THERMAL HYDRAULIC DESIGN AND OPTIMIZATION OF A TUNGSTEN CERMET LEU-NTR

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Introduction: In the summer of 2013, a small team at the Center for Space Nuclear Research in Idaho Falls, ID completed the preliminary design of a 25 klbf nuclear thermal rocket which makes use of tungsten cermet low-enriched uranium fuel [1]. The design achieves a high specific impulse (Isp) and thrust-to-weight ratio by making use of existing technology and materials. In pursuit of these goals it was necessary to conduct thermal hydraulic analyses to calculate the temperature distributions and flow characteristics of the rocket's nuclear core.

Analysis Methodology: Temperature distributions and flow characteristics were calculated for steady-state operation in order to ensure that the core materials would remain within their design limits while operating at full power. The propellant flow characteristics were calculated to determine system pressure drops and to ensure that propellant flow remains unchoked in full power operation.

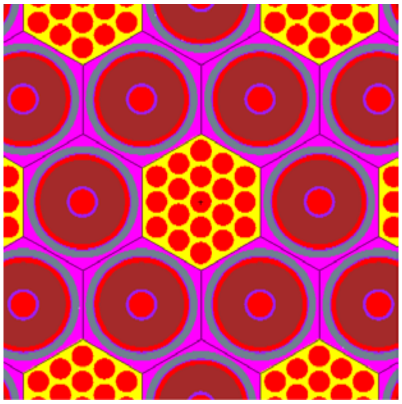

Figure 1: Fuel-moderating-element lattice

To perform these calculations a finite difference analysis code was developed. This methodology was chosen because of the complex geometry and heat transfer pathways in the moderating element. The heat transfer calculations are made conservative by applying an adiabatic boundary condition to the fuel elements and by applying the fuel centre line temperature as the boundary condition to the outer surface of the moderating elements. A top-down view of the fuel-moderating-element lattice is depicted in Figure 1.

Application of Finite Difference Code:

Calculation of fuel temperature distribution F6 tallies were used in MCNP5 to calculate the power distribution in the central fuel and moderating elements as well as in the remaining elements that make up the core lattice. The power profiles were then used to calculate the fuel temperature distribution in an equivalent tube surrounding the central coolant channel. The calculated fuel temperature distribution in the central fuel element can be seen in Figure 2.

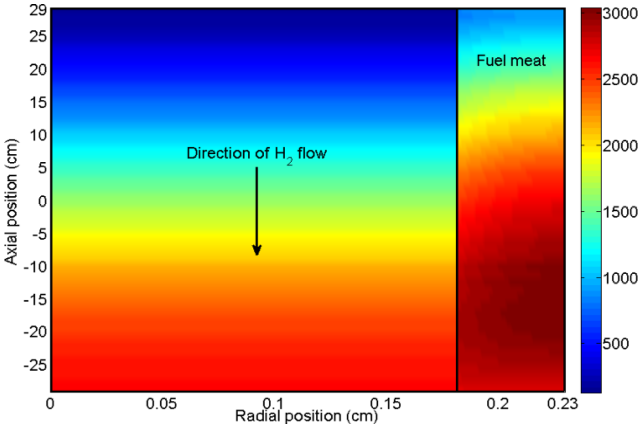

Figure 2: Temperature distribution in an equivalent tube of the central fuel element

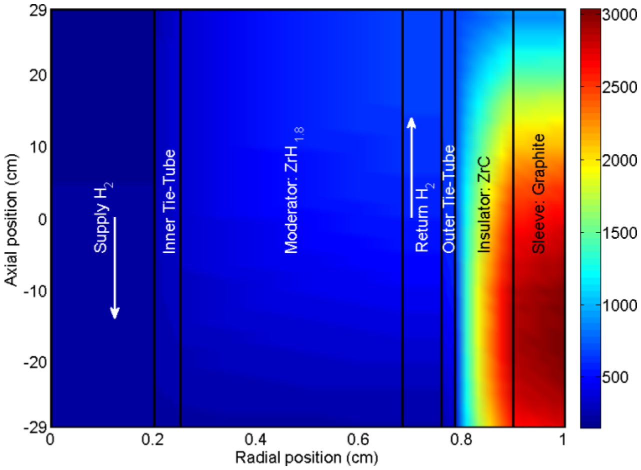

Figure 3: Temperature distribution in moderating element

Calculation of moderating element temperature distribution Power profiles from the F6 tally were available for all materials in the central moderating elements. Along with these power profiles, the fuel centre line temperature was imposed as a conservative outer surface boundary condition to the moderating elements in order to calculate the temperature distributions. The calculated moderator element temperature distribution is shown in Figure 3.

These calculated temperature distribution values could then be used to insure that all temperatures are kept within their operational bounds during steady state operation.

Optimization Methodology: The radial power peaking factor (PPF) is one of the primary constraints on NTR performance. The initial design's PPF was 1.43 and this was decreased by employing radial enrichment zoning. The fuel elements were put into four PPF bins, as depicted in Figure 4. The outermost elements are enriched to 19.75% and each successive bin's enrichment is decreased by 1%, giving the central elements an enrichment of 16.75%. The reactor was kept critical by rotating the control drums from the 90^o position to the 50^o position. These changes reduced the PPF to 1.293.

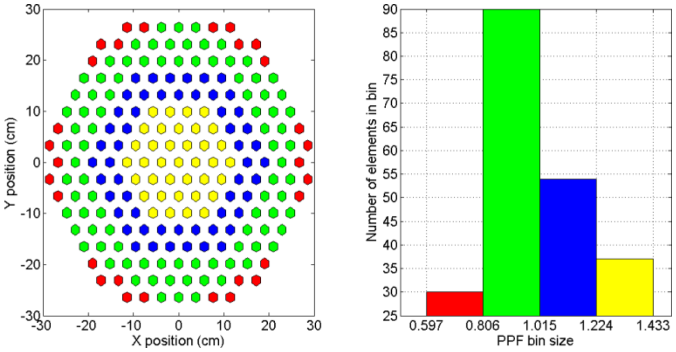

Figure 4: Radial enrichment zoning using 4 PPF bins

Further performance gains were subsequently made by employing radial coolant channel radius optimization. This analysis was performed by finding the intersection of two surfaces, the first surface constrains the fuel elements to have the same average outlet temperature, while the second surface constrains the pressure drops to be equal, Figure 5. The fuel elements were once again put into four bins based on their PPFs. The optimized radii and mass flow rates were then calculated by determining those points on the curve of intersection corresponding to the fuel elements with the highest PPF in each bin. These changes further reduced the core's PPF to 1.265.

Optimization Results: The optimization made it possible to increase the NTR's power from 460MW to 507MW while maintaining the reactor mass at 1110kg. Consequently the average propellant outlet temperature increaesed from 1856K to 2311K which increased the Isp from 802s to 935s based on the propellant properties at core outlet conditions and using a value of 1.293 for the ratio of specific heats of H_2 at 4.5 Mpa [2]. These results are summarized in Table 1.

Table 1: Comparison of the performace characteristics of the initial core to the optimized core.

Quantity	Initial Core	Optimized Core
Power (MW)	400	507
Mass (kg)	1110	1110
Mass flow rate (kg/s)	14.57	14.57
Thrust (klbf)	25.78	30.07
All-in thrust-to-weight	5.08	5.74
Core outlet temp (K)	1856	2311
Specific impulse (s)	802	935
Mass of ^{235}U	15.3	14.2
# Fuel elements	211	211
# Moderating elements	636	636

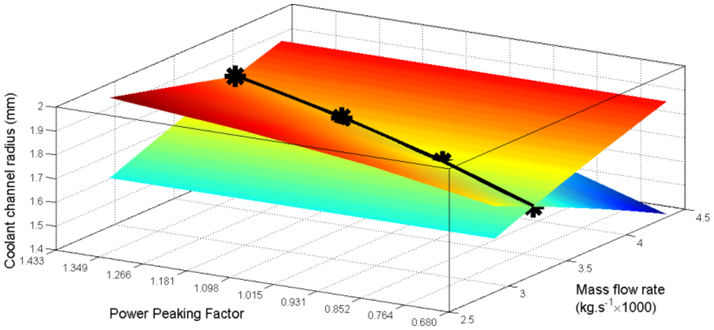

Figure 5: Curve of intersection defining radii and mass flow rate solutions

Summary and Future Work: An analysis code was written that automatically generated MCNP core input files and searched for the lowest mass, critical configuration. The lowest mass core was analyzed using the thermal hydraulic code developed by the team and initial performance characteristics were determined. Radial enrichment zoning and radial coolant channel radius optimization procedures were then implemented to lower the core's radial power peaking factor, thus making it possible to increase the core's power at constant mass and propellant mass flow rate.

References:

[1] Center for Space Nuclear Research (2013), '*Design of a Low-Enriched Nuclear Thermal Rocket*', Internal Report.

[2] U.S Dept. of Commerce (1972) '*Technical Note 617: Thermophysical Properties of Parahydrogen*', page 96.