FUEL ZONING OF NTR CONCEPTS WITH VARIABLE CHANNEL DIAMETERS.

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Introduction: For most prospective missions, the key performance parameter of a Nuclear Thermal Rocket (NTR) is specific impulse (Isp). First order, Isp is dictated by the mixed-mean outlet temperature of the reactor coolant; thus the reactor designer must try to obtain the peak outlet temperature while staying within fuel/core thermal, chemical, and structural limits. This task is complicated by the spatial variability of fission power deposition, which can be twice as high in one core region versus another. Of particular concern are "channel" and "element/hex" peaking – if one fuel element (hex) has a power deposition 10% higher than another, the coolant delta-T though that element will be ~10% higher given the same flow rate (depending on changes in specific heat). In an NTR, coolant delta-Ts are ~2500 K, so a 10% increase in power causes an outlet temperature increase of ~250 K. If the peak-power element is designed to the highest possible outlet temperature, then the off-peak elements would have much lower outlet temperatures, resulting in a much lower mixed-mean outlet temperature. Element peaking factors (peak-to-average) in unzoned NTRs generally range from 1.3 to 1.4, so the core-average delta-T would be ~1000 K lower than peak (if each channel has the same flow), which is clearly unacceptable.

Fuel Zoning Options: There are two effective options to mitigate the impact of power peaking in an NTR – 1) flatten the power distribution and/or 2) match the flow distribution to the power distribution.

Orificing. The simplest way to match element flow to power deposition is to use an orifice that restricts flow through lower power elements – ideally the flow can be adjusted to achieve exactly the same coolant outlet temperature in each element. There are two significant downsides of orificing. First, your system is required to generate and expend the energy to force the coolant through the orifices. In effect, the flow rate/thrust that could ideally be provided is reduced by the element peaking factor (30% to 40% for a typical NTR). Second, orificing works well during nominal steady-state conditions, but at low flows and during transients they can create significant flow misdistribution and/or potential flow instabilities.

Enrichment Zoning. Element power peaking can be substantially reduced by reducing fissile enrichment in higher power (flux) regions of the core. The power of each individual element could be nearly identical if each was enriched to the ideal ^{235}U concentration (except for intraelement power variations and changes in power distribution due to fuel burnup). Logistical limitations make zoning each element impractical, and no more than 10 enrichment zones, and perhaps less than 5 could be pratical. One drawback of using enrichment zones is the need for distinct downblending campaigns, and the increased level of fuel procedures, operations, and quality-assurance; which is significant because of the high cost and regulation of using HEU. Also, for almost any NTR, a system that uses all 93% enriched fuel will have a lower mass, and require less overall fuel than an NTR that uses any reduced enrichment zones (unless the concept is fully power-density limited).

Geometrical Zoning. Altering the internal geometry of fuel elements/hexes offers the ability to both flatten power distribution and match flow to power. Options include varying hole size, total number of holes and/or coating thickness both axially and radially. The most effective option may be use elements with larger flow diameters in high power regions, which simultaneously draws more flow, reduces element power (lower fuel fraction), and reduces fuel delta-T (shortens the conduction path) – this is the option investigated in this paper. Axial variations were not considered for this study, but concepts can potentially use variable coating thickness (thinner at cold end) or even a different fuel (e.g. Mo-UN) in the cooler regions.

Design Methodology: The design and analysis of these concepts has been performed by 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. Note: the current methodology does not account for thermal conduction from thrust elements to lower temperature elements, in particular to driver elements and/or slats.

Zoned Concept for 25-klb Cermet NTR: The starting-point for generating concepts with variable diameter fuel zones is a 25-klb cermet NTR, which utilizes 1-pass perimeter driver-fuel elements[1]. Schematics of a zoned reactor concept are shown in Figure 1. In each of the concepts evaluated, the fuel is 54 v/o UO_2 (93% enr.), 6 v/o Gd_2O_3 and 40 v/o W. The channel and hex liners are W (0.020 cm thick) and W25Re (0.038 cm thick) respectively. The concepts utilize a BeO axial reflector, a Be radial reflector, and 10 Be/B_4C control drums. Four concepts are shown in Table 1; the original unzoned concept followed by three 5-zone concepts: one with reduced pressure, one with reduced mass, and one with higher Isp.

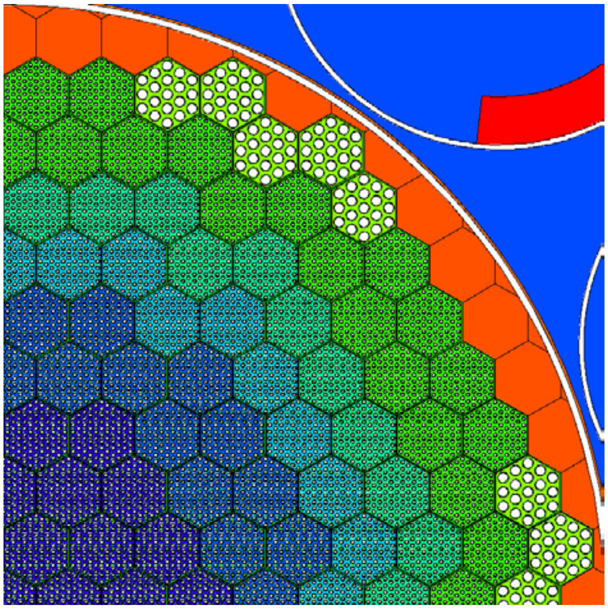

Figure 1. Zoned NTR core. Flow channel diameter is largest in central dark-blue zone, then decreases in blue, light-blue, light-green and green zones. The corner elements with large holes are driver-fuel elements, which provide high-pressure heat to the turbopump. Orange represents 20% W filler slats. The outer blue is Be reflector and red is B_4C drum poison.

Table 1. Reactor Parameters.

1	5	5	5	Number of Diameter Zones
	Lower Press.	Lower Mass	Higher Isp	Design benefit
2159	2141	1900	2216	Reactor mass (w/o shield)(kg)
308	310	291	331	^{235}U mass (kg)
49.3	49.3	48.0	47.5	Core outer dia. (slat OD) (cm)
92.4	91.4	86.1	86.6	Vessel outer diameter (cm)
70.0	70.0	66.5	80.0	Fueled length (cm)
18.0	18.0	15.0	15.0	Ax. reflector len. (inlet) (cm)
2.69	2.69	2.62	2.59	Hex flat-to-flat(incl.coat)(cm)
235	235	235	235	# thrust fuel elements
91	91	91	91	# flow chan. in thrust elem.
0.180	0.185	0.176	0.179	Max hole dia.(coat.OD) (cm)
0.139	0.144	0.135	0.138	Max flow channel dia. (cm)
0.139	0.127	0.119	0.122	Min flow channel dia. (cm)
30	30	30	30	# driver fuel elements
19	19	19	19	# flow chan. in driver elem.
0.360	0.420	0.360	0.360	Driver hole dia (coatOD)(cm)
0.319	0.379	0.319	0.319	Driver flow channel dia. (cm)
1.041	1.042	1.041	1.045	k-eff (cold,BOL,drums out)
0.962	0.964	0.966	0.961	k-eff (cold,BOL,drums in)
				Power and Thermal
542.6	542.6	541.8	545.4	Reactor power (MW)
478.4	487.6	482.4	483.4	Thrust elem. fiss. pow (MW)
54.3	45.2	50.0	52.4	Driver elem. fiss. pow (MW)
9.9	9.8	9.4	9.6	Ex-core fission power (MW)
1.373	1.299	1.291	1.270	Max hex peaking factor
1.368	1.368	1.364	1.388	Ave. axial peaking factor
14.85	13.94	14.72	13.01	Peak fuel power den. (MW/l)
7.88	7.82	8.34	7.37	Ave. fuel power den. (MW/l)
12.49	12.46	12.49	12.40	Core flow rate (kg/s)
2850	2849	2850	2850	Peak fuel temperature (K)
0.29	0.40	0.29	0.25	Peak in-core Mach number
				Rocket Parameters
0.3	0.3	0.3	0.3	Tank pressure (MPa)
15.0	10.9	15.2	15.3	Compressor outlet pres (MPa)
14.8	10.8	15.0	15.1	Driver fuel inlet pres. (MPa)
13.3	10.0	13.6	13.5	Driver fuel outlet pres (MPa)
13.1	9.9	13.4	13.3	Turbine inlet pressure (MPa)
9.5	7.5	9.4	9.5	Turbine outlet pressure (MPa)
9.3	7.4	9.2	9.3	Core inlet pressure (MPa)
5.0	3.1	5.0	5.5	Core outlet pressure (MPa)
3.8	3.1	3.5	3.6	Driver loop flow rate (kg/s)
8.7	9.3	9.0	8.8	Regen loop flow rate (kg/s)
20	20	20	20	Tank temp (K)
1000	1000	1000	1000	Turbine in (driver out) T (K)
917	927	908	913	Turbine outlet temp (K)
239	224	230	240	Regen loop outlet temp (K)
439	397	413	433	Core inlet temp (K)
2739	2735	2736	2769	Core outlet temp (K)
150	150	150	150	Nozzle area ratio
0.96	0.96	0.96	0.96	Thrust efficiency
111.3	111.3	111.3	111.2	Thrust (kN) = 25 klb
909.1	911.2	908.3	915.0	Specific impulse (s)

Conclusion: Variable-hole-size zones allowed an NTR to be designed with a significantly lower peak pressure (10.9 MPa vs 15.0 MPa) and a slightly higher Isp (911 s vs 909 s), plus the concept will also have a lower "balance-of-plant mass" (pump, piping, chamber, nozzle, etc.). Two alternative concepts were also considered: one lowered the reactor mass by 12% and ^{235}U inventory by 6%, and the other raised outlet temperature from 2739 K to 2769 K, increasing Isp from 909 s to 915 s. Note that all of these concepts are designed to push the mixed-mean outlet temperature very close to the assumed fuel temperature limit (2850 K); as a result these concepts have relatively high mass. Follow on work will examine the tradeoff between Isp and mass, as well areas where technology risk can be traded with performance: e.g. coating thickness, element size, max fuel temp, max power density, control drum design, position and requirements, etc.

References: [1] Poston D., "Driver Fuel Design for a Cermet NTR"; NETS 2014 (2014).