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SULEU NTP Core with Passive Reactivity Control and Enhanced Submersion Safety

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1. Introduction

It is widely acknowledged that nuclear thermal propulsion (NTP) is an enabling technology for manned missions to Mars and other locations beyond low-Earth orbit [1]. Without nuclear thermal propulsion, manned space travel will be severely limited by the propellant requirements of chemical propulsion and significantly longer travel times of electric propulsion. While the performance superiority of NTP is clear, its implementation has been to date unsuccessful due to the significant costs of development, implementation, and regulations associated with the heritage NTP designs. These designs are based on the use of highly enriched uranium (HEU) fuel, which, while required in order to achieve the highest performance possible, adds significant costs and security concerns that have seriously increased the difficulties of implementing NTP.

In response, recent developments at KAIST [2][3][4][5], the Center for Space Nuclear Research (CSNR) [6][7][8][9], Aerojet-Rocketdyne, Ultra Safe Nuclear Corporation (USNC) [10][11], and NASA Marshall Space Flight Center have been centered around designing NTP systems which make use of low-enriched uranium (LEU) fuel. These new systems take heritage designs and experimental results and adapt them to use LEU fuel with minimum impact on the heritage system. This is done in order to ensure their continued relevance with existing NTP research efforts and enable their rapid implementation into existing NASA efforts for human Mars mission planning. Of the current baseline NTP designs being studied, this paper concerns itself with the improvement of the Superb Use of Low Enriched (SULEU) core [10].

In this summary, SULEU has been adapted to implement some of the latest developments of LEU-NTP design efforts. These include the implementation of a rapid depletion burnable absorber to flatten the reactivity profile during operation and the addition of a lower axial reflector to help minimize the reactivity increase during the full submersion criticality accident. The purpose of this study is to show the state of current LEU-NTP designs in terms of resolving key issues such as minimizing control drum usage and resolving the full submersion criticality accident.

The calculations for this paper were done using the ENDF/B-VII [12] neutronics library and Serpent 2 [13] for the depletion calculations and MCNP6.1 [14] for the performance and steady state criticality calculations. The depletion calculations were done using 360,000 particles with 250 active cycles and 75 inactive cycles. The steady state calculations were done using 100,000 particles with 500 cycles and 50 inactive cycles. The performance calculations were done using the SPOC [7] code. The analysis methods used in SPOC for the thermal hydraulics have recently been vetted by researchers at NASA Marshall and have been found to be sound in their methodology and implementation [15].

2. Baseline Core Design

The baseline core used in this study is the SULEU core. This is a graphite-composite LEU-NTP core designed to meet the mission performance requirements of a NASA DRA 5.0 mission. It is able to provide 155 kN of thrust with 897.7 sec of specific impulse. The core power is 768.9 MW and the total core mass is 2498 kg (excluding the core shield). The fuel power density in the core is 3.542 kW/cm^3. Details for the core configuration and properties can be found in reference [10].

3. Key LEU-NTP Issues

Currently two issues have been identified in LEU-NTP reactors: minimization of control drum rotation and maintaining sub-criticality in the event of a full water submersion. The first of these issues has been presented in depth by Poston and Venneri [?]. The issue lies in the significant performance loss resulting from changes in the radial power profile. As the radial control drums are rotated to compensate for losses in reactivity due to fissile material depletion and fission product build-up, the radial power profile is altered. This in turn reduces the effectiveness of the coolant channel orificing which then results in a drop of the exit coolant temperature as the core power is reduced to prevent the melting of the fuel as the power profile changes. A plot of the effects of radial control drum position and the change in specific impulse is presented in Fig. 1.

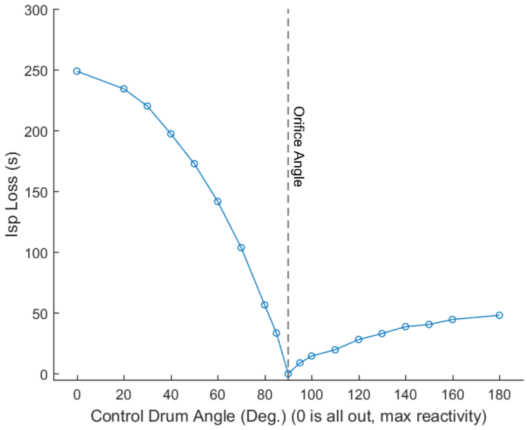

Figure 1. Reduction in specific impulse as a function of control drum position.

The second major issue requiring resolution is the need to maintain a sub-critical reactor in the case of a full submersion accident. In the current LEU-NTP core design, the core undergoes a significant increase in the core reactivity when it is fully submerged in water (~12.5$ for SULEU). This is currently just below the full control worth of the radial control drums (~15.3$), providing just shy of 3$ of excess reactivity available for fissile depletion, material impurities in the core, and reduces the margin for error in the case of one or multiple radial control drums fails to operate correctly. Furthermore, it precludes the use of the radial control drums for reactor start up for the second trans-Mar insertion burn (TMI2) due to the large negative reactivity resulting from xenon-build following the first burn. The control drum reactivity profile assuming the core has been orificed with the control drums in the center position is shown in Fig. 2, showing the full range of the control drum operation. In Fig. 2, reactivity is shown in terms of the Δk.

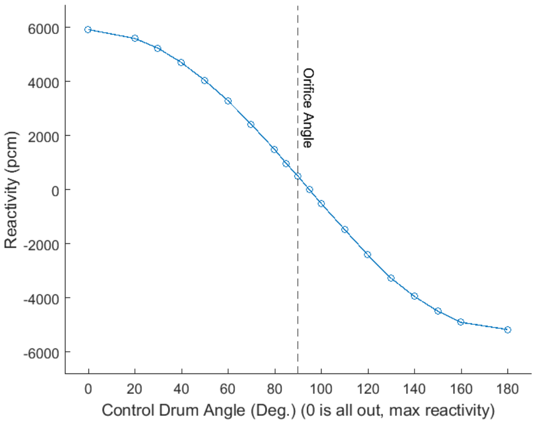

Figure 2. Control drum reactivity insertion as a function of control drum angle.

4. Rapid Depletion Burnable Poison

One of the key solutions being proposed for reducing control drum movement is the use of a low-density burnable absorber dispersed in the structural material of the core. The use of a low density absorber ensures aspects. First of all is the rapid depletion of the poison. The depletion rate required for NTP full power operation is extremely fast, mandated by the high power density and the 20 minutes operating time mandated by the typical mission profile. In this case, the core never reaches xenon equilibrium, requiring the burnable poison to counteract not only the effects of fissile material depletion but also the build-up of fission products in the core. The second aspect is the need for a linear depletion rate of the poison. By minimizing the spatial self-shielding of the poison, the depletion of the poison is close to linear during full power operation. In this study, isotopically pure ^{157}Gd was dispersed in ppm quantities in structural material elements of the SULEU core, the tie-tubes. A plot of the effect of the different Gd loadings on the depletion profile for a typical Mars mission is shown if Fig. 3.

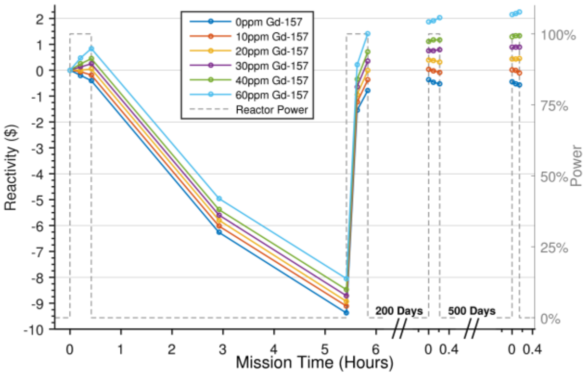

Figure 3. Effect of Gd-157 loading in the tie-tube material on reactor burn-up.

5. Lower Axial Reflector

One method by which to reduce the full-submersion criticality is to add a reflector at the core exit. The effectiveness of such an approach is largely due to increasing the clean core reactivity. This can be seen in Fig. 4 for the addition of a graphite reflector. The result of the is a net reduction of the submersion worth (the difference between the submerged core reactivity and the clean core reactivity), as shown in Fig. 5. The standard deviation for the points shown in Figs. 4 and 5 is on the order of 0.05$. The reactivities reported in Fig. 4 are with the control drums in the fully disengaged position (equivalent to the “rod out” position). This large excess reactivity can be adjusted later with the use of neutron poisons, reducing the enrichment of fuel, or reverting to the use of higher performance structural materials (nickel based alloys). The effective delayed neutron fraction (β_{eff}) was determined using Serpent 2 and was used for the conversion of Δk to $. The value used is 0.00724 with a standard deviation of 1.56E-5.

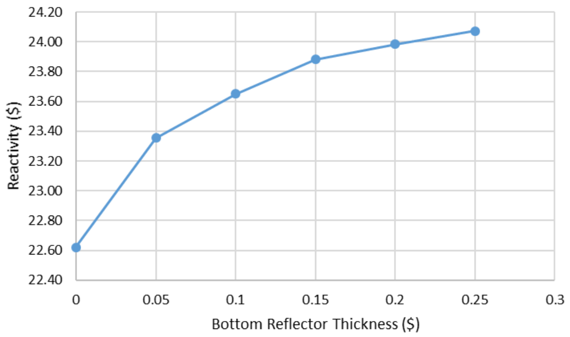

Figure 4. Effect of bottom reflector thickness on clean core reactivity.

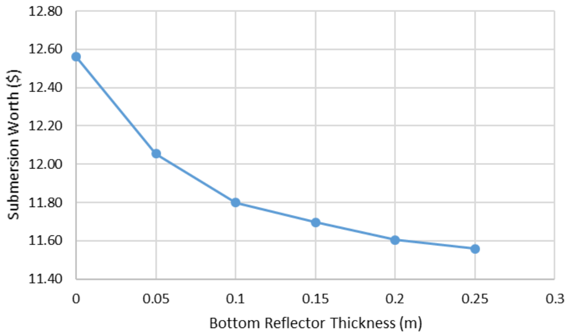

Figure 5. Effect of bottom reflector thickness on the submersion worth.

6. Conclusions

In the present summary, we have shown two pathways to address existing issues in LEU-NTP cores: minimization of control drum movement and the full-submersion criticality accident. Through the application of a rapid depletion poison in the core, control drum movement during operation can be effectively eliminated. With the addition of a bottom graphite axial reflector, the submersion worth of the core can be reduced by about a dollar.

Future work will include integrating the rapid depletion poison with other passive reactivity control devices (such as hydrogen density in the tie-tubes) and developing additional systems for mitigating the full-submersion criticality accident.

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