorophyll. In this process carbohydrates are produced and used by the plant organism as food. The relevant reaction is:

$$nH_2O + mCO_2 + h\nu \rightarrow C_m(H_2O) + mO_2 \tag{1}$$

Ozone as O_3 is photo chemically produced from O_2. The evolution of ozone will be crucial to sustaining life on Mars like on Earth. It is important for absorbing the biologically lethal solar ultraviolet radiation with a wavelength of 200-300 nm. Life on Earth is surmised to have started initially in the oceans, whose water provided shielding against it. Once the ozone layer formed, living organisms were able to propagate to the land surface about 600 million years ago. The presence of life on land initiated a complex cycling of nitrogen, carbon, hydrogen and oxygen elements and compounds between the atmosphere and the biosphere.

2.3 MARS MISSION

On Mars, nuclear power would be needed. Because of dust storms and high wind speeds, a Mars colony would have to be sheltered underground or carved into hillsides, and need a reliable power supply for heat, transportation, food production, water supply, communications and other life supporting measures. The environment on Mars is very harsh. Temperatures average at below 273 K, and are at 148 K at the polar regions. The climate is dry and hostile, threatening the astronauts at every turn.

Providing energy, particularly heating for the astronauts cannot depend on solar energy or on radioisotope generators, and needs a nuclear reactor source. A mission composed of 4 astronauts would need a power supply of about 140 kWe. Most radioisotope generators have used Plutonium^{238}, and assuming a dynamic conversion system's efficiency of 30 percent, the thermal energy needed for the astronauts is:

$$140 \times (100/30) = 466.66 \text{ kWth.}$$

One needs about 1.8 kg of Pu^{238} per kWth produced. Thus one needs:

$$1.8 \times 466.66 = 840 \text{ kgs of } Pu^{238}.$$

This amount is beyond any possible existing supply, and suggests that such a mission, for reliability reasons, would require at least two nuclear reactors producing a thermal power of 0.5 MWth each, for a total of 1 MWth of power. During the Martian day, three solar power systems at 10 kWe each, may supplements their needs.

2.4 HEAT PIPE OPERATED MARS EXPLORATION REACTOR (HOMER)

A Heat Pipe Operated Mars Exploration Reactor (HOMER) providing between 50 and 250 kWe has been proposed for life support, operations, in-situ propellant production, scientific experiments, high-intensity lamps for plant growth and other activities on a Mars mission. This is crucial, since a solar array providing the same power on Mars would require a surface area of several football fields. In addition, day and night, geographical sunlight issues, seasonal variations and dust storm environments would not affect a fission reactor system. Figure 4 shows the core design of such a design producing 125 kWth of power. The rotating drums around the circumference achieve power level control. These consist of a neutron absorbing side and a neutron scattering and reflecting side, allowing power control without the need for terrestrial used control rods. Moving parts are also eliminated by the use of heat pipes transferring heat for rejection by radiation to space without the use of pumps and moving parts.

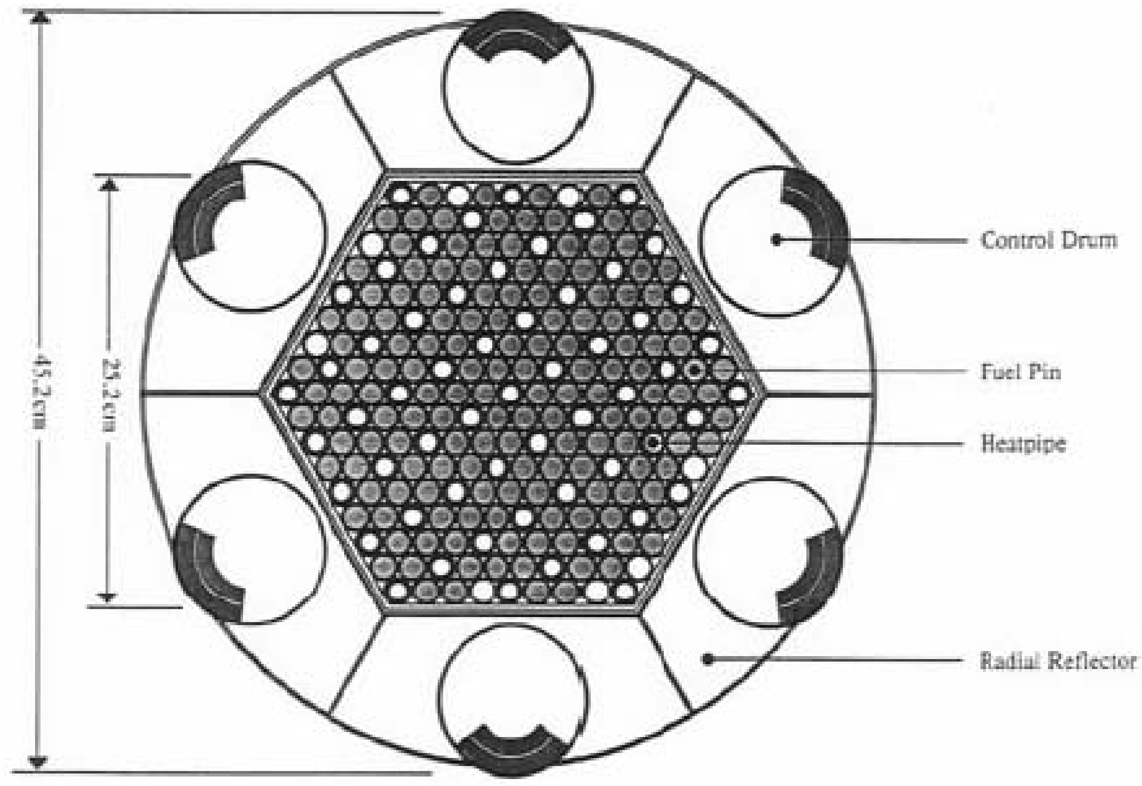

Figure 4. Cross Section of heat pipe space reactor of 125 kWth power, showing the peripheral control drums.

The core contains stainless steel clad uranium dioxide fuel. The fuel pins are structurally and thermally bonded to a sodium heat pipe. Heat is conducted from the fuel pins to the heat pipes which carry the heat to the power conversion system.

The core design is compatible with different types of power conversion cycles: thermoelectric, thermionic, Brayton, Stirling, Rankine or Alkaline Metal Thermal to Electric Converter (AMTEC) using high pressure Na vapor.

It will take at least a decade of research and development, with an expense of at least $50 billion to prepare for a Mars mission. NASA has been trying a strategy of “faster, cheaper, better,” in its exploration of Mars, leading to about a 2 out of 3 as a success rate. With manned space missions, a higher degree of reliability will be needed.

2.5 LUNAR BASE

The USA has targeted placing a base on the moon by 2020 as a precursor to launching a manned mission to Mars. Humans have been to the moon already in the 1970s as part of the Apollo program.

After the climactic triumph of the Apollo moon missions, the public lost interest in continued human exploration of the moon. The USA President Nixon administration cut deeply into NASA's forcing it to focus on robotic missions to more distant, more mysterious worlds like Mars and Jupiter and sent only two small orbiting spacecraft to the moon. Clementine, a joint effort with the Department of Defense, found signs of frozen water at the lunar south pole in 1994. In 1998 and 1999, the Lunar Prospector mission, which found even stronger evidence of ice and mapped out the moon's gravitational and magnetic fields.

A reason to return and establish a permanent base on the moon would be to assist a mission to Mars. Because the moon's gravity is 1/6 of Earth's, gathering raw materials there such as metal for the spacecraft to water for the astronauts to drink would be much cheaper than hauling them up from Earth. So the cost and difficulty of traveling to Mars would be reduced. A moon base would also serve as a proving ground for new technologies developed for a Mars mission.

The presently accepted theory about the formation of the moon is that about 4.45 billion years ago, a planetary body the size of Mars slammed into the infant Earth, tossing a blob of material into space that became the moon. With only 1/8 the Earth's mass, the moon long ago cooled to the core, leaving it geologically dead. It is also too small to gravitationally hold on to an atmosphere.

One can also suggest another theory that it was Mars itself that collided with Earth with the latter ending up in the collision with most of the water on both planets because of its larger mass.

On Earth, plate tectonics have destroyed almost all of the surface rocks from its first billion years. On the moon, those rocks are still on the surface. The youngest rocks on the moon are as old as some of the oldest rocks found on Earth at 3.2 billion years. The craters on the moon also preserve a record of the early bombardment of meteors.

The Apollo astronauts brought back 843 pounds of rocks from the moon. The similar mix of oxygen atoms in the rocks of the moon and Earth showed that the two had a common ancestry instead of the moon's forming elsewhere and then being captured by the Earth's gravity. The chemical composition also showed there had never been significant amounts of water in most areas, except possibly at the polar regions. These rocks came from just the six Apollo landing sites, leaving the rest of the surface, the size of Africa, unexplored. The top layer of crushed rock and dust, known as the regolith has not yet been explored and it holds information accumulated over billions of years.

As astronomers try to look farther into the universe, they need a large telescope that can stay focused on a single patch of sky for weeks or months. A near absolute zero temperatures and an airless environment are needed to prevent blurring. A nearby moon base would allow easy repairs and upgrades. A large infrared telescope is proposed to be constructed in a deep crater at the moon’s South Pole. The mirror of such a telescope might consist of a round dish, 20 yards wide, with a reflecting liquid such as mercury that is spun at a rate of two revolutions per minute. The centrifugal force, coupled with the moon's gravitational force, would push the liquid toward the outer edges of the dish to form a perfectly curved surface for gathering star light. Not only will a lunar telescope be more sensitive than the Hubble Space Telescope, but it should be able to detect galaxies and stars far fainter than will be seen by Hubble's planned replacement. It may even pick up light from the very first stars of the universe half a billion years after the postulated Big Bang.

A lunar base would provide a Noah’s ark protecting a copy of life beyond possible sudden and unexpected extinction from volcanic activity, viral infections or comets and asteroids impacts. Another reason to build a base on the moon is to mine it for the He^3 fusion fuel (Fig. 5). This could be used as fuel for space travel nuclear rockets, as well as be shipped to Earth to provide with deuterium from the ocean's water, a virtually inexhaustible supply of aneutronic fusion energy.

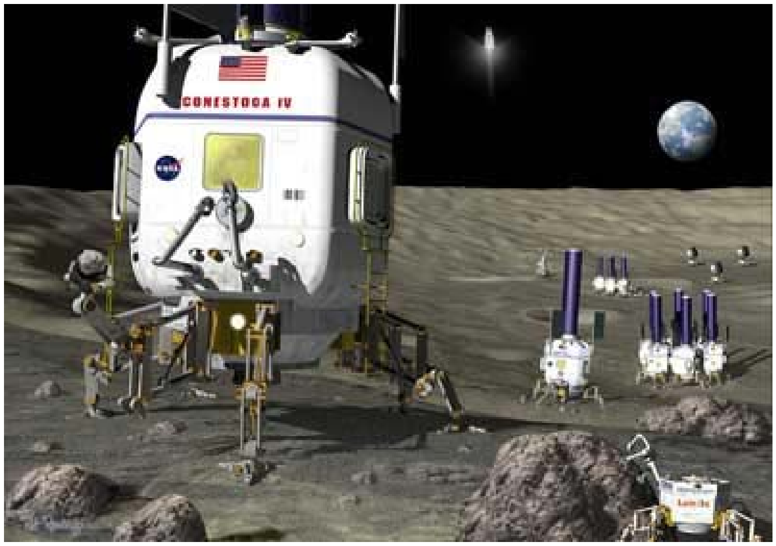

Figure 5. Mining machines could roam the moon harvesting He^3 as rocket fuel and energy source on Earth.

The surface of the moon is notorious for a significant presence of the He^3 isotope adsorbed on its surface from the solar wind. Data from lunar samples suggest that the moon contains more than a million tons of He^3. Just 50 tons could serve the electricity needs of the USA for a year.

As estimated by Gerald Kulcinski from the University of Wisconsin at Madison, for every ton of excavated He^3, 9,000 tons of life-supporting compounds such as water, oxygen, nitrogen will be mined, as well as 6,000 tons of hydrogen that could be used with oxygen to produce electrical power and water in fuel cells.

2.6 HEAT PIPE REACTORS HOMER-15 AND HOMER-25 DESIGNS

The Heat pipe Operated Mars Exploration Reactor (HOMER-15) is a nuclear fission reactor concept for future lunar and Martian surface missions. The reactor core contains uranium nitride fuel pellets contained in stainless steel fuel pins that produce a total of 15 kWth of thermal power. Sodium-filled heat pipes transfer the thermal energy to a Stirling engine that produces 3 kWe of electrical power for an overall thermal conversion efficiency of:

$$\eta_{th} = \frac{P_e}{P_{th}} = \frac{3}{15} = \frac{1}{5} = 20 \text{ percent}$$

A 25 kWe HOMER-25 version uses uranium dioxide fuel and transfers heat to six Stirling engines through potassium-filled heat pipes.

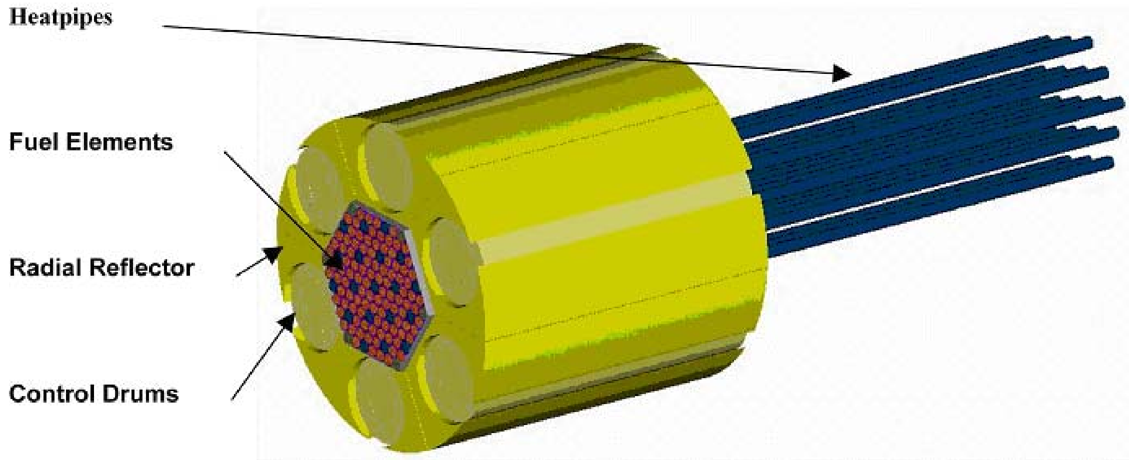

Figure 6. Heat pipe reactor HOMER-15 configuration.

The HOMER-15 reactor is a modular reactor design with an arrangement of fuel pins, heat pipes, and neutron reflectors. The mass of the reactor is shown in Table 2. There are a total of 19 heat pipes and 102 fuel pins in the core design, including 13 six-pin modules and 6 four-pin modules. Six-pin modules are located near the center and four-pin modules are located near the outside of the reactor core.

Four-pin modules, arranged around a heat pipe as shown in Fig. 7, experience higher thermal stress because of their asymmetrical arrangement. They are located near the exterior where the temperature is lowest. Fuel pin modules are arranged in a hexagonal core shape with a beryllium oxide neutron reflector pin located at each corner. The core measures 18.1 cm from one edge of the hexagon to the opposite edge.

Table 2. Mass summary for HOMER-15.

Component	Mass [kg]
Fuel pins	95.0
BeO pines	1.8
Heat pipes	9.8
Tricusps	7.9
Slats	2.3
Baffle	4.4
Radial reflector	41.5
Control drums	47.0
Support	4.7

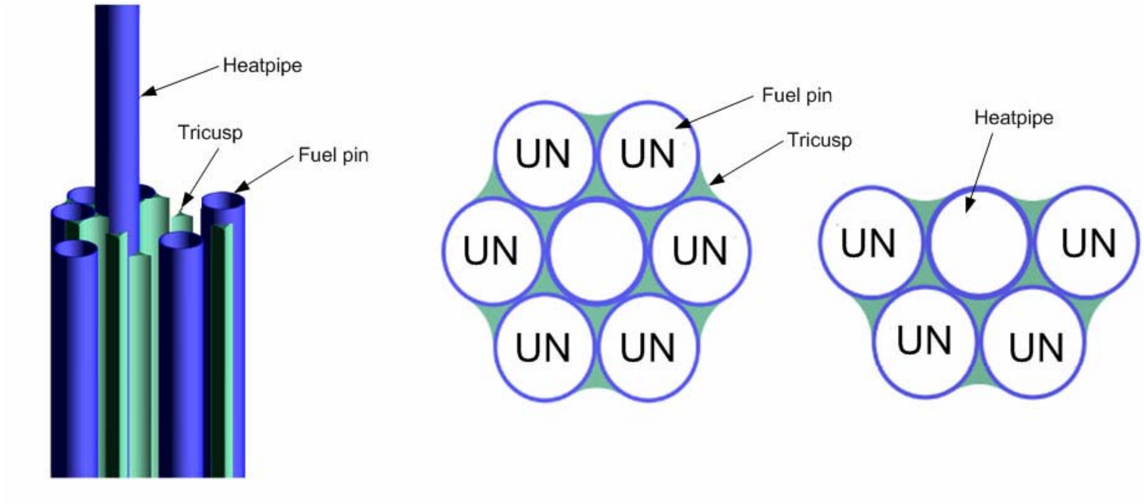

Figure 7. Cross section of four pin and six pin heat pipe modules.

2.7 HEAT PIPES AND FUEL PINS CONFIGURATION

Heat pipes are bonded to a stainless steel tri-cusps that run along the length of a fuel pin as shown. As a safety feature, the hollow tri-cusps are filled with boron carbide (B_4C) as a thermal neutron absorber. This allows the reactor to remain subcritical in the event of an accident in which the core is flooded with water such as from a leak in the reactor shielding.

Fuel pins are constructed with SS-316 with an outside diameter of 1.59 cm and thickness of 0.635 mm. Each fuel pin contains a 36 cm stack of fuel pellets contained within a stainless steel sleeve.

A 4 cm stack of BeO pellets surrounds the fuel pellets at the end of each pin. Including an end cap on each fuel pin, the total length of each fuel pin is approximately 44 cm. The fuel pellets are made of 97 weight percent enriched uranium nitride. Uranium Nitride (UN) is a high density, high thermal conductivity fuel. This results in a smaller core size with lower total mass and lower operating fuel temperatures. The stability of UN fuel is lower than uranium dioxide (UO_2). The fabricability of UN is more difficult than UO_2 and the most recently produced UN fuel in the USA was during the late 1980’s for the 100 kWe Space Reactor SP-100 radiation experiment. In the event of a cladding failure of a UN pin, there would be little effect on the thermal or neutronic characteristics of the core. In the Martian atmosphere, which is primarily carbon dioxide, this would result in surface carbonization, but UC and UN have similar densities and thermal conductivities.

The HOMER-25 is a larger scale version of the HOMER-15 reactor. The mass of HOMER-25 subsystems are listed in Table 3 and key reactor parameters are listed in Table 4.

The reactor core consists of 156 fuel pins and 61 heat pipes, arranged as shown in Fig. 4. The fuel pins and heat pipes are not bonded together in individual modules as in the HOMER-15 reactor. Instead, they are arranged in a hexagonal monolith lattice as shown in Fig. 8.

Heat pipes are located at the four corners of the hexagonal core instead of beryllium oxide reflector pins. Heat pipes in the HOMER-25 reactor use potassium instead of sodium as a working fluid. Boron carbide wire is located in the region between the fuel pins and heat pipes in the lattice as a thermal neutron absorber.

Table 3. Technical Characteristics for the HOMER-25 design.

Parameter	Value
Peak fuel temperature [K]	931.7
Average fuel temperature [K]	914.9
Peak fuel burnup	0.27 %
Average fast flux (>100 keV) [n/(cm^2/s)]	7.04×10^{12}
Average moderated flux (< 100 keV) [n/(cm^2/s)]	1.37×10^{12}
Average total flux in fuel [n/(cm^2/s)]	8.41×10^{12}
Peak fast fluence (>100 keV) [n/cm^2]	1.64×10^{21}
Average heat pipe temperature [K]	880
Boiler saturation temperature [K]	860
Stirling temperature, hot end [K]	847.8
Stirling temperature, cold end [K]	414.4
Net electrical power [kWe]	25
Stirling output power [kWe]	26.3
Reactor thermal power [kWth]	94.5
Rejected power through radiator [kWth]	67.3
Radiator temperature [K]	400
Required radiator area [m^2]	75.8

Table 4. Mass summary for HOMER-25.

Component	Mass [kg]	
Reactor (fuel, heat pipes in-core, monolith, reflector)	461.9	
Internals and controls	63.0	
Heat pipes above core and boiler	130.9	
Shield	569.2	
Reactor module subtotal		1225.0
Stirling engines	372.5	
Power management and distribution	75.0	
Cabling	37.5	

Power conversion system subtotal		485.0
Radiator	178.5	
Secondary heat transfer	60.9	
Secondary heat subtotal		239.4
Integrating superstructure		183.7
Total mass		2,133.1

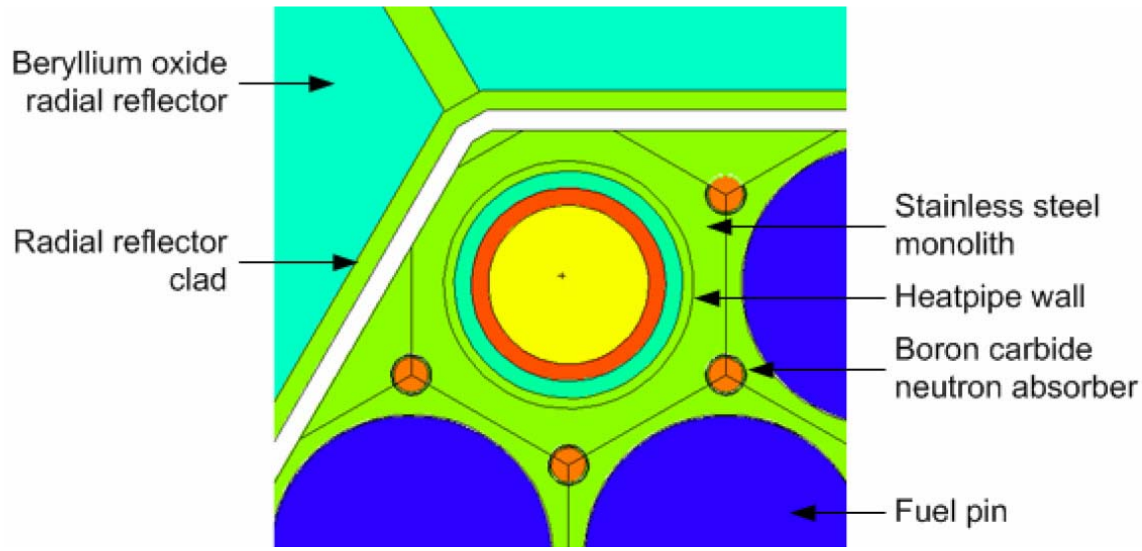

Figure 8. Fuel pins and heat pipes configuration in the HOMER-25 design.

Uranium dioxide has more design heritage than uranium nitride. UO_2 with Zircaloy cladding is used in commercial reactors and has been studied with 316 stainless steel cladding in liquid metal fast breeding reactor experiments. The Russian space program used UO_2 clad in molybdenum, but information about this is not publicly available. A domestic study of UO_2 molybdenum fuel would be required to validate its use. UN/SS and UO_2/SS are limited to clad temperatures less than approximately 973 K due to loss of creep strength in the fuel cladding.

2.8 STIRLING ENGINES

Stirling engines are desirable for space power applications since they operate at the highest efficiency of any heat engine. This decreases fuel burnup, radiation levels, and the amount of heat that must be rejected by the reactor. Heat pipes from the HOMER-15 or HOMER-25 reactor are connected to a heat exchanger that transfers heat to the heater head of the Stirling engine. The exit temperature for a stainless steel reactor is 900 K and the average temperature of the heater head is 850 K. This thermal energy is converted to mechanical energy by pistons inside the Stirling engine, which is then converted to electricity by a generator. The pistons are supported by flexure bearings in a high pressure helium working fluid.

The baseline design for HOMER-15 is a single 3 kWe Stirling engine. An alternate configuration of three 1 kWe engines, or for redundancy in case of failure, three 1.5 kWe engines could be used. In the HOMER-25 design, six Stirling engines are configured to produce 25 kWe. Only four of the six engines operate at one time, leaving two for redundancy in care of failure. This is a necessary feature since current Stirling engines technology is not suitably reliable at high temperatures.

In a single Stirling engine configuration, the unbalanced load from the single piston will cause vibration in the system. This effect can be offset by attaching a counter moving mass balance at the end of the piston. In multiple Stirling engine configurations, the engines can be arranged opposite to each other to cancel forces and angular momenta from the moving pistons.

The heat exchanger serves an important structural element. The heat pipes, reactor core, control drums, and radial reflector are suspended from the heat exchanger and the Stirling engine is supported above it. In this arrangement, the heat pipes are free to expand during the warm-up to the operating conditions.

2.9 HEAT PIPES DESIGN

The heat pipes are constructed of 316 stainless steel with the same diameter as the fuel pins, but a thickness of 0.889 mm. At one end, the evaporator section of the heat pipes in the core uses an annular wick structure, as shown in Fig. 9.

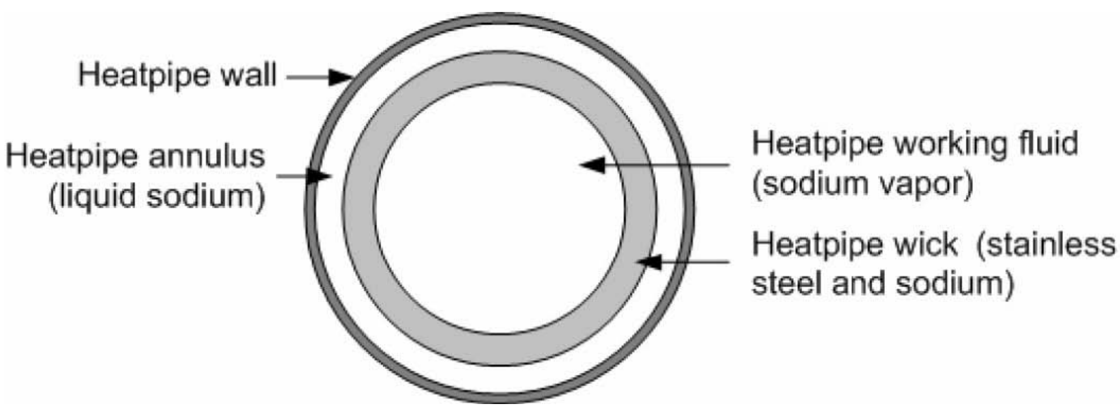

Figure 9. Evaporator region of heat pipe.

The wick is composed of stainless steel and the heat transfer fluid is sodium or potassium or reactor designs that use a sodium-potassium eutectic which is liquid at room temperature. The heat pipes pass 40 cm through the axial reactor shield. In this region, the heat pipes are insulated with a SS-316 vacuum thermos structure. The length of the heat pipes in the condenser section or sodium boiler is 20 cm. Including small axial gaps at the shield core interface and the shield-boiler interface, the total length of each heat pipe is approximately 107 cm.

Stainless steel 316 is compatible with sodium up to temperatures of 1,050 K if the oxygen content in the sodium is maintained below ~10 ppm.

2.10 MATERIAL CHOICES

The primary material for reactor components 316 stainless steel, chosen as a low cost and off the-shelf material. SS-316 also has material advantages when exposed to the Martian atmosphere, which is predominately carbon dioxide. Stainless steel is carburized by CO_2, increasing its emissivity. The CO_2 atmosphere also provides a good thermal conduction path in fuel pin and heat pipe connections. However, carburization tends to make stainless steel more brittle. The use of stainless steel structures makes it unnecessary to hermetically seal the reactor core, but dust buildup may cause problems with the internal components.

Ideally, power output could be increased by decreasing the diameter of the heat pipes and increasing the number of fuel pins per module, but this would increase the internal operating conditions of the reactor core and stainless steel is limited to use at relatively low temperatures compared to temperatures in the reactor core. Stainless steel can not be used as a structural material above 873 K due to thermal creep. The maximum allowable stress or 2/3 rupture stress for 316 stainless steel at 923 K is approximately 35 MPa for a ten year operational lifetime.

2.11 SAFETY CONSIDERATIONS

In the case of a heat pipe failure, the operating temperatures in the fuel cladding would reach 1,067 K, leading to a significant shortening of the reactor lifetime. An important design improvement would be to reduce the maximum temperature after the failure of a heat pipe to under 970 K to minimize thermal creep. Although stainless steel has several advantages in a CO_2 atmosphere, it is incompatible with CO_2 for long term exposure at temperatures above 923 K.

2.12 REACTOR CONTROL

The core reactivity is controlled by six stainless steel clad BeO cylindrical drums arranged symmetrically about the core in the radial reflectors as shown in Fig. 4. Each drum contains a 1 cm thick B_4C absorber section along a 120 degrees arc.

The drums can be rotated so that either the B_4C face or the beryllium face of the drum is oriented towards the reactor core. Each drum is independent and can be operated in sequence to provide the necessary reactivity conditions in the core.

The radial neutron reflector is composed of six beryllium oxide (BeO) sections clad in stainless steel.

A severe reduction in the strength and thermal conductivity of BeO in the reflectors and drums occurs at fluences above 2×10^{20} n/cm^2 due to radiation-induced micro cracking. Fluences of 1.2×10^{21} n/cm^2 in the HOMER-15 reactor produce more severe micro cracking below 600 K. Cracks in the BeO reflectors would allow neutrons to leak to the outside, affecting the neutron properties inside the core. There is no known solution to avoid micro cracking in BeO at fluences above $\sim1\times10^{21}$ n/cm^2 and temperatures below 900 K. Replacing the solid slabs of BeO with fine-grained BeO encased in stainless steel would prevent thermal cracking but the design lifetime of fine grained BeO is uncertain.

Below 770 K the impact of neutron irradiation fluences up to $1{\times}10^{21}$ n/cm^2 on the properties of BeO is small. Significant swelling occurs at temperatures above 900 K, requiring extra volume within the stainless steel cladding of the reflector. The proposed radial reflector operating temperature of 873 K is a high temperature for BeO.

High temperature He embrittlement in BeO from the (n, α) reaction with Be is a concern for neutron fluences greater than $1{\times}10^{21}$ n/cm^2 at temperatures above 800 K. The strength of irradiated BeO decreases rapidly at temperatures above 873 K in BeO irradiated to greater than $1{\times}10^{21}$ n/cm^2. Operation of the radial reflector below ~823 K should be suitable for the lifetime of the HOMER-15 reactor.

2.13 NEUTRON SHIELDING

Lithium hydride (LiH) has been used previously in neutron shielding technology in the ANP and SNAP space nuclear reactor programs. Of candidate shielding materials, LiH has the best neutron attenuation per unit mass due to its low density (0.775 g/ml) and high hydrogen content of 12.68 in weight percent.

Hydrogen is primarily responsible for neutron moderation in LiH. LiH has poor thermodynamic properties: low thermal conductivity and high coefficient of thermal expansion. LiH is difficult to fabricate and the only fabrication capability in the USA is at the Y12 National Security Complex in Oak Ridge, Tennessee.

At temperatures above 700 K, hydrogen dissociation is pronounced. In hot spots, a streaming path for higher energy neutrons can be created, leading to a loss of shielding effectiveness. The upper operating temperature can be increased by enclosing the LiH in a thin walled stainless steel pressure vessel. For temperatures above 800 K, the dissociation pressure and hydrogen permeation rate through stainless steel are unacceptably high. At temperatures below 600 K, radiation-induced swelling and cracking is significant. In the SP-100 reactor program LiH shield material was limited to 600 to 700 K for the final design.

Other possible candidates for shielding include lithium magnesium alloy, ZrH, TiH, and hydrogenated graphite foam.

Water shielding would be the least expensive method of shielding since there is extensive terrestrial experience with stainless steel and water. The effects of irradiation on water shielding system would be easy and inexpensive to test on Earth. One concern with water shielding is that the vapor pressure of water rises considerably as shielding temperature approaches 400 K, requiring a sturdier pressure vessel and accommodation for extra volume for water vapor. At higher temperatures, the mass of the stainless steel pressure vessel could become prohibitively large. To keep the temperature under 400 K, a potential solution is to include heat pipes bonded to the shield and connected to a radiator.

In a study by Poston, et al. [5], the amount of thermal power that would be rejected from the radial reflector into the water shield is about ~2 percent of the total reactor thermal power. An important consideration in radiator design is that a large radiator will cause greater neutron scattering, increasing the radiation dose to humans. The major drawback of using water shielding is mass. Future missions would benefit from the discovery of indigenous water to supply resources for shielding and other human requirements.

2.14 REACTOR SITING

The reactor will need to be located at an appropriate distance from human habitation and equipment to provide another level of safety. Radiation dose drops approximately by the square of the distance away from the reactor, however, increasing the distance from the reactor increases the mass of the cabling required to transmit electricity to where it is needed. An optimization between shielding mass and cabling mass would need to be determined.

Locating the reactor at a distance could also take advantage of the lunar topography. Any regolith or structures between the reactor and human habitation is beneficial for blocking radiation. The reactor could be located in a crater or on the opposite side of a ridge to provide extra safety.

To protect humans during setup, the location of the reactor could be done by moving the reactor with a vehicle or, if the reactor is launched separately from human habitation modules, a small rover on the reactor lander could transport cabling from the reactor to the habitation. A rover carrying cables would be less massive than a rover for the full reactor. A disadvantage to locating the reactor away from humans is that it becomes infeasible to transport reactor waste heat to provide habitation heat.

In locations where the topography does not have any useful shielding features, burying the reactor in a hole is an option for shielding. The depth of the hole is relative to the distance that the reactor can be located from humans. Poston found that to keep the human effective dose limit under 5 rem per year, the required hole depth, *i.e.*, depth of the bottom of the reactor, is approximately 1 m for a reactor 160 m away and 2 m for a reactor 40 m away.

Scattered neutrons irradiating the Stirling engine become a problem as the depth of the hole increases. At approximately 1.5 m, the fast neutron fluence in the Stirling alternators is minimized. For a deeper or shallower hole, the fluence increases, requiring that the Stirling engines be surrounded by thicker shielding or located at a further distance from the reactor. Either case adds system mass, so there is an optimal arrangement for shielding mass, Stirling engine configuration, and depth at which the reactor is buried. An added benefit to burying the reactor is shielding it from micro meteorites.

One important point that is not covered in regolith shielding discussion is the mass of equipment needed for burying the reactor. There are two approaches to burying the reactor: manual digging and robotic digging. The gloves on space suits used on the moon in the Apollo program were not comfortable nor suitable for extended manual labor. On Apollo 17 Astronauts Eugene Cernan and Harrison Schmitt experienced blistered knuckles and fatigued muscles from using field geology tools on their three day stay on the moon. Manually digging would require the astronauts to dig in the radiation environment in the vicinity of the reactor or to dig a hole first and have the reactor moved automatically into the hole.

An alternative to manually digging is to have a machine dig the hole for the reactor. Though using lunar regolith would decrease shielding mass, but the mass of a machine for burying the reactor would add extra launch mass. Both of these options are less preferable than finding a suitable indigenous topography that can be used. Machines used for burying the reactor could also be utilized for protecting human habitats from the ambient radiation environment. Mars and the moon do not have magnetic fields to protect from solar or cosmic radiation, and the moon lacks an atmosphere that would provide some protection. For protection, humans will be required to live in environments that have radiation shielding as part of the structure

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