SPACE MOLTEN SALT REACTOR DESIGN CONSIDERATIONS AND RESEARCH NEEDS M. Eades, J. Flanders, T. Blue and X. Sun, The Ohio State University, Eades.15@osu.edu.

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, where 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.

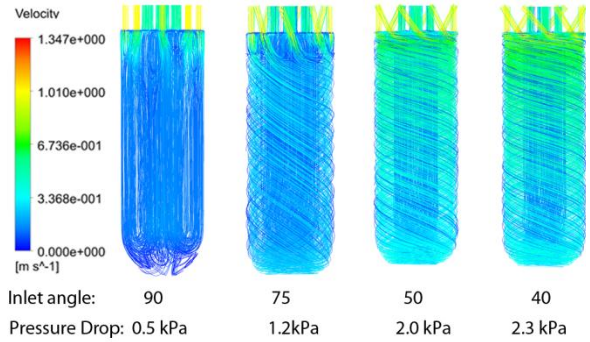

Figure 1: A series of CFD simulations of a 4 MWt space molten salt reactor. Different angles of inlet pipes were tested to minimize stagnant fuel.

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 ith group.

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

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 $\beta_{U\text{-}235}$'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 (~0.31 $\beta_{U\text{-}235}$). 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 quickly as possible. Preliminary calculations indicate that for a space molten salt reactor with a thermal power of 60 MWth, a β_{eff} >0.8 $\beta_{U\text{-}235}$ 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 over lifespand of the reactor. With more accurate fuel chemistry models, rigorous time-dependent multi-physics models will be possible.

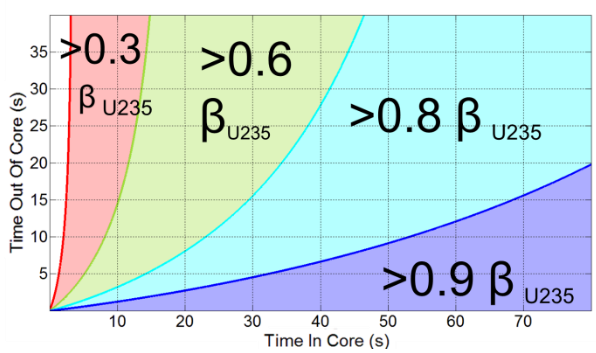

Figure 2: Regions of β_{eff} in terms of equivalent solid fuel $\beta_{U\text{-}235}$ for a molten salt reactor fueled with U-235 as a function of time in and out of the core.

References:

[1] Eades M. et al. (2012) Proceedings of Nuclear and Emerging Technologies for Space, Paper 3293. [2] Fraas, A. P., and Savolainen, A. W., (1956) Oak Ridge National Lab, ORNL-TM-2095. [3] Cantor, S., (1968) Oak Ridge National Lab, ORNL-TM-2316.[4] Khokhlov V. (2008) Journal of Fluorine Chemistry, Volume 130, Issue 1 30-37.