

Development of Molten Salt Reactor Technology for Space

Undergraduate Honors Thesis

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By Michael Eades

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Abstract

Nuclear reactors are an appealing energy technology for space applications because of their ability to supply large amounts of power over extended periods of time regardless of the proximity to the sun. Specific space applications ideal for nuclear reactors include nuclear electric propulsion for fast manned travel to Mars or surface power for long term human settlements on the Moon or Mars. A unique subclass of molten salt reactors (designated fuel-in-salt reactors) utilizes fissile material dissolved in a molten salt as an alternative to solid nuclear fuels. Initial work at The Ohio State University funded through the NASA Steckler Space Grant on fuel-in-salt reactors for space applications indicates favorable characteristics such as high power densities, high fuel burn up percentages, and high temperature operation. However, little research has been done on the application of fuel-in-salt reactor technology to space applications such as nuclear electric propulsion and surface power and the reactors are not as well understood as solid fuel reactors. A central part of the continuing research is to determine and understand the unique design considerations of molten salt reactors. Some methods employed in this work include Brayton cycle analyses, reactor dynamics, and fuel salt chemistry modeling using CALPHAD methods. With this work, the general space fuel-in-salt reactors' design space has been narrowed and figures of merit for key systems have been identified. Key relations that have been derived included relating to hottest temperature in the power conversion cycle to total system mass, and how the rate the fuel effects circulates control parameters among others. This work will aid in the continued development of space fuel-in-salt reactors. The long term goal of the work is to aid in extending mankind's reach into the space.

Acknowledgments

I would like to thank Dr. Thomas Blue for giving me such a wonderful opportunity to pursue research that interest me and has led to the many experiences that have shaped me as a young researcher. It was all started with the email sent out by Dr. Blue late December of 2009 looking for undergraduate students for the Steckler Project. If it were not for that I would have not had a chance to participate in formative experiences such as traveling to conferences, having a role in proposal writing, or frantically putting together a presentation when given 20 hour notice that Kirk Sorenson, the CEO of FliBe energy, was coming to OSU. Also I would thank all the other professors involved in the Steckler project. There continued assistance in deeply appreciated. Dr. Sun, Dr. Denning, Dr Windl and others have all contributed to my education in ways that classroom instruction cannot. I would like to give a special thanks to Justin Flanders who's work has been instrumental to the project and has produced a number of figures used in this document. In addition, I would like to thank Dr. Juhasz at NASA Glenn Research Center who's research is the biases for some of this work.

Finally, all work is funded through the NASA Ralph Steckler Space Grant Colonization Research and Technology Development Opportunity and I would like to thank all the NASA personal who have made this project possible.

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Publications and Presentations

“Space Molten Salt Reactor Concept For Nuclear Electric Propulsion And Surface Power”

Michael Eades, Justin Flanders, Niko McMurray, Richard Denning, Xiaodong Sun, Wolfgang Windl, and Thomas Blue.

The Journal of the British Interplanetary Society (Submitted at request 2012)

“Space Molten Salt Reactor Design Considerations and Research Needs”

Michael Eades, Justin Flanders, Thomas Blue, Xiaodong Sun.

Nuclear and Emerging Technologies for Space (2012)

“Heat Exchanger Considerations for Molten Salt Reactors in Space”

Justin Flanders, Michael Eades, Thomas Blue, Xiaodong Sun.

Nuclear and Emerging Technologies for Space (2012)

“Space Molten Salt Reactor Concept For Nuclear Electric Propulsion And Surface Power”

Michael Eades, Justin Flanders, Niko McMurray, Richard Denning, Xiaodong Sun, Wolfgang Windl, and Thomas Blue. *Nuclear and Emerging Technologies for Space* (2011)

Fields of Study

Major Field: Engineering Physics

Specialization and Minor in Nuclear Engineering

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Introduction

This document provides an extensive overview of the research on the development of molten salt reactor technology for space that Michael Eades has been involved in as student lead of the Ralph Steckler/Space Grant Space Colonization Research and Technology Development Opportunity at OSU (hereafter referred to as The Steckler) over the December 2009 to May 2012 timeframe. Due to the nature of the two and half year project, not all work can be covered in detail in this document. A focus is given to technical activities conducted by the author in the last year which contribute to understanding the design considerations of molten salt reactor technology for space applications. Specifically, figure of merits relating to power conversion, fuel chemistry and reactor dynamics are discussed. A heavy reliance on appendices is used to provide documents explaining previous work.

Key Achievements in the December 2009 to May 2012 Timeframe

Listed below are some of the key achievements of the author as a result of the research conducted under The Steckler. This provides an overview of all the work completed in the project and serves to introduce the documents in the Appendices.

- Principal author on a journal publication in *The Journal of the British Interplanetary Society*. (Included in Appendix A: Related Publications and White Papers)
- NASA Space Technology Research Fellowships based on an extension of the research started under The Steckler. (an excerpt of which is included in Appendix B: Proposed research under NSTRF)

- Department of Energy Nuclear Energy University Program fellowship based on an extension of the research started under The Steckler.
- Author or Co-author on 3 conference publications at *Nuclear and Emerging Technology for Space*. (Included in Appendix A: Related Publications and White Papers)
- Central role in producing a winning Steckler Phase 2 Proposal.
- Successful graduate capstone class that explored the terrestrial applications of The Steckler Project research.
- Successful undergraduate capstone class based on The Steckler Project's research.
- Five research conferences or workshops external to OSU
- 3 research forums internal to OSU

The Steckler

In late 2009, the OSU nuclear engineering program won a Phase I Steckler grant from NASA. OSU was one of 18 universities to win one of these grants. The Steckler's purpose was to fund research that would aid in the long term exploration and colonization of space. OSU won a grant by proposing an investigation of molten salt reactors for space. OSU was awarded a Phase II Steckler grant in early 2010. OSU was one of 5 universities to be awarded such a grant. In August 2013, OSU will apply for the Phase III of The Steckler grant which if awarded, will fund the project through 2015.

In Phase I, Seven undergraduate students from five different engineering majors were assembled into a team to explore space nuclear concepts and the potential advantages of molten salt reactors for space applications. Three of these students worked full time over the 2010 summer and produced the conference proceeding publication "Space Molten Salt Reactor Concept For Nuclear Electric Propulsion And Surface Power" for *Nuclear and Emerging*

Technologies for Space 2011 which outlined the key advantages of molten salt reactor technology for space.

In Spring 2011 Phase II of the Steckler Project was awarded to OSU and currently funds research activities. Phase II continues the work of Phase I by exploring the design considerations of molten salt reactors in space. As a part of Phase II of the Steckler Project, 3 design studies are being conducted: a 500kWe surface power reactor, a 3 MWe surface power reactor, and a 15 MWe nuclear electric propulsion reactor.

Tentatively, if awarded in 2013, Phase III of the Steckler will explore how molten salt reactor technology would be developed and continue to investigate applications of molten salt reactor technology for space.

Molten Salt Reactors

Molten salt reactors are very different from traditional solid fuel reactors. In a molten salt reactor, the fissile material (uranium) is dissolved in a molten salt. An example of some molten salt that might fuel the reactor can be seen in Figure 1. The molten salt circulates through the core and other systems. Heat is generated via fission when the molten salt is in the core. Eventually that heat is transferred to a power conversion system. In a traditional solid fuel 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.

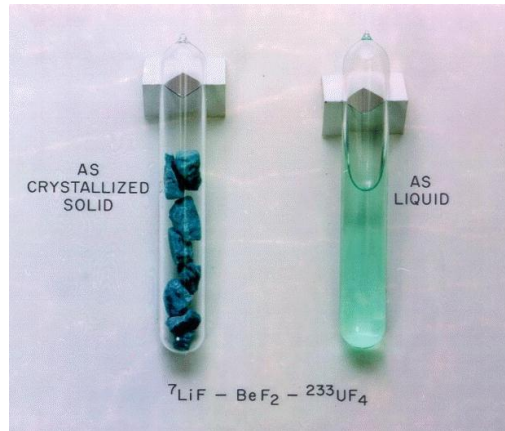


Figure 1: Molten salt fuel developed by Oak Ridge National Laboratory for the Molten Salt Reactor Experiment 1964. In the picture above it is shown in both its solid and liquid form.

Early on in the Steckler, some key advantages of molten salt reactors for space applications were identified. Some of these are stated in brief below [1].

1. Very high burn up percentages made possible by a lack of fuel 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 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. This is largely caused by the expansion of fuel.
5. Due to the flexibility of a liquid fuel, mission architectures can be formulated that address concerns of proliferation and safety. In addition, because of the high burn up, less fuel is

required for a molten salt reactor than for solid fueled reactors, which assists further in minimizing proliferation and safety concerns.

6. High temperature operation at lower pressure operation than liquid metal coolants such as lithium and NaK because of the very low vapor pressure of molten salts.

Molten Salt Reactor History

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 [2]. The program was canceled in favor of ICBM technology.

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, handling 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 [3].

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 [4]. 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 Need for Reactors in Space

Long term science outposts on the Moon and Mars will require multi megawatt surface power. Necessary applications such as in-situ resource utilization (using local resources), closed loop life support, and high powered science equipment are energy intensive processes. Fission surface power is by far the most suitable technology for multi megawatt surface power. Figure 2 contains two graphics from a NASA presentation to the Department of Energy's Nuclear Research Advisory Committee in 2002. The first one depicts approximate regions where one energy technology will become advantageous (in terms of specific energy) over another for space applications. Similar graphics have been presented in the International Atomic Energy Agency report "The Role of Nuclear Power and Nuclear Propulsion in the Peaceful Exploration of Space".

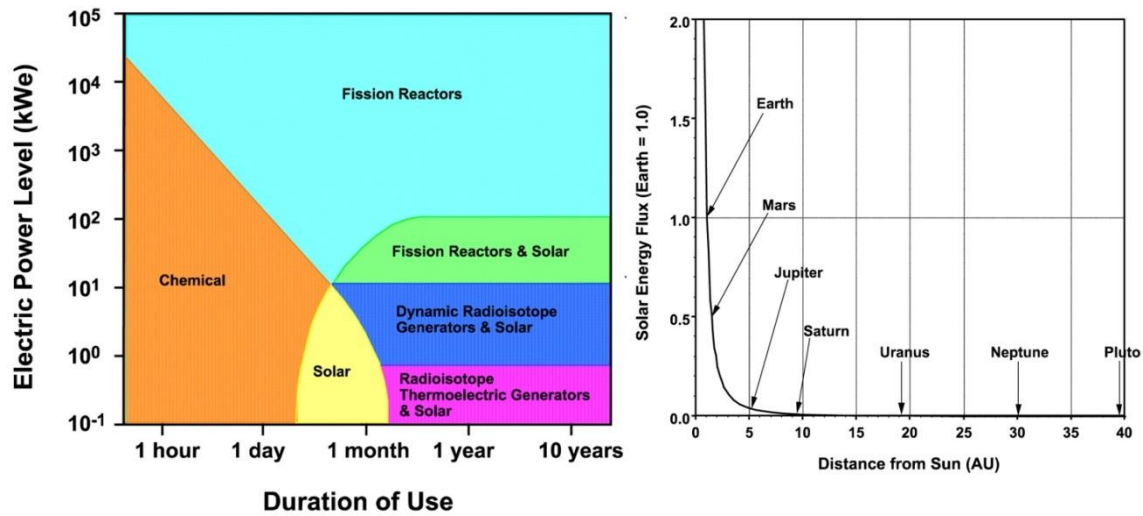


Figure 2: (Left) Optimal energy technology defined by duration of use and electrical output (Right) Solar flux as a function of distance away the sun (Source [5])

Technical activities

Brayton System Optimization

As a part of the Steckler Project, a unique approach to power conversion optimization was taken. Early in the Steckler Project, Brayton cycle power conversion was chosen as the system that was to be primarily studied due to its comparatively high technological readiness, low mass, and high efficiency. A number of studies have attempted to optimize the mass of Brayton cycle power conversion systems for space nuclear systems [6] [7] [8] [9] [10] [11]. All these studies rely on extrapolated mass models for high temperature space rated turbo machinery and heat transport components. The accuracy of these mass models is questionable, and with current technology, impossible to test.

The assumption made for this work is that the radiator would be the largest component of the system mass and thus the minimum radiator area configuration would be approximately equal to the minimum mass configuration. This assumption was found to be true in nearly all studies of

large space nuclear systems utilizing Brayton power conversion systems. Table 1 is from [8] and it can be seen that the radiator makes up more than 42% the mass of the entire system for a reactor with a turbine inlet temperature of 1640K. This percentage would be even higher for a system with a lower (and much more achievable) turbine inlet temperature.

Table 1: Mass breakdown taken from [8] for a 15 MWe NEP system.

Parameter	Gas Brayton Baseline
Turbine inlet temperature (K)	1,640
Reactor thermal power (kW _t)	61,579
Thermal efficiency (%)	24.4
Reactor mass (kg)	6,648
Shield mass (kg)	4,290
Heat exchanger mass (kg)	0
Turbine/generator mass (kg)	4,480
Main radiator temperature (K)	746-541
Main radiator area (m ²)	5,563
Secondary radiator area (m ²)	1,899
Total radiator mass (kg)	22,386
Power conditioning mass (kg)	15,106
Total mass (kg)	52,910
Specific mass (kg/kW_e)	3.53

Method

With the assumption stated above, a MATLAB code was written to minimize a nuclear heated Brayton system for total radiator area. A copy of the MATLAB code can be found in Appendix C: Brayton Optimization Source Code.

Figure 2 provides an overview of the system to be optimized with the hottest temperature in the system labeled TTI (Temperature into Turbine Inlet). This is a simple Brayton cycle that is investigated in most space nuclear studies. It is generally accepted that advanced features that might increase efficiency such multiple turbines with reheat are not advantageous from a mass standpoint. Also under the Steckler Project, heat removal by running the working fluid of the Brayton system directly through the radiators was not investigated because of issues associated with pressure drop that would increase mass. Also, the increased area that the working fluid (helium or He-Xe mix) would need to flow over would likely be problematic in terms of reliability; the possibility for leaks goes up.

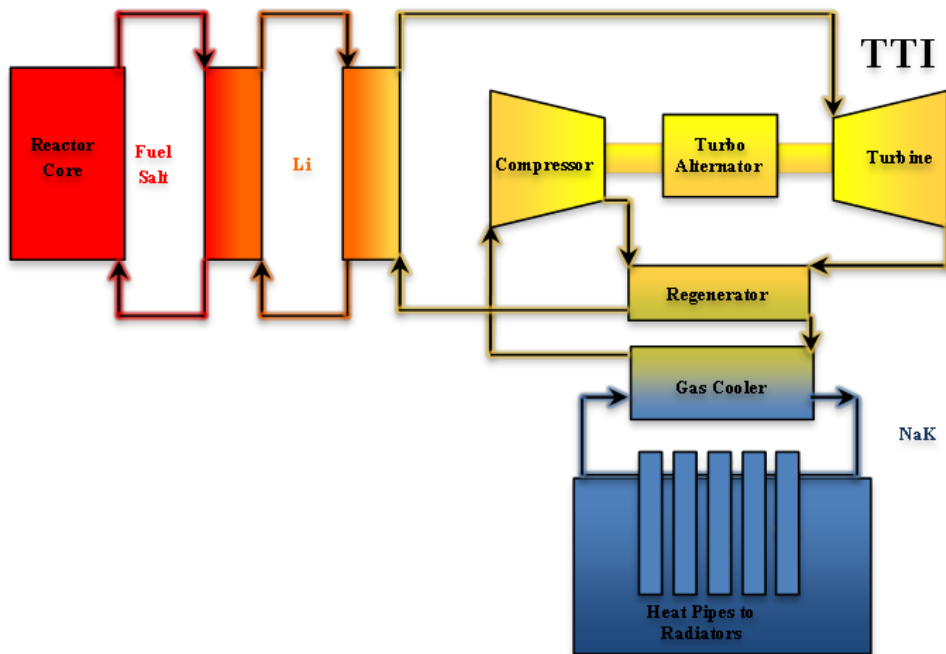


Figure 2: Overview of Brayton Cycle Diagram to be Optimized

Most of the governing equations in the Brayton optimization code are basic thermodynamics that will be familiar to individuals who have taken any undergraduate engineering class in cycle analysis. An exception to this is Equation 1 below for radiator area that comes from [12]. This equation was chosen as the most accurate method for calculating radiator area found in the literature, and was central to the optimization code.

$$Ar = \dot{m} \cdot c_p \left(\frac{-2 \left(-\text{ArcTan} \left[\frac{T_{wex}}{T_s} \right] + \text{ArcTan} \left[\frac{T_{win}}{T_s} \right] \right) + \text{Log} \left[\frac{(T_s + T_{wex})(-T_s + T_{win})}{(-T_s + T_{wex})(T_s + T_{win})} \right]}{4T_s^3 \epsilon \sigma} + \frac{\text{Log} \left[\frac{-T_s^4 + T_{win}^4}{-T_s^4 + T_{wex}^4} \right]}{hr} \right) \quad (\text{Eq 1})$$

Ar=radiating area, m²

Cp= working fluid specific heat, J/kg-K

\dot{m} = Mass flow rate of fluid, kg/s

hr=effective heat transfer coefficient from fluid to radiative area W/(m²- K)

Ts= space sink Temperature, K

Twin=wall surface temperature at Radiator duct inlet, K

Twex=wall surface temperature at Radiator duct exit, K

ϵ =radiator surface emissivity

σ =Stefan-Boltzmann constant (5.67*10⁻⁸ W/(m²*K⁴))

Table 2 lists the assumptions made by the code for various cases and compares it to studies that were extensive enough to include their assumptions. Assumption Set 1 is meant to be a baseline where numbers similar to other studies were chosen. Assumption Set 2 increased hr (effective heat transfer from fluid to radiating area) by a factor of 10. Assumption Set 3 is an optimistic scenario where more than one value can be improved upon over the baseline.

Table 2: List of Assumptions used in Brayton System Optimization

	Assumption Set 1: Baseline	Assumption Set 2: Improved hr	Assumption Set 3: General Improve.	Longhurst (2001)	Mason (2004)
PrL ((Prt*Prc)^-1)	0.95	0.95	0.97	0.95	0.94
Turbine Isentropic Efficiency	90%	90%	90%	90%	90%
Compressor Isentropic Efficiency	80%	80%	80%	80%	80%
Recuperator Effectiveness	95%	95%	95%	95%	95%
Alternator Efficiency	95%	95%	95%	95%	92%
Gas Cooler Effectiveness	95%	95%	95%	95%	94%
Hot Leg Gas Cooler Delta (K)	46	46	46	46	36
PMAD Efficiency	97%	97%	97%	97%	95%
Emissivity	0.85	0.85	0.85	Unknown	0.85
T sink (K)	200	200	200	0	200
hr (W/(m^2*K))	200	2000	2000	200	∞

Results of Brayton Optimization

Figure 3 presents the predicted radiator area per MWe as a function of TTI for various assumption sets and compares it to other studies. Figure 4 takes the baseline assumption set and changes hr to various values. All radiator areas are physical areas of a two sided radiator (ie ½ the total radiating area).

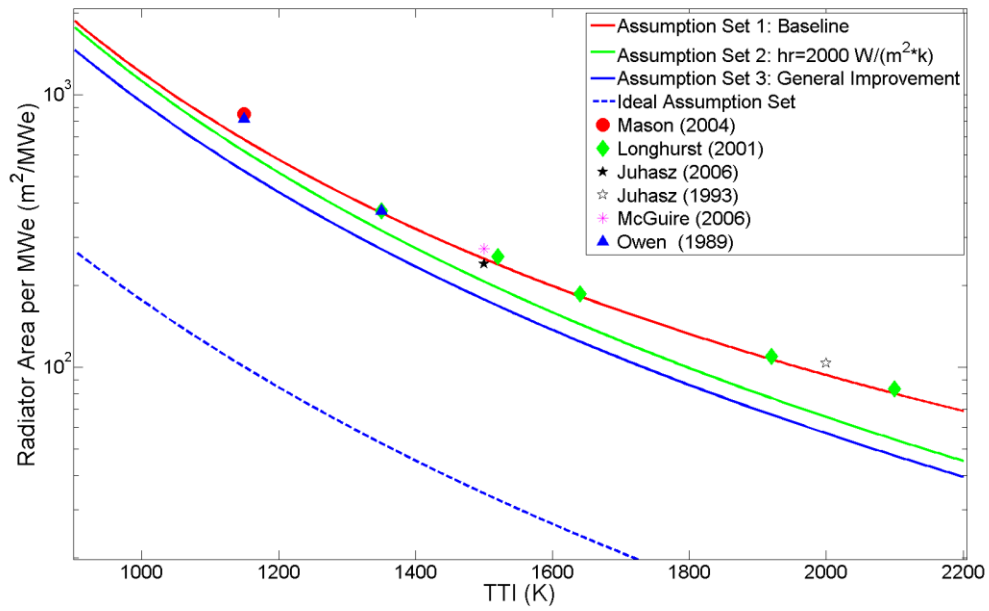


Figure 3: The Author Produced Model with Various Assumption Sets Compared to Other Studies

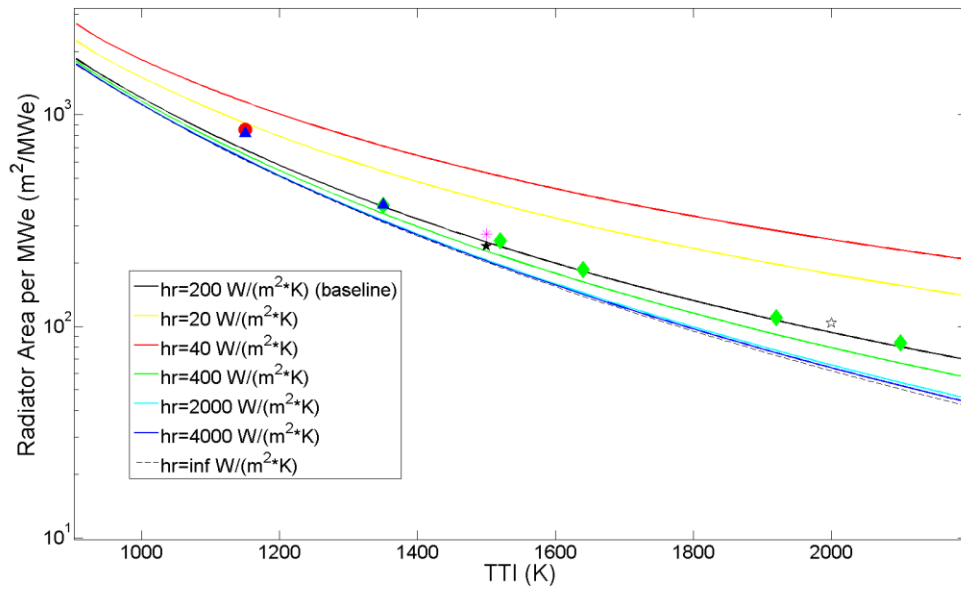


Figure 4: The Author Produced Model with Various Values for hr

Brayton System Optimization Conclusion

Three key conclusions can be made from the results of the Brayton system optimization study. First, in Figure 6 it can be seen that the author produced code is in general agreement (in terms of radiator area per MWe) with a number of nuclear heated Brayton power conversion studies. While the author produced code cannot be compared with physical nuclear powered spacecraft, this agreement with well funded studies from federal agencies indicates an accurate model. This agreement is particularly intriguing considering that the studies the author produced code is compared to come from many different reactor configurations and mission

For a simulation to be useful, it has to be able to have predictive capability. The second key conclusion from the Brayton optimization study is a figure of merit for primary heat exchanger design. Equation 2 is a polynomial fit made with MATLAB's surface fitting toolbox that relates an increase in temperature into the turbine inlet to pressure loss. This is useful for determining the optimal delta T between the Brayton loop and the intermediary lithium loop.

$$Ar = 9.112e4 - 1.33e5 * PrL - 79.77 * TTI + 5.208e4 * PrL^2 + 89.45 * PrL * TTI + 0.02061 * TTI^2 - 27.45 * PrL^2 * TTI - 0.0102 * PrL * TTI^2 + -2.03e6 * TTI^3 \text{ (Eq 2)}$$

$$R^2 = 0.985$$

The final key conclusion that can be drawn from the Brayton optimization study relates to the importance of the hr and the possibility of increasing it. A hr = 200 W/(m²*K) is low considering the proposed designs of space radiators. A common design and the assumed design of this study uses a liquid metal eutectic of sodium and potassium (NaK) that is in direct contact with the heat pipes in the radiator. Independent hand calculations by two members of the research team found that a hr of 2000 W/(m²*K) is easily achievable in this configuration. The effect of assuming an hr of 2000 W/(m²*K) and other values can be seen in Figure 3 and Figure 4.

Fuel Optimization and Choice

LiF-UF4 (65-35) was chosen as the fuel salt for all power levels. The primary reason for choosing this as a fuel salt is recent work by Lawrence Livermore National Laboratory for their fusion fission hybrid LIFE Engine supplies a model estimate the vapor pressure of LiF-UF4 binary system [13]. For many other fuel salts, only temperature range dependent experimental data exists, and the temperature ranges do not extend to the temperatures needed for space reactors. Vapor pressure is important because a liquid boils when its vapor pressure is in equilibrium with its surroundings. The lower the vapor pressure, the less the reactor has to be pressurized. Minimizing pressurization has many benefits, such as greatly reducing mechanical stresses and allowing for the possibility of operating at high temperatures.

The models published by Lawrence Livermore National Laboratory were used to optimize for lowest vapor pressure at 2000K. Other published models were used for the calculation of the rest properties. Table 3 summarizes the results. Figure 5 is a graph that compares the vapor pressure of the fuel components compared to liquid lithium metal. Liquid lithium metal is a common choice for advanced space reactor concepts. It can be seen that the molten salt fuel has a much lower vapor pressure than liquid lithium metal and therefore is capable of operating at higher temperatures.

Table 3: Fuel Properties

Property	Value
Fuel Composition	LiF-UF4 (65-35)
Melting Temp (°C)	585
Density Equation	$\rho(\text{g/cm}^3)=5.96-9.41 \cdot 10^{-4} \cdot T(\text{K})$
Density at 1200K (g/cm³)	4.83
Specific Heat Capacity (J/(g*K))	0.8375
Boiling Temperature on Earth at 1 atm(C°)	1808

Boiling Temperature on Mars 0.006 atm (C°)

1228

Viscosity Equation

$$\mu(\text{cP}) = 0.07696 * e^{(4976/T(\text{K}))}$$

Thermal Conductivity Equation

$$k(\text{W}/(\text{m} * \text{K})) = -0.0771 + 5 * 10^{-3} * T(\text{K})$$

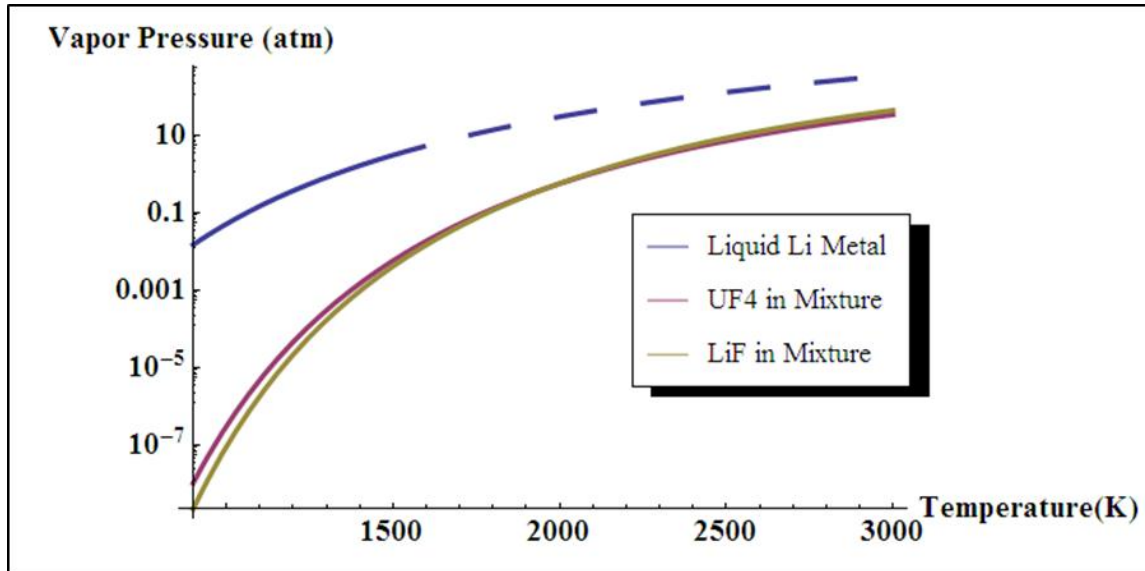


Figure 5: The LiF-UF4 Molten Salt Fuel Compared to Liquid

Material Selection

Another component of fuel optimization is how it leads to material selection. Once the vapor pressure of a fuel is established, it is possible to determine the material and thickness of the vessel structure. In the case of the 3 MWe configuration, it was decided that the best candidate material was a Mo-Re5 alloy with a thickness of 2.5mm. This was decided by looking at high temperature creep behavior with Larson-Miller parameter analysis.

Reactor Dynamics

In a molten salt reactor, reactor dynamics changes are more complex than they are in solid fuel reactors. Reactor dynamics in a molten salt reactor are affected by the amount of precursor nuclei that decay outside of the core as the fuel circulates and by the resultant reduction in the

effective delayed neutron fraction (β_{eff}), which affects the reactor kinetics and hence the reactor control. In general, the reactor becomes less controllable as the fuel spends more time out of the core and less time in the core.

Equation 3 was derived using a modified point reactor kinetics model for circulating fluid reactors to quantify the effect on control of decay of precursor nuclei outside of the core. Specifically, Eqn. 1 calculates the margin to super prompt critical (MSPC) in pcm as a function of time in the core (τ_c) and time out of the core (τ_{hx}). n is the total number of delayed neutron groups and β_i and λ_i are, respectively, the delayed neutron fraction and the radioactive decay constant for the i th group. This equation was derived as a figure of merit for core heat removal systems.

$$MSPC = \sum_{i=1}^n \left(\frac{\beta_i * \lambda_i}{\lambda_i + \tau_c^{-1}(1 - \text{Exp}(-\tau_{\text{hx}} \lambda_i))} \right) * 10^5 \quad (Eq. 3)$$

Figure 6 is a visual representation of the results of Equation 3 using β_i and λ_i for U-235 for a fast spectrum. Equivalent solid fuel $\beta_{\text{U-235}}$'s are marked as a function of the fuel's time in and out of the core. The closer to $\beta_{\text{U-235}}$ the more stable the reactor is. The leftmost region on the chart is approximately the region where the margin to super prompt critical is equivalent to that for a Pu-239 solid fueled reactor. To maximize the margin to super prompt critical, the heat exchanger that removes heat from the fuel salt needs to be designed to return the fuel back to the core as quickly as possible. Preliminary calculations indicate that for a space molten salt reactor with a thermal power of 60 MWth, a $\beta_{\text{eff}} > 0.8 \beta_{\text{U-235}}$ is achievable.

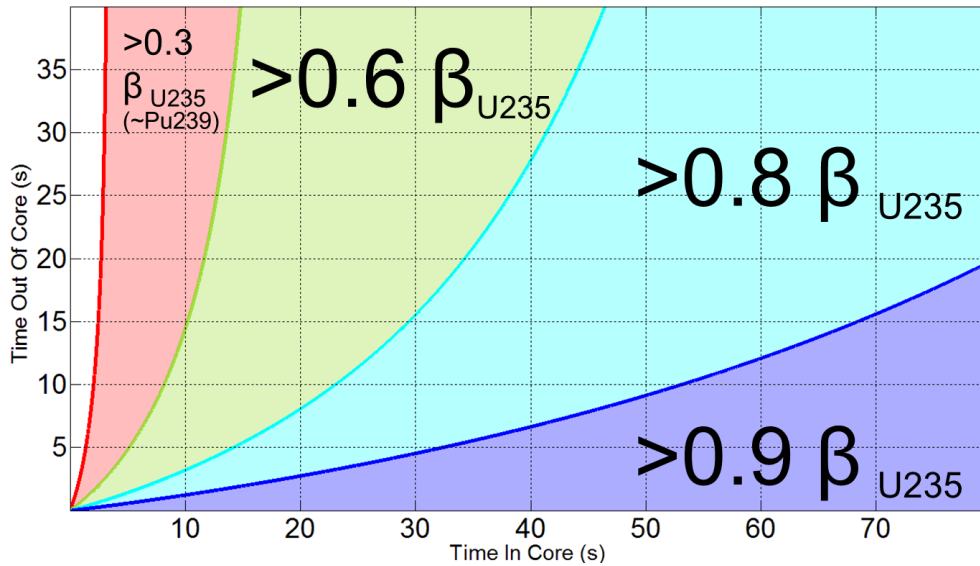


Figure 6: Visual Representation of Equation 3

Future plans

The Steckler Project at OSU has funding through August 2013, at which time OSU will be applying for an additional 2 years of funding. Furthermore, other closely related projects may be funded through the NASA Institute for Advanced Concepts and the NASA Space Technology Research Fellowship program.

A central piece of research to continue is the incorporation of multiphysics simulations in the study molten salt reactors. Multiphysics simulations are an emerging field in engineering and are producing data that was previously only possible with experiments. For accurate predictions of key values of molten salt reactors, these techniques must be utilized. This is a rigorous thermal-hydraulic–neutronic analysis that uses MCNP for nuclear related calculations and FLUENT for thermal-hydraulic calculations. This analysis could generate very accurate values relating to critical size and burn up.

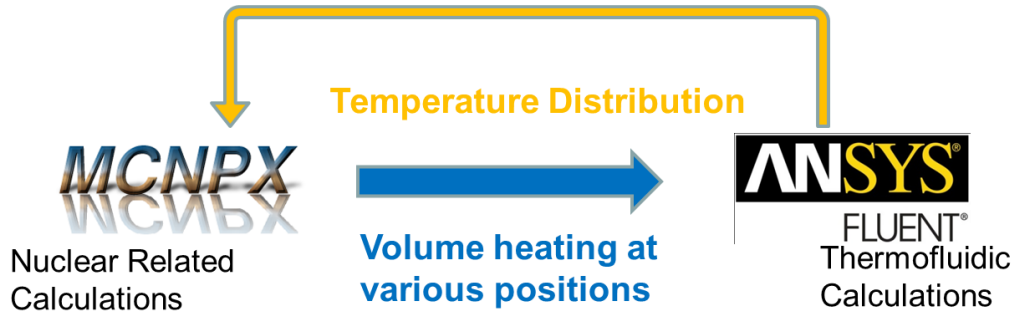


Figure 7: An Overview of Multiphysics simulations with MCNPX and FLUENT.

In house computer resources were acquired in Winter 2012 to aid in future Multiphysics simulation work. The need for in house computer resources is driven by export control issues associated with MCNPX. If it were not for these export control issues, less expensive external super computer resources would be utilized. It should be noted that the design and successful purchase of a high end workstation is an accomplishment in itself and will aid in future multiphysics simulation research on molten salt reactors.

Key stats of the new in house computer resources are listed below:

- 4x AMD Opteron 6176 SE 2.3GHz 12MB 12-Core (48 Cores Total)
- 128GB (32x4GB) DDR3 SDRAM ECC Unbuffered
- NVIDIA GeForce GTX 560 Ti (Fermi) 1GB
- 3x Seagate Barracuda 2TB 7200RPM SATA 6.0Gb/s 64MB Cache

Furthermore, current Department of Energy Secretary Steven Chu has identified multiphysics simulations as a central component of nuclear reactor development and study in the modern age. This is due in large part to the increase cost associated with large scale nuclear experiments.

Multiphysics simulations programs are a very active part of a larger Science Based Research and Development initiative in the DOE.

Under the DOE's Science Based Research and Development initiative, rigorous analysis with multiphysics simulations are to be used to build to small scale engineering demonstrations. Fitting with the DOE's approach, the Steckler project is researching how to build an electrically heated technological demonstration unit (TDU) for verifying of predictions of multiphysics simulations. No electrically heated technological demonstrations of a molten salt reactor have been built, and there are many unique challenges to this. Also, reliance on engineering demonstrations like this are also more in line with the more traditional R&D approaches still held at NASA.

As a part of the development of a TDU, basic irradiation work at the OSU research reactor will take place to identify impurities in molten salt and salt substitutes that could become a radiological hazard when activated. This information will add in the small scale molten salt tests that take place in radiations fields.

Conclusion

The work presented in the body of this document will aid in the continued development of molten salt reactor technology for space. The investigation into molten salt reactor dynamics, fuel chemistry, and pioneering a unique approach to Brayton system optimization for space fission systems, among other technical activities, is a necessary activity in exploring the design of space nuclear systems and finding the role molten salt reactors can play in it. Some portion of the success can be seen in the successful dissemination of the idea in the form of publications.

Additionally, the publications provided in the appendices of this document provide a clear idea why molten salt reactor technology is being explored for space, of current research activities, and a look into the wide breadth of the currently 2.5 year old project.

Research on space molten salt reactors will continue with the author as student lead on the Steckler Project through its funded period. As work moves forward, figures of merit discussed in the body of this document will be utilized and multiphysics simulations will be incorporated using computer resources acquired during the last year.

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Parts of this document are based on modified from the work of the author, Michael Eades, conducted in the 2011-2012 undergraduate engineering physics capstone class and the publications found in Appendix A

Appendix A: Related Publications and White Papers

“Space Molten Salt Reactor Concept For Nuclear Electric Propulsion And Surface Power” Michael Eades, Justin Flanders, Niko McMurray, Richard Denning, Xiaodong Sun, Wolfgang Windl, and Thomas Blue. *The Journal of the British Interplanetary Society* (2012)

“Space Molten Salt Reactor Design Considerations and Research Needs” Michael Eades, Justin Flanders, Thomas Blue, Xiaodong Sun *Nuclear and Emerging Technology for Space* (2012)

“Heat Exchanger Considerations for a Space Molten Salt Reactor” Justin Flanders, Michael Eades, Thomas Blue, Xiaodong Sun *Nuclear and Emerging Technology for Space* (2012)

“Thorium Fueled Molten Salt Reactor Energy Systems for Sustainable and More Capable Space Exploration” Thomas Blue, Michael Eades NASA Institute for Advanced Concepts White Paper (2012)

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, BeF₂ and highly enriched U²³⁵F₄ 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

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

SMSR concept include compact, high-efficiency power fission systems for surface power and NEP with power levels ranging approximately from 100kWe to 15MWe.

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.

This paper was presented at the Nuclear & Emerging Technologies for Space (NETS-2011) conference, Albuquerque, New Mexico, 7-10 February 2011. Printed with permission of the American Nuclear Society

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, handling 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.

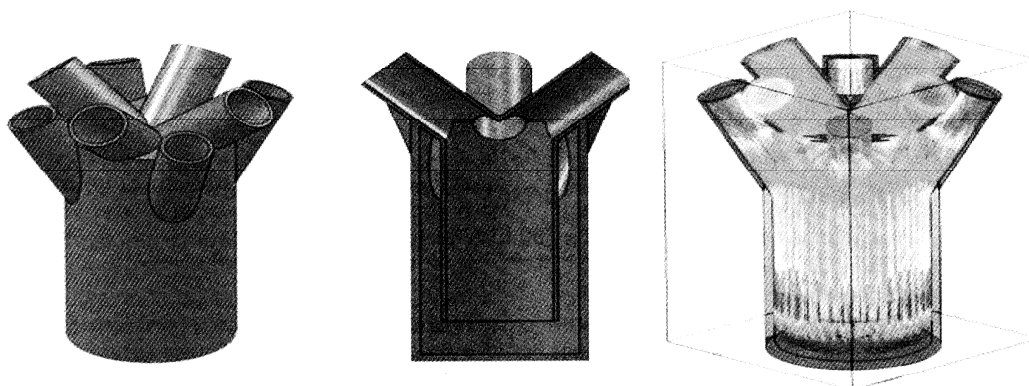


Fig. 2 Cross section of the SMSR generated in MCNPX Visual Editor with colored labels. The shield is representative of a shadow shield that might be used for NEP. For surface power, the reactor would likely have a different shield and/or be buried.

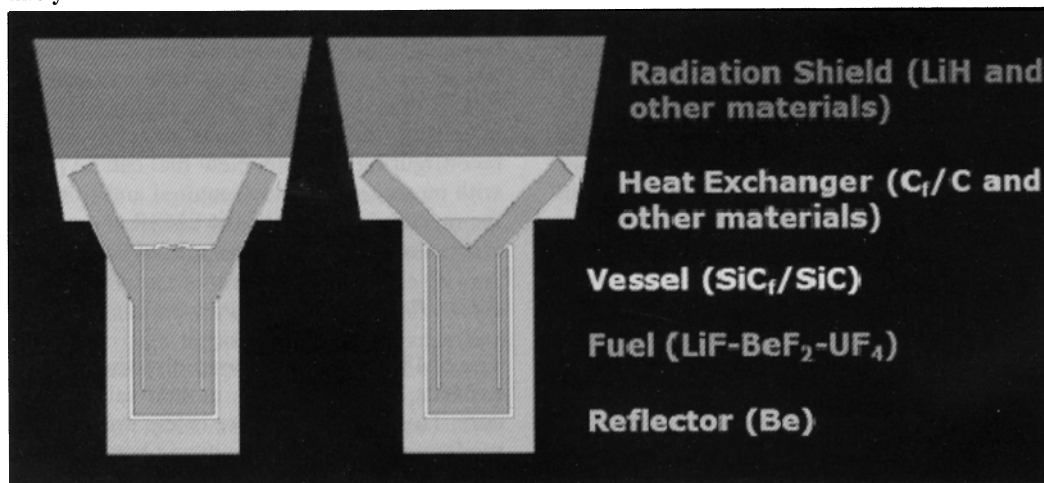


TABLE 1: Characteristics of the SMSR.

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-

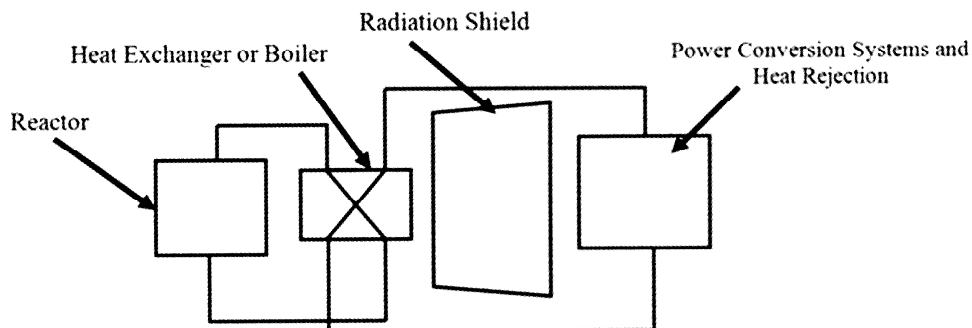


Fig. 3 SMSR general NEP layout.

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 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 a potassium 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

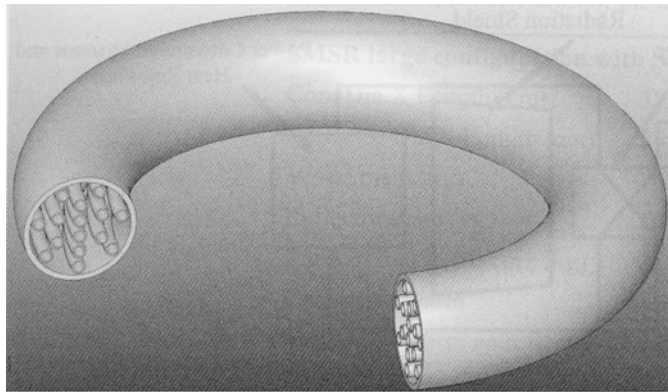


Fig. 4 Potassium boiler and lithium heat exchanger cutaway model.

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/cm³ (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-BeF ₂ -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/cm³ (Zinkle 1998). In addition SiC_f/SiC has been irradiated in a fluence of 1.2x10²⁶ n/m² (>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 SiC_f/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 mm³.

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/cm³ (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 (Ti₂O₃) and yttria (Y₂O₃). 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 10²⁷ n/m² 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, SiC _f /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 it 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.

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

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 MSR 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. CONCLUSION

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

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.

ACKNOWLEDGMENTS

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Introduction: Research at the Ohio State University conducted under the NASA Ralph Steckler Space Grant Colonization Research and Technology Development Opportunity has identified molten salt reactors as a potentially appealing technology for high power, high temperature space fission systems[1].

Central to the molten salt reactor concept is the use of fissile material dissolved in a molten salt liquid medium (such as LiF-BeF₂-UF₄) as both fuel and coolant. The fuel is constantly circulating through the reactor core and other reactor systems, such as the heat exchanger. From the heat exchanger, a power conversion system converts the heat to electricity for surface power or nuclear electric propulsion. This approach is in contrast with the traditional solid fuel approach where solid fuel is affixed in the core, and heat is transferred from the fuel to a separate coolant.

The unique design considerations of a space molten salt reactor are discussed below. In particular, the design considerations of a molten reactor are compared with those of solid fueled reactors.

Molten salt reactor background. The potential for molten salt reactor technology to provide an ultra-compact and lightweight power source was first examined in the early 1950s with the Aircraft Nuclear Propulsion Program. The U.S. military wanted to develop a reactor that was small enough to power an airplane, with the constraint that the aircraft could remain airborne for several weeks. In this program, a land-based prototype 2.5 MWt reactor was built and tested in 1954. Systems for fuel chemistry control, such as gas sparging to remove xenon, were designed and tested. In addition, Designs were made for a prototype 60 MWt reactor [2]. However, the program was canceled in favor of ICBM technology.

Many advantages of molten salt reactor technology have been identified. The development of high temperature solid nuclear fuel for space reactors applications is technologically challenging. Solid nuclear fuels swell, crack, and interact with the fuel clad at high temperatures and high neutron fluence. A molten salt has no organized internal structure to damage and thus is largely unaffected by high temperatures and high neutron fluence.

Furthermore, 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 affected by burn-up.

Neutronically, molten salt reactors are appealing because they have very little internal support structure. As a result, few neutrons are lost to parasitic absorptions. This allows for high burn-up percentages and small critical sizes.

Molten salt reactors have very large negative temperature reactivity feedback. Molten salt reactors, studied under the Steckler grant, have a negative temperature reactivity feedback coefficient of approximately 1.5-1.8 Cents/K. The reason for this is that molten salt 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.

Finally, implementing online refueling of a molten salt reactor is much easier than for solid fueled reactors. This may open a number of mission architectures that rely on a reactor that can be refueled in mid-operation [1].

Power Peaking Factor and Stagnant Fuel: In a solid fueled reactor, it is desirable to have a low power peaking factor for a number of reasons relating to safety and performance. The power peaking factor is much less of a concern for molten salt reactors because the fuel is constantly in motion and mixing.

An analogous concern to power peaking for the molten salt reactors is the issue of stagnant fuel. Stagnant fuel in the core of a space molten salt reactor can potentially become too hot and boil. Fuel is continuously moving through the core. Heat is generated within the moving fuel when it is in the core, but that heat is not removed from the fuel until the fuel enters the heat exchanger. If some portion of the fuel becomes stagnant, such as by swirling in a corner, it will spend more time in the core and become hotter than fuel that is not stagnant. If the stagnant portion of the fuel is in the core too long, it can become too hot and boil. For this reason, it is essential to ensure that no fuel is stagnant in the core of a space molten salt reactor.

We have investigated the issue of stagnant fuel for a 4MWt space molten salt reactor with computational fluid dynamic simulations produced with FLUENT. Figure 1 provides illustrations of the results of FLUENT simulations for various angles of inlet pipes with respect to the tangent to reactor vessel top.

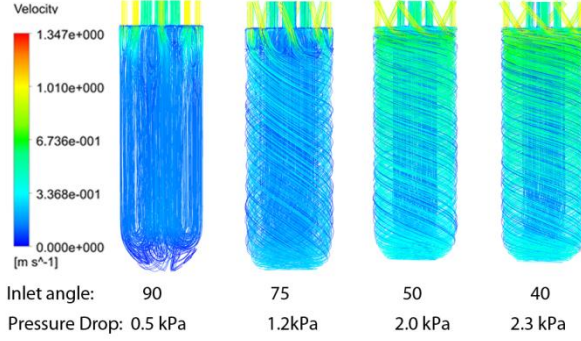


Figure 1: A series of CFD simulations of a 4 MWt space molten salt reactor. Different angles of inlet pipes were tested to minimize stagnant fuel.

Power Density Limitations: To minimize the mass of a space fission system, it is advantageous to have a high power density (W/m^3) because shield mass is approximately a linear function of reactor volume.

In advanced solid fueled space reactors, power density is primarily limited by in-core heat transfer. In a molten salt reactor, power density is limited by the fraction of precursor nuclei that decay outside of the core as the fuel circulates and the resultant reduction in the equivalent delayed neutron fraction (β_{eff}), which affects the reactor kinetics and hence the reactor control. The relationship between power density and β_{eff} is a complex relationship involving heat exchanger design, control parameters, fuel properties, and core volume.

Equation 1 was derived using a point reactor kinetics model to quantify the effect on control of decay of precursor nuclei outside of the core. Specifically, Eqn. 1 calculates the margin to super prompt critical (MSPC) in pcm as a function of time in the core (τ_c) and time out of the core (τ_{hx}). n is the total number of delayed neutron groups and β_i and λ_i are, respectively, the delayed neutron fraction and the radioactive decay constant for the i th group.

$$MSPC = \sum_{i=1}^n \left(\frac{\beta_i * \lambda_i}{\lambda_i + \tau_c^{-1}(1 - \text{Exp}(-\tau_{hx} \lambda_i))} \right) * 10^5 \quad (1)$$

Figure 2 is a visual representation of the results of Eqn. 1 using β_i and λ_i for U-235 for a fast spectrum. Equivalent solid fuel β_{U-235} 's are marked as a function of the fuel's time in and out of the core. The leftmost region on the chart is approximately the region where the margin to super prompt critical is equivalent to that for a Pu-239 solid fueled reactor ($\sim 0.31 \beta_{U-235}$). To maximize the margin to super prompt critical, the heat exchanger that removes heat from the fuel salt needs to be designed to return the fuel back to the core as quick-

ly as possible. Preliminary calculations indicate that for a space molten salt reactor with a thermal power of 60 MWth, a $\beta_{eff} > 0.8 \beta_{U-235}$ is achievable.

Limited Fuel Salt Data: Extensive experimental data exists for the specific salt mixtures tested under the Aircraft Nuclear Propulsion Program and Molten Salt Reactor Experiment. From data gained in these programs and other research, empirical models have been devised to calculate essential properties for molten salt reactor designs [3] [4]. Unfortunately, these models have large error margins and do not include formulae for many of the properties needed for space reactor design. In particular, few methods for modeling vapor pressures at high temperatures have been published and liquedus temperature diagrams do not exist for many higher order salt systems.

Future Work: In the immediate future, rigorous coupled thermal hydraulic-neutronic calculations with MCNPX and FLUENT are planned to better understand the operation of a space molten salt reactor. In addition application specific design studies are in progress.

Beyond what is planned under this research, additional experimental data on fuel properties would greatly assist in studying space molten salt reactors. Existing models of fuel properties are not yet complete enough to accurately model fuel chemistry overtime. With more accurate fuel chemistry models, rigorous time-dependent multi-physics models will be possible.

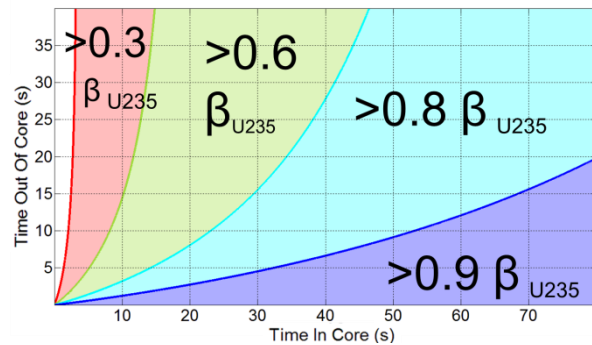


Figure 2: Regions of β_{eff} in terms of equivalent solid fuel β_{U-235} for a molten salt reactor fueled with U-235 as a function of time in and out of the core.

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Introduction: Research at the Ohio State University under the *NASA Ralph Steckler Space Grant Colonization Research and Technology Development Opportunity* has identified molten salt reactors as a potentially appealing technology for high power, high temperature space fission systems. Here, the design aspect of the heat exchangers is discussed.

Central to the molten salt reactor concept is the use of fissile material dissolved in a molten salt liquid medium (such as LiF-BeF₂-UF₄) as both fuel and coolant. In a traditional solid fuel reactor, the fuel is affixed to the core and the heat is removed by a separate coolant. A molten salt reactor functions differently; the fuel is constantly circulating through the reactor core and the heat exchanger. From the heat exchanger, a power conversion system converts the heat to electricity. To promote cycle efficiency, heat exchanger must achieve as high an effectiveness as possible.

Design Considerations: Before selection of heat exchanger types can proceed, one must first consider the specifics of the power cycle being used. A closed Brayton cycle with a helium working fluid has been selected. The full power conversion system can be seen in Figure 1. The fuel is a mixture of LiF - UF₄ and acts as the primary coolant in the loop. Liquid lithium was chosen as the coolant for the secondary loop on the basis of high thermal conductivity (~55 W/m-K at 1000°C), high boiling temperature (1615 K at 1 atm) and because lithium has been shown to be an acceptable coolant in radiation environments. The lithium is enriched Li-7 to minimize the He-4 and H-3 produced in the secondary loop from the (n, α) reaction in Li-6. [1] Although Li-7 would be an expensive coolant, no other liquid metals that matched our criteria possess a

stable isotope with which neutrons hardly react. The mass reduction of a compact system with liquid metals would help counteract this cost during launch.

Heat rejection. To decrease the pressure losses in the helium loop, a fourth loop consisting of elemental lithium is used to transport heat to the radiator setup, which consists of heat pipes at descending temperatures. One end of each heat pipe enters the lithium loop to allow direct contact with the lithium. This lithium does not need to be enriched Li-7 because it is not located within the radiation field.

Figures of merit. The figures of merit for heat exchangers for molten salt reactors with space applications differ from terrestrial solid fueled reactors. The biggest difference is that with a liquid fuel, the delayed neutron fraction that is produced in the core is a major contributor to controllability. The result is that returning the fuel to the core as fast as possible becomes very important. The size and weight of the heat exchanger is also extremely important for space applications, due to the cost per unit mass of transporting material out of Earth's gravitational influence; this is especially true for the size of the primary heat exchanger, as its size affects the solid angle required for radiation shielding. The final figure of merit is the pressure drop. A lower pressure drop requires less pumping power and, in the case of the helium loop, where a pressure drop results in extractable enthalpy being lost, a higher cycle efficiency is obtained.

Material considerations. Few materials exist that can withstand a very high temperature, corrosive salt, high fast neutron flux environment. Refractory alloys such as molybdenum, rhenium, and tantalum have

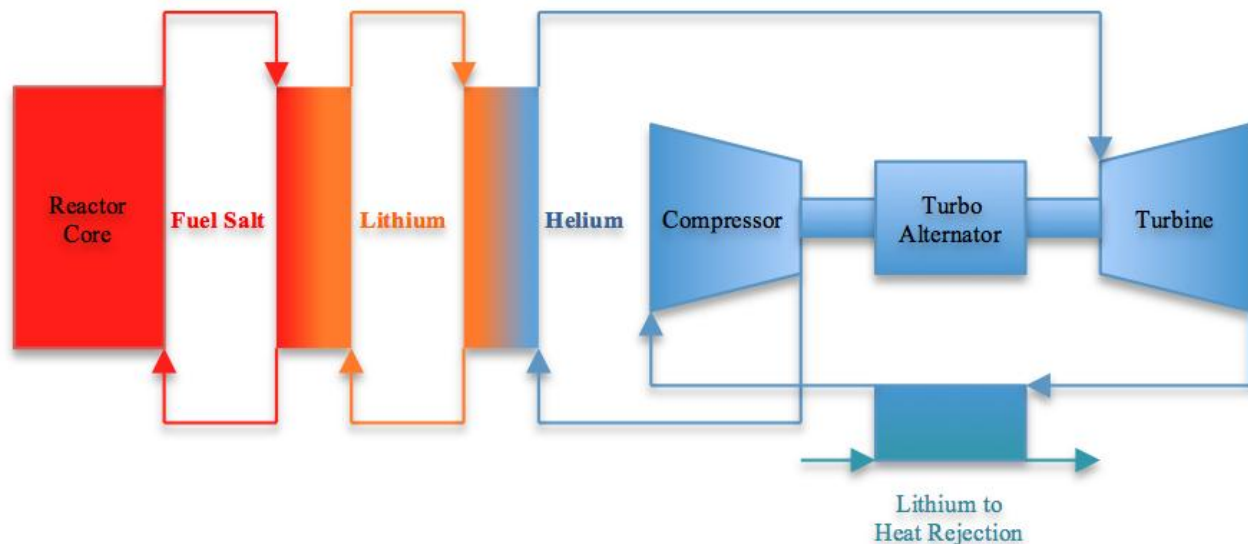


Figure 1: Power Conversion System for a Space Molten Salt Reactor

been shown to handle such temperatures and are acceptable in a fluoride salt environment, provided O₂ is not present, which is the case for this reactor. This makes them ideal material choices for the primary, secondary and tertiary coolant loops. Where temperatures below 1150 K exist, such as in the Brayton cold leg and the heat rejection loop, nickel superalloys would be acceptable materials. [3]

Heat Exchanger Selection: For the secondary lithium to helium heat exchanger, an offset fin strip heat exchanger was selected. For liquid to gas heat transfer, offset fin strip heat exchangers have been shown to be very effective at producing a small compact design. [4] The calculations performed were generated in MATLAB using numerical correlations developed by Joshi and Webb. [5] For a 2 MWt heat exchanger, the length was calculated to be just below 0.5 m and a cross sectional face of only 100 cm² was calculated, all while maintaining a helium pressure drop of less than 20 kPa.

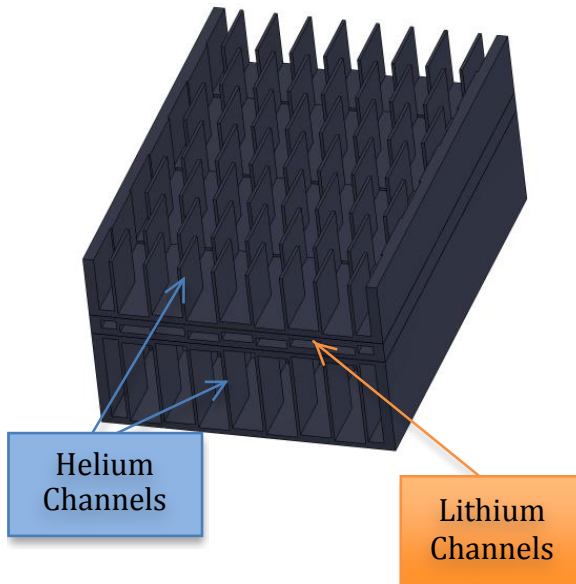


Figure 2: Offset Fin Strip Compact Heat Exchanger Model

For the primary heat exchanger, it was found that a tube in shell heat exchanger was able to return the fuel salt to the core in a shorter amount of time than an offset fin strip heat exchanger. With the fuel salt being rather ineffective for heat transfer, having a thermal conductivity of 0.4 W/m-K and a viscosity of 16.9 cP, to keep the pressure drop below 1 MPa, which is still unfavorably high, the flow velocity had to be kept below 0.15 m/s. This resulted in poor convective heat transfer and a heat exchanger approximately 8 m long, resulting in 53 second fuel salt residency within the heat exchanger. In terms of controllability, this is not a

desirable solution; nearly all of the delayed neutrons will be emitted outside the core. With a tube in shell heat exchanger, and the fuel salt within the tubes, the fuel salt residency time in the heat exchanger was reduced to 7.9 seconds.

Scaling considerations. Under the scope of the Steckler grant, three power levels are to be considered: a 500 kWe reactor for surface power on the moon, a 3 MWe reactor for surface power on Mars, and a 15 MWe reactor for nuclear electric propulsion. It is therefore important to consider the effect of higher power on the heat exchanger figures of merit. In general, an increase in power will increase the mass flow rate of the heat exchanger, the pressure drop, and the size dimensions. The design should be optimized so that the pumping power to electrical output ratio decreases for higher power systems. Since the physical size of a molten salt reactor does not increase significantly, higher powers result in a shorter time spent by the salt in the core. This means that in order to obtain the same delayed neutron fraction in the core, the fuel must be returned more quickly for a higher power reactor. Generally, this increase in flow rate enhances heat transfer. Therefore, with an only slightly larger heat exchanger, the time spent within it can still be reduced.

Future Work: Currently, the primary and secondary heat exchangers have been designed for only the 500 kWe system. After an optimized solution for the heat rejection heat exchanger has been obtained, the process will be repeated for the two larger power systems. The design of an effective header for each heat exchanger inlet is also required to maintain accuracy. These calculations assume uniform flow distribution between channels, which must be ensured in the designed header in order to validate the assumption.

Because many of the calculations performed on the heat exchangers are based on empirical correlations, such as the Nusselt number correlations, it is important to verify that the designs are reasonably accurate. In order to validate the design, a CFD model using FLUENT will be created. In particular, the pressure drops of the helium loop need to be verified because they will directly affect the reactor thermal power through cycle efficiency.

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Thorium Fueled Molten Salt Reactor Energy Systems for Sustainable and More Capable Space Exploration

Introduction and Potential Impact

The proposed research explores a scalable, thorium based energy architecture capable of powering space exploration through the 21st century and beyond. The architecture will capitalize on the abundance of thorium as a fertile nuclear fuel to supply a comparatively limitless source of energy, the compactness of a reactor that utilizes Uranium-233 as fuel, and the high temperature, low pressure operation of molten salts. The architecture and technology utilized for this study will be assessed under the mission context of the first permanent human outposts on Mars, though parts of the study will be applicable to everything from small, deep space probes to powering a multiplanetary civilization.

Central to the architecture will be molten salt reactor (MSR) technology and a common molten salt fuel that will be shared between high power nuclear electric spacecraft, nuclear surface power installations, and unmanned probes. The fuel in MSRs is fissile material dissolved in a molten salt liquid medium (such as LiF-BeF₂-UF₄) used as both fuel and coolant.

Thorium is 3.6 times more abundant than natural uranium and 493.8 times more abundant than the uranium-235 isotope used in most space fission systems concepts [1]. Supplies of highly enriched uranium-235 (>90% U-235) are more than sufficient for near missions and fission systems concepts, but supplies could be strained in the future. A large space fission system for a high powered nuclear electric craft, like those proposed for human transport to Mars requires hundreds, if not thousands, of kilograms of highly enriched uranium (HEU). The production of HEU requires substantial natural resources and considerable amounts of energy to enrich. More so, its use is highly politically contested due to proliferation concerns.

Thorium has the same potential energy density as HEU, but is more technically challenging to utilize. Nuclear reactors require fissile material to operate. HEU is a fissile material, while thorium is a fertile material that can be bred into a fissile material, uranium-233. In addition, uranium-233 has a smaller critical mass than uranium-235. Reactors using uranium-233 can be smaller and lower mass than those that use uranium-235.

MSRs were only recently identified as a potentially appealing technology for space [2]. The proposed research will examine the technology as an advanced, very high temperature technology. Current models indicate that with less than 1 MPa of pressurization, molten salt fuels can operate at 2500 K [3]. High temperature allows for higher performance power conversion systems. Molten salts are one of the few coolants capable of such extremely high-temperature low-pressure operation. In addition, molten salt fuels are very well suited for high-temperature operation in comparison to solid fuels because of their lack of structure to damage. Very little research has been conducted on molten salt reactors operating at 2500 K temperatures for space applications and the proposed research will be the first of its kind.

Concept and Method of Study

A scalable energy architecture with reactor point designs will be developed for the first permanent human outposts on Mars. This architecture will include high powered manned and unmanned nuclear electric propulsion (NEP) craft to make routine round trips between Earth and Mars. Surface operations will be powered by nuclear surface power. The architecture will allow for much more frequent Earth-Mars trips than would be possible under HEU approaches.

In this analysis, high powered NEP spacecraft and orbital fueling stations will breed fissile material from thorium. These will be the sources of fissile material. The surplus fissile material that these sources produce will go to starting new reactors, including reactors that

cannot breed due to performance limitations and reactors that cannot breed due to technical limitations. These will be the sinks of the fissile material. An equilibrium between sources of fissile material and sinks of fissile material will be established for various scenarios.

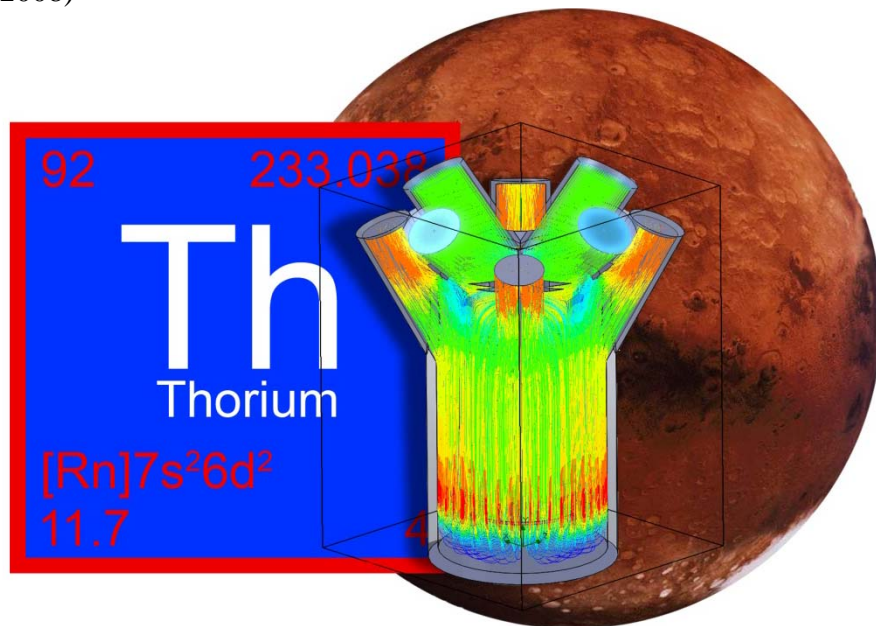
The primary method of study will be reactor design with MCNPX and multiphysics simulations. In addition, programs such as CHEBYTOP and MALTO will be used for trajectory analyses. Key values such as breeding ratio, specific mass, initial fissile inventory, and payload will be established. Components of the architecture capable of breeding thorium into excess uranium-233 will be identified.

Terrestrial Spinoff Technology and Green Energy Impact

Thorium fueled molten salt reactors have been recognized as a potential technology to supply Earth with clean and sustainable energy. As mentioned before, thorium is more abundant than uranium and can be used to much higher degrees of efficiency. The technology that would be needed to implement thorium fueled molten salt reactors on Earth is much simpler and can operate at lower temperatures than what would be needed to implement the technology for large scale space exploration. Research in thorium fueled molten salt reactors for space will aid in advancing the technology for earth and bring attention to a promising technology for terrestrial applications.

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Molten Salt Reactors utilizing thorium and uranium-233 fuels can provide the energy to enable permanent human outposts on Mars and the routine travel between Earth and Mars that would be necessary to support and expand those outposts.

Appendix B: Proposed Research Under the NSTRF

Educational Research Area of Inquiry and Goals

Introduction

It is my strong belief that space fission systems will be critical in the exploration of the solar system. For this reason, I have made space fission systems the center of my academic pursuits throughout my undergraduate career. As I enter graduate school, I plan to continue my study of space fission systems and to work towards their advancement as a viable technology for space exploration. Specifically of interest to me are advanced sub-100 KWe reactors for science missions and MWe class reactors for human exploration.

Fission systems hold great promise as a technology capable of powering exploration beyond low Earth orbit. The exploration of space necessitates power systems with low specific masses (kg/kW). In addition, power systems that are utilized for propulsion need to maintain low specific masses to achieve desirable performance. No other power technology with a comparable technological readiness level can achieve the specific masses of space fission systems and provide large amounts of power over an extended duration. More so, space fission systems are capable of providing power independent of their proximity to the Sun, thus making them suited for exploration missions anywhere in the solar system. [1] All this is particularly evident in an age of Pu-238 shortages that will limit planetary science missions to the outer solar system in the coming years.

Figure 1 contains 2 graphics. The first leftmost one depicts approximate regions where one energy technology will become advantageous (in terms of specific energy) over another for space applications. The other graphic in Figure 1 shows the sharp decrease in solar flux as a function of distance away from the sun. These graphics are from a NASA presentation to the Department of Energy's Nuclear Research Advisory Committee [2]. Similar graphics have been presented in NASA's draft Space Technology Road Maps and the International Atomic Energy Agency's report "The Role of Nuclear Power and Nuclear Propulsion in the Peaceful Exploration of Space".

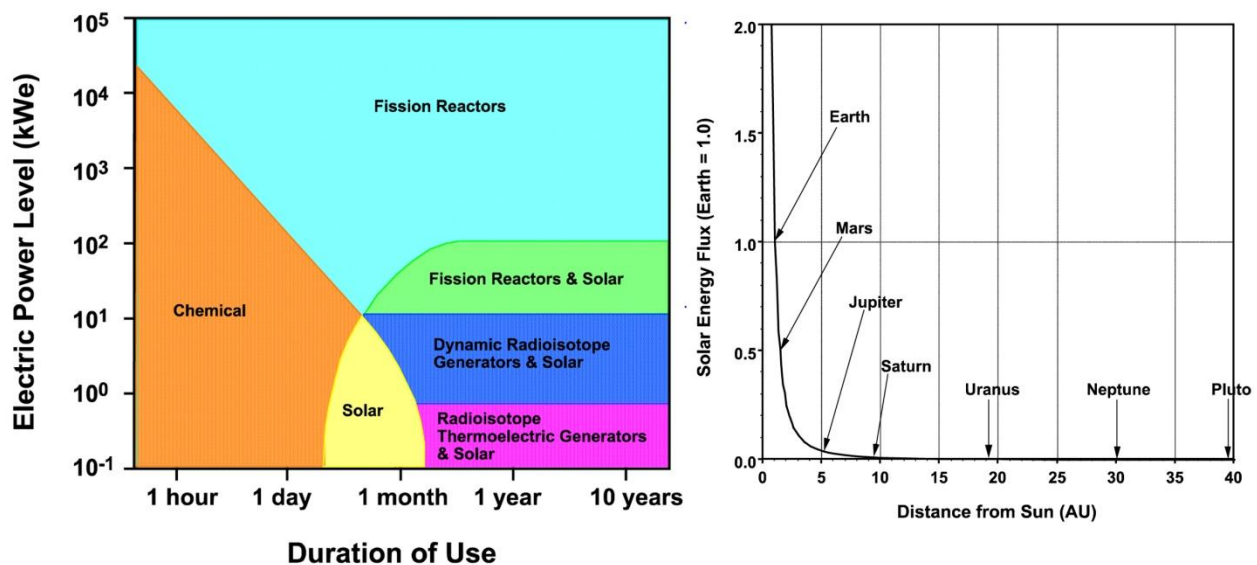


Figure 1: (Left) Optimal energy technology defined by duration of use and electrical output (Right) Solar flux as a function of distance away the sun (Source: [2])

Educational Research Area of Inquiry

Throughout my undergraduate studies, I have been driven and ambitious in researching space fission systems. I am the student lead on a NASA funded space fission system research project at The Ohio State University (OSU). Recently, I have had my first peer reviewed journal article accepted. Its topic is space fission systems. This paper was requested for submission for publication by *The Journal of the British Interplanetary Society* based on the editors' reading of another paper for which I was first author that was published in the Proceedings of the 2011 Nuclear and Emerging Technologies for Space (NETS) conference. In addition, I have presented my space fission system related research at meetings such as the Nuclear and Emerging Technologies for Space (NETS) and INEST Space Nuclear Power workshops.

This August, I will be a nuclear engineering graduate student at The Ohio State University (OSU) pursuing a master's degree and PhD. I have decided to stay at OSU, so that I may continue my unique and rewarding research in space fission systems.

It is my plan to leverage the knowledge in space fission systems that I gained while an undergraduate student to investigate energy systems currently relevant to NASA's research agenda.

Specifically, my undergraduate research was directed toward understanding how a particular type of nuclear reactor, called a molten salt reactor (MSR), can be used to aid in the colonization of space. The research was funded through the *NASA Ralph Steckler Space Grant Colonization Research and Technology Development Opportunity* activities at The Ohio State University (hereafter referred to as "The NASA Steckler Grant"). I am the student lead on the project.

The NASA Steckler Grant was chosen for funding and the funding was begun, during the time the now canceled Project Constellation was active. At that time, a long term lunar outpost was a central goal of NASA. Exploration and science missions are now central goals and power system needs have changed.

In graduate school, it is my plan to explore how molten salt reactor technology can be used to power sub-100 kWe reactors for science missions and for MWe class reactors for human exploration in the 2023-2028 timeframe. Both of these applications are cited as relevant to current US goals in space in NASA's Draft 2010 Space Power and Energy Storage Roadmap.

Molten Salt Background

Central to the molten salt reactor concept is the use of fissile material dissolved in a molten salt liquid medium (such as LiF-BeF₂-UF₄) as both fuel and coolant. The fuel is constantly circulating through the reactor core and other reactor systems, such as the heat exchanger. From the heat exchanger, a power conversion system converts the heat to electricity. A diagram of a possible implementation of the heat transport and power conversion systems for a space molten salt reactor, studied under The NASA Steckler Grant, is presented in Figure 2. The fuel-in-salt molten salt reactor approach is in contrast with the traditional solid fuel reactor approach where solid fuel is affixed in the core and heat is transferred from the fuel to a separate coolant.

The potential for molten salt reactor technology to provide an ultra-compact and lightweight power source was first examined in the early 1950s with the Aircraft Nuclear Propulsion Program. The U.S. military wanted to develop a reactor that was small enough to power an airplane, with the constraint that the aircraft could remain airborne for several weeks. In this program, a land-based prototype 2.5 MWt reactor was built and tested in 1954. It operated at a maximum steady state temperature of 1130 K. [3] In addition, designs were made for a prototype 60 MWt reactor. However, the program was canceled in favor of ICBM technology.

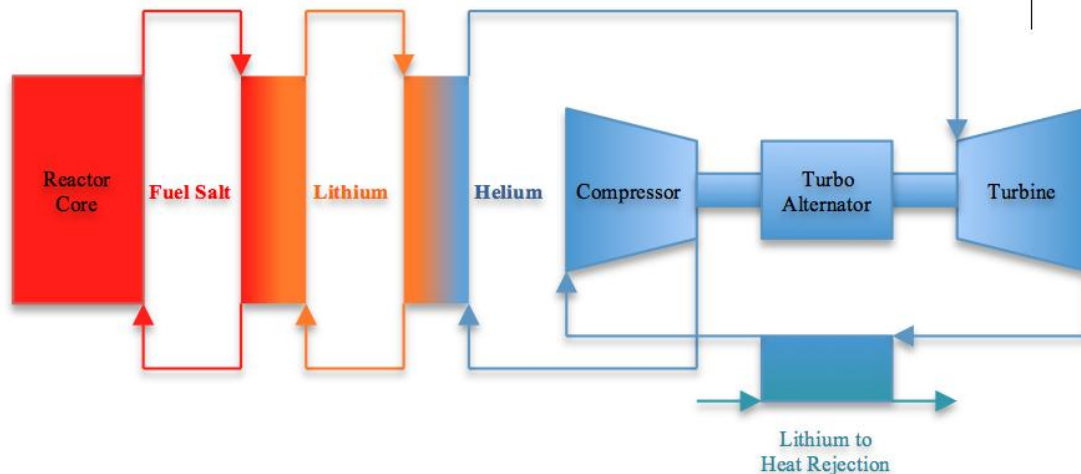


Figure 2: This configuration uses a Brayton system with indirect heat rejection. An intermediate loop ensures that the core will stay at low pressures if a heat exchanger fails. This was envisioned for 3 MWe surface power with a turbine inlet temperature of 1300K.

Advantages of Space Molten Salt Reactors

I have identified the sub-100 KWe science mission reactors and MWe class human exploration reactors as applications for which MSR's may excel as compared to traditional solid fueled reactors. I have chosen this area of inquiry based on my experience in working on the NASA Steckler Grant for nearly 3 years. Also, in my experience, I believe that investigating both of these topics is reasonable in the 3 year time frame as I earn my Master degree and Ph.D. Reasons why I believe that MSR's are suited for these applications are listed below:

High Temperature, Low Pressure Operation- Vapor pressures of molten salts are typically lower than liquid metals. This allows for very high temperatures operation at low pressures. Current models indicate that salt operating temperatures greater than 1500K are possible at Martian atmospheric pressures (~600 Pa). High temperature operation is desirable because of the difficulty of rejecting waste heat in a space environment. Low pressure operation minimizes vessel weight and issues associated with high temperature creep.

Controllability- Controlling small reactors, like those desired for space exploration, is very difficult. A paper present at Nuclear and Emerging Technologies for Space 2011 found that the random shifting in the control drum design in NASA's 40kWe Fission Surface Power System could easily result in more than a dollar of reactivity being added to the core [4]. Such a superprompt critical scenario would result in a rapid increase in power that would likely be catastrophic for a solid fuel reactor.

MSR's are very controllable because of the strong negative temperature reactivity coefficients. The MSR's 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 to fission. The end result is very large negative temperature reactivity feedback, with a reactivity feedback coefficient that is on the scale of -1.6 Cents/K. In addition, multi-physics simulations of terrestrial molten salt reactors indicate that MSR can recover from superprompt critical transients. [5] The ability for a reactor to passively control itself like the MSR is important for long term science missions, where the reactor is several light-hours away from Earth and human interaction.

Very high fuel 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. With proper fuel chemistry control, fuel burn ups greater than 20% are possible. This is in comparison to the ~3% or lower burn up offered by most solid fueled space fission system concepts. High fuel burn up technology is essential for MWe class reactors which would otherwise require 1000 kg of HEU for a round trip to Mars. Such large quantities of HEU would likely be an insurmountable political issue [6].

In brief, other advantages of space MSRs include: a simple, compact core because of the lack of internal support structure, a considerable body of relevant previous research from programs such as the Aircraft Reactor Experiment, and flexibility in mission architectures that is made possible by a liquid fuel.

Hypotheses, Goals, and Methods

Under the NSTRF12, I will investigate if molten salt reactor technology is suited for sub-100 kWe science mission reactors and MWe class human exploration reactors. My goal is to answer key research questions needed to understand how MSR technology would be used for these applications. Some of these research questions include:

- Estimate key values such as specific mass (kg/kW), Technological Readiness Level, development costs, total system mass, etc...
- Identify missions that would benefit or be enabled by MSR technology
- Formulate a plan for MSR development and identify key technologies that would require development.
- Determine power ranges in which EM pumps would be suitable for molten salt reactors.
- Conceptually develop a compact system to remove excess fission gasses for small sub-100 kWe reactors and low mass shielding options for the MWe class reactor.
- Understand and identify what power conversion technologies would be appropriate for MSRs in both applications, weighing factors such as Technological Readiness Level and specific mass.

I plan on answering these questions by utilizing and building on the tools and skills that I have gained working on The NASA Steckler Grant. These include utilizing MCNPX for neutronic calculations, FLUENT for thermal-hydraulic simulations, and organized system engineer approaches as outlined in the NASA System Engineer Handbook. Topics I hope to

build strongly upon include multi-physics simulations to model reactor dynamics and CALPHAD (Computer Coupling of Phase Diagrams and Thermochemistry) analytical tools for understanding salt mixtures with little experimental data. Throughout the project, I will be in contact with the strong network of professors who have helped me in The NASA Steckler Grant.

It is my end goal to produce a series of studies that will be in sufficient detail that planers at NASA will have enough information to consider MSR technology for future mission and technology road maps.

On-site NASA experience

Space fission system research is a small field, but an important field. The vast majority of the world's space fission system expertise is at NASA and its affiliates. On-site interaction would be an invaluable learning experience to a young engineer interested in space fission systems. I would be grateful for any NASA collaboration in my graduate studies.

Of particular interest to me is the work being conducted at Glenn Research Center for a Technology Demonstration Unit for the 40 kWe fission surface power project, and the future plans for a nuclear criticality demonstration. On site experience with these projects would help me understand how to bring a space fission system into reality in the modern era. This knowledge will help shape all my space fission system research activities. In addition, I have interest in working with individuals' who are experienced in parametric studies related to space fission systems. This would assist greatly in describing a novel piece of technology like space molten salt reactors so that this technology can be better understood in future design studies.

Terrestrial Spinoff Technology and Green Energy Impact

Terrestrial MSRs have been recognized as a potential long term solution to Earth's energy needs. [7] Molten salt reactors have the ability to efficiently utilize thorium. Thorium is an alternative nuclear fuel that is roughly 4 times as abundant as uranium. In addition, the thorium fuel cycle produces comparatively little waste and has many proliferation resistant features compared to fuel cycles using uranium. Thorium fueled molten salt reactors have not been used on large scales on Earth, due in large part to previous investment in uranium based technology and the low cost of fossil fuels. Development of the MSR for space could result in spin-off technology to aid in the development of terrestrial MSRs. Specifically, the development of advanced multiphysics tools for MSRs, like those proposed here, will aid in the study, design, and licensing of future terrestrial MSRs.

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Appendix C: MATLAB Code for Brayton Optimization

```

function [radarea] = braytonsys104(x,y)

t1=x(1);%Temp into compressor
comp= x(2);%Comp ratio
t3=y(1); % TTI
hr=y(2);
Qe=10^6;%generates numbers per megawatt
molarmass=4;
cp=2078.6/molarmass;
regen=.95;
k=0.397590361; %gamma-1/gamma
beta=(1/.97)^k;
efft=.90;% Isentropic effency of turbine and compressor
effc=.80;% Isentropic effency of turbine and compressor
altroe=.95;% alternator effency
gcef=.95; %gas cooler effecincy
tempdiff=30;
pmadeff=.97;

%work done by turbine and compressor
wt=(t3*(1-(beta/(comp^k))))*efft;
wc=(t1*((comp^k)-1))/effc;

t4=(t3)-wt;
t2=(t1)+wc;
t2r=regen*(t4-t2)+t2;
t4r=(t2-t2r)+t4;
mdot=(Qe/(altroe*pmadeff))./((wt-wc)*cp);
Qt=mdot*cp*(t2r-t3);

%rad cons

if (mdot < 0)
mdot=10^10-mdot*10^9;
end
if (t4 < t1)
t4= 10000-t4;
t1=400;
mdot=10*mdot;
end
sig=5.670373*10^-8;
epso=.85;
ts=200;
%rengnerator eff= (cold he-Hot he)/(Cold metal-hot he)

tout=((t1-t4r)/gcef)+t4r;
tin=t4r-tempdiff;
qrjc=(t4r-t1)*mdot*cp;
%tout=t1;
%tin=t4r;

twex=fzero(@(twexp) (twexp + (sig *epso/hr)*(twexp^4 - ts^4) - tout),tout);
twin=fzero(@(twinp) (twinp + (sig *epso/hr)*(twinp^4 - ts^4) - tin),tin);

```

```

%radiator area eq
radarea=(qrjc/(tin-tout))*((1/4).*epso.^(-1).*sig.^(-1).*ts.^(-3).*(-
2).^(-1).* ...
    atan(ts.^(-1).*twex)+atan(ts.^(-1).*twin))+log((( -1).*ts+twex).^ ...
    -1.*(ts+twex).*(( -1).*ts+twin).*(ts+twin).^(-1)))+hr.^(-1).*log(( ...
    (-1).*ts.^4+twex.^4).^(-1).*(( -1).*ts.^4+twin.^4))/2;
end

```