DRIVER FUEL DESIGN FOR A CERMET NUCLEAR THERMAL ROCKET.

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Introduction: High-thrust, high specific impulse (ISP) Nuclear Thermal Rockets (NTR) require high volumetric flow rates and high pressure drops; because flow area is limited by criticality and high velocity is needed to reduce film temperature drop. This combination of high flow and pressure drop requires considerable pumping power. A turbopump is the usually considered the best pumping option, except for extremely low-thrust systems where an electric pump, tank pressure, or other options might work.

Pumping Power Options: For low-thrust NTRs (~10 klb) the pumping power can sometimes be gained via parasitic power losses, in particular from chamber enthalpy lost to the nozzle and reactor energy deposited in ex-core components (reflector, drum poison, shield, structure, etc.). At thrusts >>10 klb the only practical way to get this pumping power is to utilize power from the reactor core.

A hot-bleed cycle is an option, but it introduces significant complexity and performance issues. The low-pressure, hot gas from the chamber will likely be transpiration-cooled at the bleed inlet, which can reduce bulk fluid temperature via mixing, and after powering the turbine it must be discharged at a low temperature/specific impulse. In addition to the design complexities, this can lower ISP by > 50 s [1], a huge penalty for any propulsion system.

In traditional high-thrust, graphite-based NTRs, the pumping power is obtained from the tie-tube assemblies, which also provide core support and neutron moderation. High thrust, fast-spectrum cermet-fueled NTRs do not have a dual- or tri-use application for something akin to tie-tubes, so a different kind of option may be desirable. This paper examines the utilization of “driver” fuel to power the turbine; i.e. dedicated fuel elements plumbed into a high-pressure loop that feeds/drives the turbopump.

Driver Fuel Options: A driver element will likely have fewer, larger flow channels than a thrust element, which makes fabrication easier, improves neutronics (lower coating fraction) and most importantly reduces pressure drop. The best configuration will likely have that driver flow entering and exiting at the reactor inlet. Three in-core options are discussed below (ex-core, reflector fuel could also be considered).

Perimeter Elements. These could be 2-pass elements, or 1-pass elements with the return flow in slats or an adjacent element. Pros: Easiest plenum design, prevents thermal conduction loss from thrust elements (helps ISP), modest power density (may be optimal). Cons: Will make external control more difficult (mass penalty, or in some cases make drums infeasible), long elements and small total flow cross sectional area (pressure drop), axial thermal expansion mismatch with thrust elements (uncertain if significant issue).

Internal Elements. These elements would be 2-pass elements very similar in function to the tie-tube elements in graphite-based reactors. Pros: Design heritage of tie-tube plenum, could provide core structural support if needed (non-issue or major advantage depending on how development progresses). Cons: In addition to the long flow path and small area, the high power density and need for 2-pass flow will make low-pressure drop difficult, as well as reduce the element fuel fraction (overall neutronic negative), plus axial thermal expansion mismatch with thrust elements.

Inlet Elements. These would be short elements placed at the core inlet. The best option might be a 3-path element, which would allow passage of the primary core coolant through a large central hole (low pressure drop and heat transfer), with internal flow channels cooling the fuel, and driver flow returning around the element exterior. Alternatively, a 2-path design could be used, with the 3rd flow path being the slat region plumbed into an axial plenum between the driver and thrust regions. Pros: Short elements with the full core available for flow area (very low pressure drop), no axial expansion issue. Cons: Most complex plenum design. Pro and con: Low power density gives design flexibility, but requires more fuel and higher mass.

Design Methodology: The design and analysis of driver fuel elements/configurations has been incorporated into NTRgen, an automated tool that calculates system dimensions, temperatures, etc. and creates input files for the transport code MCNP. MCNP then calculates criticality and power depositions which are fed back into the design. NTRgen also has the capability to perform simplified thermal-hydraulic and gas-dynamic calculations to estimate rocket performance. This allows a self-consistent design of the integrated system; most importantly the thrust region, driver region, reflector/drums, pump, expander, and nozzle.

A Driver Fuel Concept for 25-klb Rocket: A driver fuel concept was created for a 25-klb cermet NTR, which utilizes 1-pass perimeter elements. Schematics of the reactor concept are shown in Figures 1 and 2. The fuel (light-blue) is 54 v/o UO2 (93% enr.), 6 v/o Gd2O3 and 40 v/o W. The channel and hex liners (purple) are W (0.020 cm thick) and W25Re (0.038 cm thick) respectively. The slat region (green) is 20% W 80% void. The radial reflector (blue) is Be, the drum poison (orange) is B4C (95% enr.), and the axial ref-

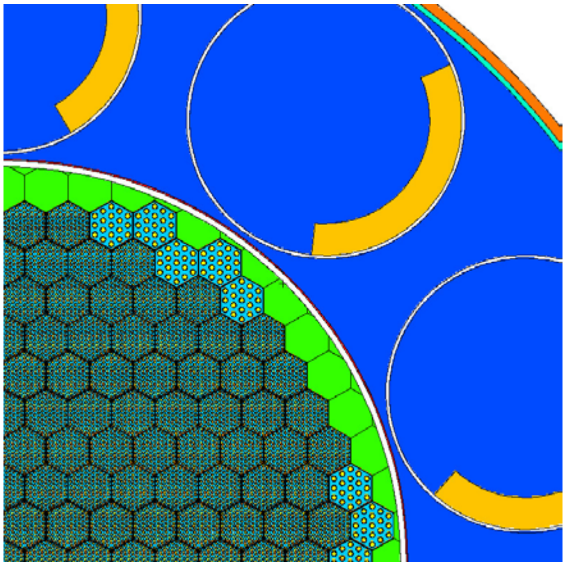

Figure 1. Driver Elements at Corners of Core.

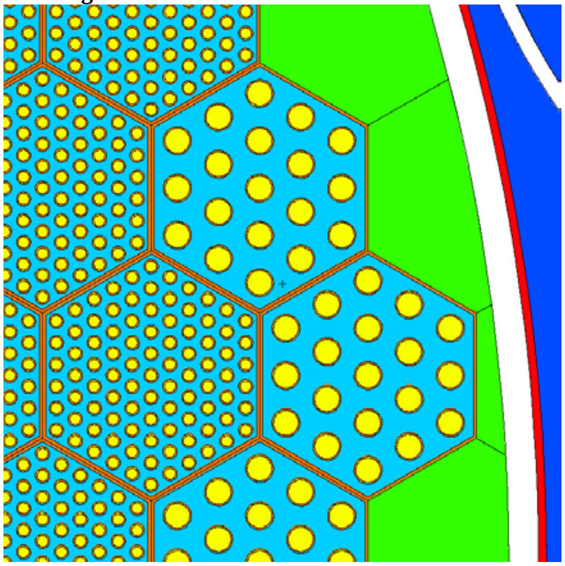

Figure 2. Close up of Thrust and Driver Elements.

lector (not shown) is BeO. The driver fuel elements are easily noticed by the large holes. There are 30 driver elements placed at the corners, which simplifies plenum design and provides a thermal barrier between the thrust elements and reflector where the slats are thinnest. Several reactor parameters are in Table 1.

The rocket flow splits into 2 parallel paths downstream of the pump: one stream goes through the driver fuel, slats and expander while the other goes through the nozzle, reflector and shield. These 2 streams recombine and then pass through the thrust elements en route to the nozzle. The estimated pressures, temperatures, flow rates, and rocket performance are shown in Table 2.

References: [1] Belair M., Sarmiento C., Lavelle T. (2013) *AIAA 2013-4001*.

Table 1. Reactor Parameters

543	Reactor power (MW)
2159	Reactor Mass Estimate (w/o shield) (kg)
901	Fuel mass (kg)
308	U-235 mass (kg)
49.3	Core outer diameter (outer slat)(cm)
92.4	Vessel outer diameter (cm)
70.0	Fueled length (cm)
18.0	Axial reflector length, cold end (cm)
2.69	Fuel element flat-to-flat (includes coating) (cm)
	Thrust Fuel Elements
235	Number of elements
0.180	Fuel hole diameter (coating OD) (cm)
0.139	Flow channel diameter (cm)
478.4	Zone power (MW)
12.49	Zone flow rate (kg/s)
14.85	Zone peak fuel power density (MW/l)
7.88	Zone average fuel power density (MW/l)
2850	Zone peak fuel temperature (K)
	Driver Fuel Elements
30	Number of elements
0.360	Fuel hole diameter (coating OD) (cm)
0.319	Flow channel diameter (cm)
54.3	Zone power (MW)
3.75	Zone flow rate (kg/s)
10.28	Zone peak fuel power density (MW/l)
7.09	Zone average fuel power density (MW/l)
1528	Zone peak fuel temperature (K)

Table 2. Rocket parameters.

0.28	Tank pressure (MPa)
15.01	Compressor outlet pressure (MPa)
14.81	Driver fuel inlet pressure (MPa)
13.34	Driver fuel outlet pressure (MPa)
13.14	Turbine inlet pressure (MPa)
9.50	Turbine outlet pressure (MPa)
9.30	Core inlet pressure (MPa)
5.00	Core outlet pressure (MPa)
3.75	Driver flow rate (kg/s)
8.74	Regen flow rate (kg/s)
20	Tank temp (K)
40	Compressor outlet temp (K)
1000	Turbine inlet temp (K)
917	Turbine outlet temp (K)
239	Regen loop outlet temp (K)
439	Core inlet temp (K)
2739	Core outlet temp (K)
909	Specific impulse (s)
111	Thrust (kN) == 25.0 klb