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SPACE MOLTEN SALT REACTOR CONCEPT FOR NUCLEAR ELECTRIC PROPULSION AND SURFACE POWER

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Students at The Ohio State University working under the NASA Steckler Grant sought to investigate how molten salt reactors with fissile material dissolved in a liquid fuel medium can be applied to space applications. Molten salt reactors of this kind, built for non-space applications, have demonstrated high power densities, high temperature operation without pressurization, high fuel burn up and other characteristics that are ideal for space fission systems. However, little research has been published on the application of molten salt reactor technology to space fission systems. This paper presents a conceptual design of the Space Molten Salt Reactor (SMSR), which utilizes molten salt reactor technology for Nuclear Electric Propulsion (NEP) and surface power at the 100 kWe to 15 MWe level. Central to the SMSR design is a liquid mixture of LiF, BeF_2 and highly enriched $U^{235}F4$ that acts as both fuel and core coolant. In brief, some of the positive characteristics of the SMSR are compact size, simplified core design, high fuel burn up percentages, proliferation resistant features, passive safety mechanisms, a considerable body of previous research, and the possibility for flexible mission architecture.

Keywords: Nuclear Electric Propulsion, Surface Power, Molten Salt, Liquid Fuel

1. INTRODUCTION

The exploration and colonization of space necessitates power systems with low specific masses (kg/kW). The need for low specific masses is driven by the high cost per kilogram for putting an object into orbit and the much higher cost of putting an object beyond low earth orbit. In addition, power systems that are utilized for propulsion need to maintain low specific masses to achieve desirable performance. Nuclear fission systems perform well as low specific mass power systems because of their ability to utilize fuel with extreme energy densities. The National Aeronautics and Space Administration Authorization Act of 2010 instructs NASA to make investments, technologies, and capabilities relating to in-space power, propulsion, and energy systems to allow for capabilities beyond near Earth space. For this, nuclear fission systems are a prime candidate technology.

This paper presents a conceptual design of the Space Molten Salt Reactor (SMSR). The SMSR is a possible implementation of concepts and technologies developed for the terrestrial based molten salt reactor to applications relevant to space exploration and colonization. Central to this approach is a circulating liquid fuel in the form of a molten salt. This approach not only shows promise for space applications, but it also has the potential, if developed, to produce technologies with tremendous terrestrial benefit. The unique nature of the SMSR has been used to address issues that have traditionally been problematic for space fission systems such as fuel lifetime. Applications of the SMSR concept include compact, high-efficiency power fission systems for surface power and NEP with power levels ranging approximately from 100kWe to 15MWe.

NOMENCLATURE

ACTL	Auxiliary Cooling and Thawing Loop
C_f/C	Carbon Fiber in a Carbon Matrix
NEP	Nuclear Electric Propulsion
SiC_f/SiC	Silicon Carbide fiber in a Silicon Carbide Matrix
SMSR	Space Molten Salt Reactor

An important distinction to make is the difference between molten salt reactors that utilize fissile material dissolved in a molten salt as both fuel and coolant, and a molten salt reactor that utilize molten salts only as a coolant. In the context of this report, molten salt reactors refer to those reactors that utilize a molten salt medium as fuel.

1.1 History of Molten Salt Reactor Concept

Little research has been conducted on the use of molten salt reactor technology for space applications, but the MSR concept has been developed since the early 1950's. As a result, a body of relevant research exists upon which the SMSR can be built. Research into MSRs started as a part of a U.S. military effort to build an ultra-lightweight reactor for its Aircraft Nuclear Propulsion Program. The U.S. military wanted a reactor small enough to be put on an airplane that could stay airborne for several weeks. In this program, a land-based prototype 2.5 MWt reactor was built and tested in 1954. Designs were made for a prototype 60 MWt reactor (Fraas 1956). The program was canceled in favor of ICBM technology.

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Work continued on MSRs at Oak Ridge National Lab. The focus shifted from military to civilian applications. Specifically, it was seen that a MSR could efficiently breed U-233 from Th-232 with a thermal neutron spectrum. In this program, a 7.4 MWt reactor was built in 1964 and it ran for 5 years. In this time, large amounts of data on materials, behavior of fission products, handing of fuel, and many other subjects were collected. The project ended in the late 1970's when the Atomic Energy Commission decided to put its available resources into fast breeder reactor research. It has been speculated that this outcome was in large part driven by political rather than technical concerns, with the political concerns arising because the MSR program was concentrated at ORNL with almost no participation in the program by other national labs (MacPherson 1985).

MSR research has continued and today there is renewed interest in the concept. Notable work includes the MSR being selected as an initial Generation IV reactor system and research at Oak Ridge National Lab utilizing MSRs to burn used fuel from light water reactors (Forsberg 2007). In addition, very high temperature molten salt compatible materials research has been conducted for fusion reactors that intend to use molten salts as coolants.

The work in the programs described above has produced a considerable amount of knowledge and technical data that has been very useful in the conceptual development of the SMSR. By utilizing this information, the SMSR can be unique amongst most space reactors while maintaining a high technological readiness level with little space specific development.

2. DESCRIPTION OF THE SMSR

The SMSR fissile material is dissolved in a molten salt. Specifically, the configuration presented in this report studies a mixture of LiF-BeF2-UF4. The fuel is constantly circulating through the reactor core and other reactor systems, such as the heat exchanger. The core of the SMSR is almost entirely free of internal structure and a nearly homogeneous liquid material entirely fills the interior cavity of the vessel. In Fig. 1, a CAD model of the SMSR with a CFD flow visualization is presented, and in Fig. 2, a MCNPX Visual Editor generated cross section is shown. Important properties and dimensions of the SMSR are presented in Table 1.

In a traditional solid fuel space reactor, solid fuel is placed in the core, heat is generated in the fuel via fission, and that heat is transferred to a coolant that is also inside the core. This establishes a number of contradictory goals for a space reactor. For example, to minimize shielding mass and the mass of the reactor vessel, it is desirable to have a small core volume; but for optimal heat transfer, a high surface area to volume ratio is desired for the solid fuel, thus increasing the size of the core. As another example, non-fissile neutron absorbing structures internal to the reactor core are detrimental to maximizing fuel

Fig. 1 From right to left: A CAD model of the SMSR's vessel, cutaway model, CFD flow visualization with red indicating areas of faster flow and blue indicating areas of slower flow.

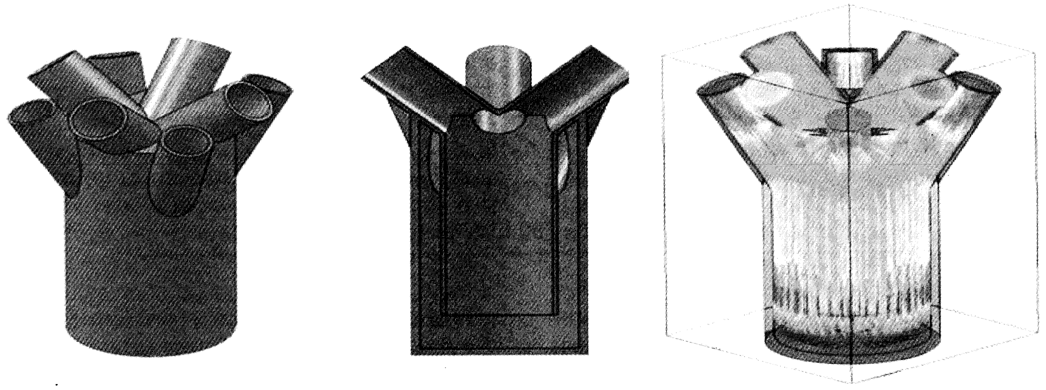


Fig. 2 Cross section of the SMSR generated in MCNPX Visual Editor with colored labels. The shield is representative of a shadow shield that might be used for NEP. For surface power, the reactor would likely have a different shield and/or be buried.

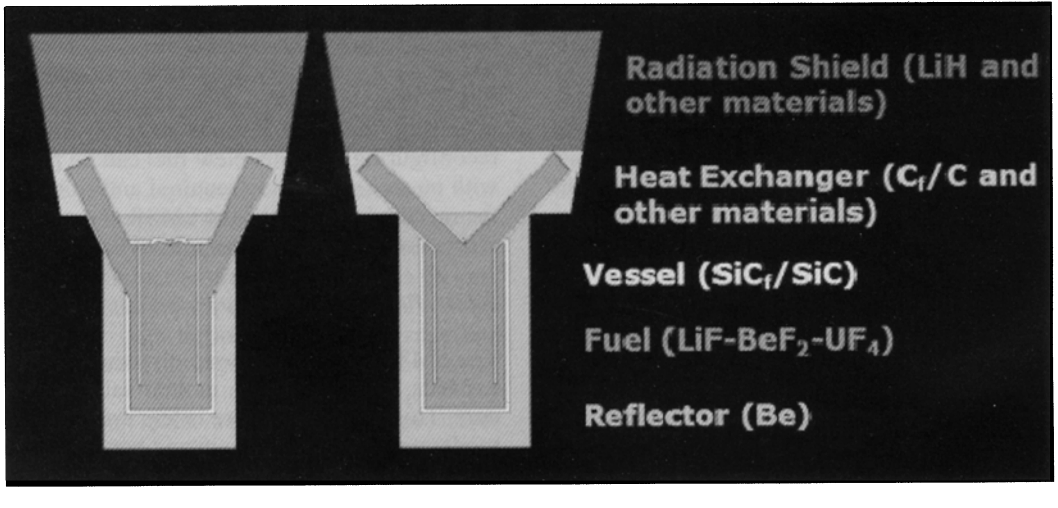


TABLE 1: *Characteristics of the SMSR.*

SMSR large configuration with SiC_f/SiC vessel material	
Core Dia X Length (cm)	38 X 74
Reflector Dia X Length (cm)	56 X 100
Vessel mass (kg)	76.4
Reflector mass (kg)	104.5
Mass of fuel to fill core (kg)	368.7
keff, BOL, warm	1.1447
keff, BOL, warm no reflector	0.7308
Possible power range	100kWe to 15MWe
SMSR Small configuration with SiC_f/SiC vessel material	
Core Dia X Length (cm)	34 X 54
Reflector Dia X Length (cm)	54 X 76
Vessel mass (kg)	44.5
Reflector mass (kg)	84.3
Mass of fuel to fill core (kg)	178.4
keff, BOL, warm	1.0617
keff, BOL, warm no reflector	0.5970
Possible power range	100kWe to 7MWe
SMSR Large configuration with TZM (an Mo alloy) vessel material	
Core Dia X Length (cm)	38 X 74
Reflector Dia X Length (cm)	56 X 100
Vessel mass (kg)	228.9
Reflector mass (kg)	104.5
Mass of fuel to fill core (kg)	368.7
keff, BOL, warm	1.0512
keff, BOL, warm no reflector	0.7567
Possible power range	100 kWe to 15MWe

burn up. For example, fuel clad is a non-fissile neutron absorbing internal structure, a standard structure for a solid fuel reactor. The SMSR avoids this difficult optimization problem by moving the process of heat transfer to outside the core. In the SMSR, heat is generated in the core, and then the fuel flows out of the core into a heat exchanger to be cooled. No major cooling of a differential volume of fuel occurs until the fuel volume leaves the core. This allows the core to be mainly optimized for neutronics and the heat exchanger for thermal-hydraulics.

2.1 Operation and Power Conversion

Figure 3 shows a schematic diagram of the SMSR. The heat exchanger is put behind a radiation shield because the molten salt fuel is highly radioactive and can still fission outside the core. When the reactor has depleted its fuel, new fuel can be added and old fuel can be removed with a path not depicted in Fig. 3.

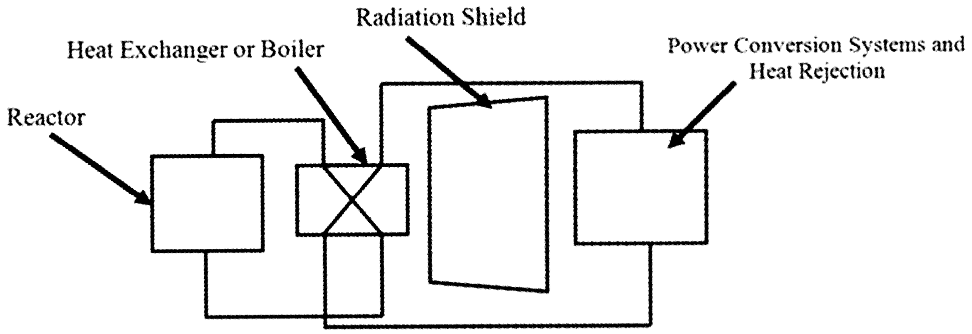
Like many space reactors, active control of the SMSR is achieved by changing the amount of neutrons reflected back into the core from the reflectors. This may be achieved by B4C control drums, liquid Li-6 control tubes, or by changing the geometry of the reflectors to leak more neutrons to space. In this report, the SMSR reflectors are modeled as a homogeneous cylinder of beryllium without any focus on the specific mechanisms for the active control.

Different configurations of the SMSR can run at a multitude of powers given that it has an appropriate heat removal system for operation at that power. Disregarding issues relating to precursor nuclei that will be discussed later, the size of the SMSR's core is largely not a function of the power at which the SMSR operates. Also, unlike traditional solid space reactors, refueling the SMSR does not require dismantling and reconfiguring the core. New fuel can be pumped into the core with no reconfiguration required and from a position far from the reactor. In principle, the SMSR can run almost indefinitely if it has an inexhaustible supply of liquid fuel.

2.1.1 Passive Controls

The SMSR fuel expands rapidly when heated. When the fuel expands, portions of the molten salt are pushed outside the core. This means that there is less uranium in the core and less moderation from the lithium and beryllium. The end result is a very large negative temperature reactivity feedback of approxi-

Fig. 3 SMSR general NEP layout.



mately 1.5-1.8 Cents/K. In the case of severe events, where the fuel is heated faster than thermal expansion of the liquid fuel can act to shut down the reactor, liquid fuel may boil. Boiling will quickly place the reactor in a subcritical state. Unlike the case for a solid fuel reactor, such a large transient overpower is not a disastrous event, since there is not any solid fuel to be damaged. With the proper thermal hydraulic design and spatial power peaking factor, it is possible to ensure that fuel boiling occurs before any component of the reactor is damaged. In this case, after the reactor cools down and the fuel condenses back to a liquid, normal operation can be reinitiated. In addition to negative reactivity feedback that is caused by the fuel expanding when heated, Doppler broadening in the SMSR's uranium causes a smaller but still significant reactivity feedback coefficient on the scale of 0.10 Cents/K.

2.1.2 Gas removal

Noble gases can be removed continuously from the SMSR by sparging the fuel with helium. By removing noble gases, notable neutron poisons like Xe-135 and Kr-83 are also removed. While the removal of these neutron poisons is not as important as it would be a in a thermal reactor, their removal assists in achieving a high burn up in the SMSR. In addition, because these radionuclides are produced in such large numbers, it is necessary to remove them in a controlled fashion.

Pumps have been designed and tested that remove noble gases from molten salt fuels (Smith 1970). These pumps rely largely on centrifugal forces to separate the gas from the liquid; and in principle, a similar design could be used in a low gravity or microgravity environment. In addition, there are a number of designs for microgravity bubble separators. The SP-100 reactor design concept used a gas/liquid separator that used centrifugal acceleration, caused by diverting flow, to push its lithium coolant to the outside of a pipe and produce a bubble of helium along the pipe's center. Conceptually, this method can be employed in the SMSR for its molten fuel.

2.1.3 Power Cycle

A potassium Rankine and a helium Brayton cycle were both considered for power conversion in the SMSR. A potassium Rankine cycle would incorporate a boiler to transfer heat from the hot molten salt-fuel mixture to the potassium. This process produces superheated potassium vapor for use in a multi-stage turbine. A Brayton cycle goes through no phase change and hence uses only simple heat exchangers.

A concern for molten salt reactors is the amount of precursor nuclei decay outside the core, and how this affects the delayed neutron fraction. The lower the delayed neutron fraction, the more difficult the reactor becomes to control. To maximize the amount of delayed neutrons, it is necessary to maximize the time the fuel stays in the core and minimize the time that it is outside of the core. For a core of a given volume, this becomes difficult at higher powers because fluid must flow quickly to transport heat from the core to the heat exchanger. A point kinetics model of a flowing liquid fuel is described in Engel (1980) with a delay differential equation.

For the large configuration of the SMSR, the issue of delayed neutrons decaying out of the core is not a concern for reactor powers up to about 30 MWt. At higher powers, the fraction of delayed neutrons that are produced by decay within the core becomes small. This concern is one of the major factors that limits the maximum power at which a SMSR type reactor can operate. Preliminary calculations that consider apotassium Rankine and a Brayton cycle, utilizing a secondary loop of liquid lithium with a tube and shell heat exchanger at the 60 MWt level, indicate that a delayed neutron fraction of 0.002 can be maintained. A delayed neutron fraction of 0.002 is similar to that of a Pu-239 system. To operate at powers much higher than 60 MWt, the SMSR design would have to be modified to increase the volume of its core, move a portion of the heat exchanger inside the core, or decrease the time per pass that the fuel spends in the heat exchanger.

Control of the reactor is improved when the time that the fuel is spent out of the core per pass through the reactor core is minimized. Therefore, it is imperative to have an efficient heat exchanger that can quickly transfer heat from the fuel to the power conversion system. In addition, it is important to have a spatially compact heat exchanger to minimize system mass. This is not only because of the direct effect of the mass of the heat exchanger on the system mass, but also because a larger heat exchanger requires a shield of greater mass. A critical dimension for the heat exchangers is its thickness relative to the long axis of the spacecraft. Since the heat exchanger is placed between the reactor core and the shield (as shown in Figure 3), an axially thicker heat exchanger displaces the conic section of the shield further from the focal point of the shield. This increases the transverse dimensions of the shield and the total shield mass that is necessary for the shield to subtend the same solid angle.

An investigation into the heat exchanger that would be needed for a potassium Rankine or a Brayton cycle power conversion system was conducted for the 60MWt power level. The analysis considered a counter-flowing, coiled tube and shell heat exchanger. Figure 4 shows a conceptual model of the heat exchanger. Because of the low thermal conductivity of molten salts and helium, a direct fuel to gas heat exchanger would not return fuel quickly enough back to the core. To maintain a delayed neutron fraction equivalent to a Pu-239

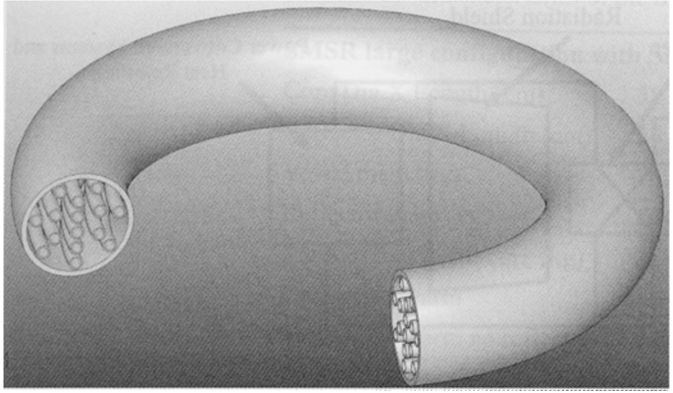


Fig. 4 Potassium boiler and lithium heat exchanger cutaway model.

system, an intermediary liquid lithium metal was investigated instead.

In the analysis, the potassium boiler and lithium heat exchanger were found to have an uncoiled length of 7.6 m and 7.17 m respectively. When coiled, the heat exchanger adds about 0.4 m to the total length of the reactor in the large configuration. Both designs were able to return the fuel back to the core quickly enough to maintain a delayed neutron fraction similar to that of a Pu-239 system, and required far less than 1% of total electrical output for pumping. The designs of the heat exchangers are not fully optimized and particularly conservative estimations were made for the potassium Rankine boiler because of the difficulties of modeling two-phase flow in microgravity and low gravity situations.

No configuration of the fuel to gas tube and shell heat exchanger was found to be able to return fuel back to the core quickly enough to maintain a delayed neutron fraction similar to that of a Pu-239 system. While a heat exchanger that transfers heat quickly enough to the power conversion system likely exists, it would require much more pumping power than the other designs, which use fluid with higher thermal conductivity. At lower powers it becomes much more feasible that a fuel to gas heat exchanger would be able to maintain a suitable delayed neutron fraction, because at lower powers the fuel can have a longer residency time in the core and have more of its precursor nuclei decay in the core.

Carbon fiber in a carbon matrix (C_f/C) as a heat exchanger material is a particularly appealing option for the SMSR. C_f/C has a high thermal conductivity in the range of 690 W/m*K and low density, much lower than metals at around 2.1 g/cm^3 (Golecki 1998). Specifically in molten salt reactors, carbon has a very low solubility in molten salts and carbon based materials have good corrosion resistance in molten salts. Noble metals present in the molten fuel are less likely to plate out on carbon surfaces than they are on metal surfaces (Forsberg 2004). In addition, a heat exchanger made of carbon materials may assist in shielding by scattering and slowing down neutrons.

2.2 Fuel

There exist many possible molten salts for use in the SMSR. The properties of the molten salt used in this report are categorized in Table 2. The salt mixture was chosen for its high uranium density, favorable neutronics properties, relatively low melting point, and abundance of previous research on related salts. The salt mixture that was chosen is not optimized for all missions. The mixture that was chosen contains a larger uranium nuclei percentage than the salts that have been chosen for other molten salt reactors, so that the SMSR reactor system can be small compared to other space fission systems. The lithium is has a reduced Li-6 percentage, since Li-6 is a thermal neutron poison and as such can increase the minimum size and decrease the burn up in even an epithermal-fast spectrum reactor. In general molten salts have very low vapor pressures and high boiling points; so high temperature, low pressure operation is possible (Forsberg 2004).

Operation around 1350 K was chosen for the SMSR, because SiCf/SiC composite could be used as a structural material at these temperatures, and minimal pressurization of the fuel would be needed to prevent boiling and cavitation in the pumps. If TZM would be used as vessel material, operation up to 1700 K would be possible with proper pressurization of the fuel.

2.3 Materials

SiC$_f$/SiC is a promising structural material for the SMSR, and much of the analysis provided assumes the reactor's structure is this material. It has been speculated that SiC$_f$/SiC composites are capable of operating in space fission systems at tempera-

TABLE 2: *Fuel Mixture Properties.*

Property	Value	Source of Estimation or Comment
Chemical Composition	$LiF\text{-}BeF_2\text{-}UF_4$ (70-5-25)	
Melting Point (K)	773	Weaver (1960)
Boiling Point at 1 atmosphere(K)	~1670	Forsberg (2002), Precise value not established
Density at 1100°C (g/cm^3)	4.05	Cantor (1963)
Specific Heat Liquid (J/(g*K))	1.0	Cantor (1963)
Specific Heat Solid (J/(g*K))	$0.35 + 5.3*10^{-4}*T(K)$	Cantor (1963)
Thermal Conductivity (W/(m*K))	0.47	Cornwell (1971)
Heat of fusion (J/g)	164.61	Cantor (1963)
Coefficient of Thermal Expansion (g/(cm^3*K))	$8.11*10^{-4}$	Cantor (1963)
U-235 Enrichment	97%	Similar to the SP-100 (Angelo 1985)
Li-7 Enrichment	99.9%	Natural lithium is ~92.4% Li-7

tures over 1300 K (Busby 2007). SiC_f/SiC is very lightweight with a density of 2.55–3.25 g/cm^3 (Zinkle 1998). In addition SiC_f/SiC has been irradiated in a fluence of 1.2x10^{26} n/m^2 (>0.1 MeV) at 1020 K and was found to maintain its physical strength (Ozawa 2007). Testing needs to be conducted regarding its performance in a high temperature molten salt environment. If SiCf/SiC is not appropriate for use in a high temperature molten salt environment, then a diamond-like carbon coating may be used to greatly increase its corrosion resistance. This coating has been tested in other highly corrosive industrial settings and it will likely be appropriate for use with molten salts. In addition, SiC with CVD diamond coatings has been tested in fast fluencies and at high temperatures (Yano 2008). If needed, these coatings should not be cost prohibitive. At present, diamonds produced through chemical vapor deposition can be purchased for \$0.42 per mm^3.

A few other materials could be used in the SMSR. The first is the refractory alloy TZM. TZM is a molybdenum-based alloy that has been found to be compatible with molten salt fuels at 1370 K (Koger 1969). It has been predicted to be able to operate at up to 1700 K in space fission systems. It is much denser than SiC_f/SiC with a density of 10.16 g/cm^3 (El-Genk 2005). Its biggest disadvantage in comparison to SiC_f/SiC is its poor neutronics properties. TZM has a larger cross section for neutron absorption than SiC_f/SiC. The results of how this will impact the operation of the SMSR is discussed in the section titled "Burn Up".

Another potential materials for use in the SMSR are ODS Steels. ODS Steels have oxide additives like titania (Ti_2O_3) and yttria (Y_2O_3). These additives block dislocations and help the material resist irradiation swelling. ODS Steels have several advantages over the refractory alloys: they are lighter, irradiation resistant, more widely available, and have high strength (El-Genk 2005). However, they have not been tested at higher temperatures and are predicted to not operate at temperatures as high as refractory alloys. El-Genk (2005) states, Inconel MA-ODS754, Incoloy MA-ODS956, and Incoloy MA-ODS957 appear to be promising alternative structural materials for potential use in space nuclear reactors up to a temperature of 1373K (1100 °C), and possibly higher. Additionally, irradiation tests have shown that fast neutron fluences of 10^{27} n/m^2 have not caused any irradiation swelling or embrittlement (El-Genk 2005). Additional testing of ODS Steels, especially in a molten salt environment, needs to be performed.

2.4 Burn Up

In a solid fuel reactor, the physical limit of fuel burn up is usually determined by fuel-clad life-time. In a molten salt reactor, no such limit exists because the fuel has no clad or organized structure to be impacted by the effects of burn up (Forsberg 2006). This allows a molten salt reactor to achieve very high burn up percentages. The maximum burn up in molten salt reactors is determined by the solubility limits of fission products in the fuel and the necessity of maintaining enough fissile material within the reactor core for the core to be critical.

The SMSR has a very high maximum burn up. Table 3 how the maximum burn up of the large and small configuration of the SMSR compared to other space fission systems. The burn up is large because the core is almost entirely free from internal structure so few neutrons are lost to parasitic absorptions. Like most small reactors, neutron leakage is quite considerable and thus burn up is increased considerably by increasing the thickness of the reflector.

TABLE 3: *Burnup Percentages for Various Reactors.*

Reactor	Atom Burn Up (%)
SAFE 400 (Poston 2002)	1.7
SP-100 (Angelo 1985)	3.6
SPR-8 (Walter 1985)	5.0
SPR-6 (Angelo 1985)	3.3
SMSR, SiC_f/SiC , Small Configuration	9.2
SMSR, TZM, Large Configuration	7.8
SMSR, SICf/SIC, Large Configuration	25.3

Some of the advantages of high burn up are fuel cost savings, mass savings, and proliferation resistance. Multi megawatt space fission systems with low burn ups often call for more than a thousand kilograms of weapons grade uranium (Angelo 1985). This is more than enough uranium to make 40 nuclear weapons, as per the IAEA definition of a significant quantity. Regarding fuel costs, at present, 1 kg of 97% enriched uranium costs between \$50,000 and \$60,000 as calculated using spot prices from UxC for uranium ore, conversion and separation work units. This does not include the costs for handling and regulating special nuclear materials. While this is not an insurmountable cost for even large solid fuel multi megawatt space fission systems that requires a thousand kilograms of uranium, there could be a notable reduction in system cost, due to the smaller fuel mass of the SMSR, especially if the price of uranium ore increases in the future.

A number of processes exist to cleanse a molten salt fuel of fission products and maintain a high concentration of fissile material in the molten salt. These processes were studied as a part of the molten salt reactor program at ORNL (Scott 1966). If these processes were implemented, they could greatly increase maximum burn up, although preliminary calculations indicate that these systems are not advantageous from a mass saving stand point and thus are not elaborated upon in this report.

2.5 Start Up

Before the SMSR starts its normal operation, it is necessary to melt the fuel. For the SMSR, this process requires several mega-joules of heat in order to both heat and melt the fuel. It has been speculated that a molten salt reactor in space can melt its fuel with heat generated by fissions in the fuel when it is in a solid state (Patton 2002). This can be accomplished either by bringing the reactor to a low power critical state or by utilizing sub-critical multiplication when the reactor is in cold shutdown.

While this approach is potentially difficult to develop, the problems to be overcome are similar to those investigated in thawing lithium coolant in the SP-100. Both cases deal with using fission heat to thaw a liquid that expands when melted. Also, for parts of the system, the frozen liquid may be far away from the reactor core, and hence the source of heat energy. Methods for melting lithium in the SP-100 were well designed, and preliminary tests were carried out (Choe 1993). These methods relied upon an Auxiliary Cooling and Thawing Loop (ACTL) that uses a coolant (like He) that is not solid at cold shutdown (Kirpich 1989). A similar method could be used in the SMSR with the addition of a loop that carries heat away from the core to other reactor systems (such as heat exchangers and pumps) that require thawing.

Another option is to melt the fuel with electrical heating. This approach requires less complex development and has a safety advantage that will be covered in the "Mission Architecture" section of this paper. Table 4 lists the energy required to heat the fuel from zero Kelvin and melt enough fuel to fill the core of the SMSR. Also, Table 4 presents the mass of energy storage systems, either in the form of NiH batteries or advanced fuel cells, that would be necessary to store the energy required. The overall mass of a system to thaw the fuel would be larger.

2.6 Shielding

Generating meaningful data on shielding mass for a conceptual design such as the SMSR is difficult without a comprehensive description of a specific mission. A number of factors, such as how thoroughly people and electronics are shielded from cosmic radiation, specific dimensions of a NEP vessel, and the availability of in-situ shielding for surface power, greatly affect shielding mass and shape. The SMSR is presented in sufficient detail to observe two important characteristics that will favorably reduce the amount of shielding required. The first of these is the small outer diameter of the SMSR. The small diameter is especially pronounced at the 15MWe level. The other factor that minimizes shielding in the SMSR is the moderation that is attributable to low Z nuclei which are present in the core. Although the SMSR operates with an epithermal-fast spectrum, the spectrum is less energetic than the neutron spectrum for a solid fuel reactor with a core made of high Z metals. Since the neutron spectrum is softened by the presence of the low Z nuclei within the core, the shielding materials will have higher scattering and absorption cross sections and will consequently be better able to shield neutrons.

2.7 Mission Architectures

Liquids can be pumped through pipes, put in a container of any shape, and mixed. In the SMSR, this could potentially allow for the easy transport of fuel that is separate from the reactor. This design feature has many implications. From a launch safety stand point, it is very advantageous to have the ability to send the fuel up in a vessel, that is separate from the reactor, and that has as its main design criteria that is stores the fuel in a manner such that the container remains sub-critical and intact under all possible conditions. In addition, the ability to transport the fuel separate from the reactor has been cited as a property that assists with security (Poston 2002). This is because it allows the fuel to be produced in facilities with the security to handle special nuclear materials, while the reactor and other equipment can be built and tested in other facilities that are less secure.

In addition, the liquid nature of the fuel allows the SMSR to more easily be refueled in space. In a solid fuel reactor with fuel pins or rods, consideration has to be given to where new fuel is placed and some used fuel elements might be need to be shuffled to new locations in a core for optimum fuel utilization. This process could be very difficult to perform in space. Refueling in the SMSR is much simpler. Any quantity of old fuel can be removed from the core and replaced with new fuel. It is also possible that new fuel could be added far away from the reactor in a low radiation environment. Since fuel can be added in any amount, it could be possible to refuel a reactor over a long period of time with small amounts of uranium added, continuously. An example of this would be a long-term lunar or Martian outpost that receives less than a significant quantity (25 kg) of uranium at a time after the reactor has been installed and initially fueled, thus reducing concerns of proliferation.

3. TERRESTRIAL BENEFIT

Development of the SMSR could result in spin-off technology for terrestrial nuclear reactors. For example, high temperature reactors are thermodynamically more efficient than traditional light water reactors, so further development of the SMSR would improve Earth-based energy systems for electrical power production. In addition, a utility reactor that operated at temperatures similar to the SMSR could be used for hydrogen fuel production. Materials research and testing of C_f/C, SiC_f/SiC materials and diamond coating technologies would provide materials capable of working in a very high temperature environment.

Another benefit of the SMSR is that it will act as a further demonstration of molten salt technology that may eventually lead towards thorium fueled MSRs for terrestrial power generation. Thorium is an alternative nuclear fuel that is roughly 4 times as abundant as uranium. MSRs' ability to effectively utilize abundant fuel may allow them to be used to address the long term energy needs of mankind (Juhasz 2009).

4. CONCULUSION

The SMSR is a conceptual space fission system that applies molten salt reactor technology to space applications in the 100 kWe to 15 MWe range. It utilizes a liquid fuel consisting of a mix of LiF, BeF2 and UF4. In brief, some of its unique features are listed below:

1. Very high burn up percentages made possible by a lack of internal structure and continuous removal of Xe-135 and Kr-83.
2. A simple, compact core with a small outer diameter which assists in minimizing shielding mass.
3. A considerable body of relevant previous research from

TABLE 4: *Energy to Melt Fuel.*

Configuration	Energy Required (MJ)	Mass Of NiH Batteries Needed* (kg)	Mass of Advanced Fuel Cells Needed** (kg)
Large Configuration	156.9	581.3	87.2
Small Configuration	87.41	359.8	48.6

*NiH batteries are assumed to have a specific energy of 0.27 MJ/Kg
**Advanced fuel cells are assumed to have a specific energy of 1.8 MJ/Kg

programs such as the Aircraft Reactor experiment, the Molten Salt Reactor Experiment, and recent material information from fusion research that seeks to use molten salts as a coolant.

4. Very strong negative temperature reactivity coefficients on the scale of -1.6 Cents/K. This is largely caused by the expansion of fuel.
5. Due to the flexibility of a liquid fuel, mission architectures can be formulated with the SMSR that address concerns of proliferation and safety. In addition, because of the high burn up, less fuel is required for the SMSR than for solid fueled reactors, which assists further in minimizing proliferation and safety concerns.

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