High Performance Bimodal Nuclear Thermal Rocket K. Shipley[1], L. Sudderth[1], W. Deason[1], D. Casey[1], L. Fischhaber[1], J. Marquis[1], R. Saleem[1], [1]Center for Space Nuclear Research

Introduction: Space propulsion methods that enable decreased transit time to Mars and other neighboring planets at a lower cost are of increasing interest. One method of providing such propulsion is through the use of bimodal nuclear thermal rockets (BNTRs). BNTRs provide a higher specific impulse (I_{sp}) than chemical rockets, a higher thrust than electric propulsion systems, and have the ability to power on-board systems from the fission reactor system excess heat. Furthermore, the use of tungsten cermet fuel allows for higher operating temperatures and maintains the structural integrity of the core [1]. As part of the 2011 Summer Fellows program at the Center for Space Nuclear Research at the Idaho National Laboratory, we examined the feasibility of a high performance BNTR that produces 100 kW of electrical power and 6000 lbf of thrust.

Method: *Reactor* Reactor design began with integration of the power plant with a typical NTR core. The Brayton cycle flow channels, which can remove heat independently or during propulsion, were symmetrically distributed throughout the tungsten cermet core. The number of flow channels used was based upon conservative calculations of the temperature rise across fuel elements during power mode. During propulsion mode, hydrogen provides primary heat removal and the temperature rise across the fuel is relatively independent of the Brayton cycle mass flow rate.

Monte Carlo N-Particle Transport Code (MCNP5) Version 5 with ENDF libraries at a fuel temperature of 2500K was used to determine the critical configuration with the lowest mass and the temperature defect caused by the maximum fuel temperature of 3000K [2]. Burnup calculations were evaluated in MCNPX using the maximum operating power for a mission to Mars (200 MWt for 1 hour in propulsion, 700 kWt for 706 days in power cycle) [3].

The submersion accident scenario, which considers the reactivity effect caused by the reactor falling in wet sand and filling with water, was evaluated using MCNP5. Reactor conditions with and without an intact reflector were considered [4].

Power cycle Design of the HeXe cooled Brayton cycle began with the construction of a thermodynamic analysis code in MATLAB [5]. System analysis included pressure drops through all components and mass optimizations were done to reach the lowest possible system mass.

Propulsion System The propulsion system was modeled as an expander cycle featuring a single turbopump and conical cooling jacket. Hydrogen was chosen as the propellant due to its high specific energy. An analytical model of the system was developed using MATLAB, [5] and Star-CCM+ was used to validate resultant fuel element temperatures [6].

The analytical fuel element was modeled as a cylindrical tube [7] where the maximum fuel temperature was the peak design factor. The maximum temperature was set to 3000K, just under the melting point of UO_2.

Hydrogen properties were determined using CEA [8] and were used to develop an accurate model of the heat transfer between the propellant and reactor. The reactor power profiles, both radial and axial, were determined using the MCNP5 energy deposition tally in 2cm segments of a fuel element through the center of the reactor.

Shielding The shadow shield for electronics and the SmCo magnets of the alternator were sized using the MCNP5 point flux tally as a mass estimate for the mission to Mars.

Results and Discussion: *Reactor* The core consists of 247 hexagonal fuel elements. The tungsten cermet fuel (60% UO_2 - 40% W/Re by volume, 93% enriched ^{235}U) allows for higher operating temperatures and maintains the structural integrity of the core [1]. The Brayton cycle flow channels, shown in Figure 1, substitute fuel hexes in the final reactor configuration, shown in Figure 2.

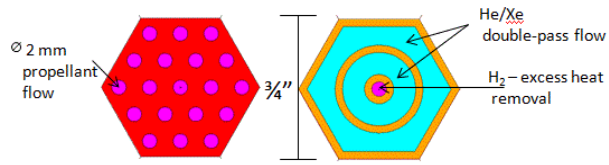

Figure 1. Fuel Element (left) and Brayton fluid flow (right)

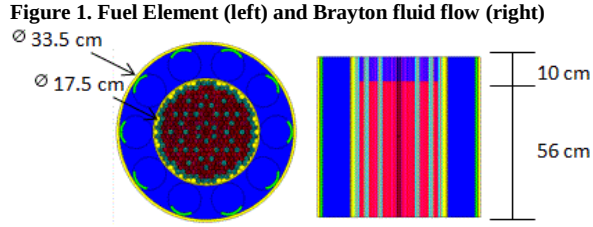

Figure 2: Radial (left) and Axial (right) cross-sections: Be (blue), B_4C (green), pressure vessel (yellow), fuel (red).

The excess reactivity ($2.41), temperature coefficient of reactivity (-4.05E-4 $/K), and low burnup allow for a minimum lifetime of 12.5 years at 3000K. A longer lifetime can be expected due to the overestimation of the power levels in the burnup calculation. The high worth reflector ($31.92) minimizes the

critical mass, while the control drums provide $8.37 of negative reactivity and redundancy from the ability to shutdown the reactor with only 3 out of the 10 drums. This also allows for fast removal of excess heat when switching from propulsion to the power cycle and reduces the amount of propellant required to cool the reactor during this time. The total mass of the reactor is 942.2 kg.

Submersion analysis evaluated the reactor in the event of a launch failure. Since the reactor remains shut down until low-earth orbit, the control drums maintain a k_{eff} of 0.991. If the reflector separates, the reactor remains subcritical at $k_{eff} = 0.997 \pm 6.0 \times 10^{-4}$.

Power Cycle The closed Brayton Cycle was chosen as the power conversion cycle for its low specific mass and technological readiness level. HeXe, with a molar mass of 40 g/mole was chosen as the working fluid for its performance in low mass closed Brayton Cycles [9]. With a turbine inlet temperature of 1300K and a compressor inlet temperature of 450 K, a system efficiency of 20% was calculated. To produce the lowest system mass, the sizes of the regenerator and radiator heat exchanger and the temperature of the compressor inlet were varied. It was found that a higher compressor inlet temperature decreased system efficiency but lowered system mass due to a lower radiator size.

Propulsion System The system performs at 6000 lbf with a 3.2 kg/s mass flow. This results in a specific impulse of 860 seconds, a maximum fuel temperature of 3000K, a maximum propellant temperature of 2900K, and an 80 psi pressure drop through the core. The CFD analysis resulted in higher fuel temperatures of 3200 and 3300 with and without an axial reflector. Further analysis is needed to determine the cause of the temperature difference between CFD and analytical calculations.

The final system configuration is shown in Figure 3. Temperatures and pressures are given through each step of the expander cycle from the fuel tank through the nozzle exit.

Shielding The shield, composed of Tetramethylammonium borohydride (TMAB) and lead for neutron and gamma attenuation respectively, was designed for the dose limits of the alternator and electronics [10, 11, 12]. With the recuperator placed directly behind the shield, the required shield mass for a mission to Mars, was estimated to be 756.6 kg.

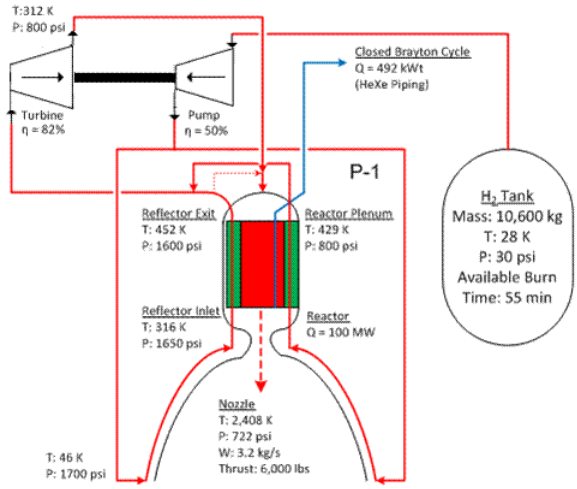

Figure 3: Propulsion System

Conclusion: A high performance BNTR was achieved by using W-Re cermet fuel, allowing for a peak fuel temperature of 3000 K. The BNTR is capable of achieving a thrust to weight ratio of 1.3 with 6000 lb_f thrust. The electrical power system produces 100 kWe with a system mass of 3600 kg, including the reactor, shield, Brayton components, and radiators. Further work is still needed to verify the developed CFD model, optimize shielding, and to explore the performance enhancement capabilities of fuel enrichment zoning.

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References:

[1] Webb, J. and Gross B. (2011) A *Conceptual Multi-Megawatt System Based on a Tungsten CERMET Reactor, NETS* 3275. [2] X-5 Monte Carlo Team (2005) *MCNP – A General Monte Carlo N-Particle Transport Code - Version 5*, LA-UR-03-1987, Los Alamos, NM. [3] X-5 Monte Carlo Team, (2008) *MCNP – A General Monte Carlo N-Particle Transport Code - Version 2.6.0*, LA-CP-07-1473, Los Alamos, NM. [4] Bess J., (2010) *Reactor Submersion*, Letter to Laura Sudderth. [5] *Matlab & Simulink Student Version* (2011) Computer software. MathWorks. [6] *Star-CCM+ (2011)*, CD adapco. [7] Emrich B., (2010) *Nuclear Rocket Propulsion*. [8] McBride, J. and Gordon S., (2005) *Chemical Equilibrium with Applications*. [9] El-Genk et al. (2007) *Noble-Gas Binary Mixtures for Closed-Brayton-Cycle Space Reactor Power Systems, JPP* 23.4. [10] Craft, A. E. and King J. C. (2010) *Radiation Shielding Options for a Nuclear Reactor Power System Landed on the Lunar Surface, Nuclear Technology* 172.3, 255-72. [11] Craft A., (2009) *Mass Optimization Studies of Reactivity Control Schemes and Radiation Shielding Options for Space Nuclear Reactors*, Thesis, Missouri University of Science and Technology. [12] Angelo J. A. and Buden D. (1985) *Fundamentals of Radiation Protection and Shielding, Space Nuclear Power, Orbit Book*.