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25,000-lbf Thrust Engine Options Based on the Small Nuclear Rocket Engine Design

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Advancement of U.S. scientific, security, and economic interests through a robust space exploration program requires high performance propulsion systems to support a variety of robotic and crewed missions beyond low Earth orbit. Past studies, in particular those in support of both the Strategic Defense Initiative (SDI) and Space Exploration Initiative (SEI), have shown nuclear thermal propulsion systems provide superior performance for high mass high propulsive delta-V missions. An extensive nuclear thermal rocket technology development effort was conducted from 1955-1973 under the Rover/NERVA Program. The Small Nuclear Rocket Engine (SNRE) was the last engine design studied by the Los Alamos National Laboratory during the program. At the time, this engine was a state-of-the-art design incorporating lessons learned from the very successful technology development program. Past activities at the NASA Glenn Research Center have included upgrading and modernizing nuclear thermal propulsion system models and analysis methods. The SNRE had been adopted to serve as a computational benchmark for these activities. A highly detailed MCNP Monte Carlo transport model of the reactor core was developed and exercised along with a number of simpler MCNP models of the reactor core. The reactor core models, calculated results, and comparisons with available documentation for the SNRE were described in a previous (2007) Joint Propulsion Conference paper. The SNRE was a nominal 16,000-lb$_f$ thrust engine originally intended for unmanned applications with relatively short engine operations and the engine and stage design were constrained to fit within the payload volume of the then planned space shuttle. Future mission applications may require or benefit from moderately larger higher thrust engines. The recent NASA Design Reference Architecture (DRA) 5.0 Study re-examined mission, payload, and transportation system requirements for a human Mars landing mission in the post-2030 timeframe. Nuclear thermal propulsion was again identified as the preferred in-space transportation system. Recent activities at Glenn Research Center have included extending the SNRE engine design into the 25,000-lb$_f$ thrust range. Results are presented for not-yet optimized SNRE-based engine designs that meet or exceed the performance characteristics baselined in the DRA 5.0 Study.

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Nomenclature

DRA	=	Design Reference Architecture
k-eff	=	effective multiplication factor
K	=	temperature (Kelvin)
lbf	=	pounds thrust
MCNP	=	Monte Carlo N-Particle transport code
MWth	=	thermal power (megawatts)
NEDS	=	Nuclear Engine Definition Study
NERVA	=	Nuclear Engine for Rocket Vehicle Applications
NESS	=	Nuclear Engine System Simulation code
SNRE	=	Small Nuclear Rocket Engine

I. Introduction

Advancement of U.S. scientific, security, and economic interests requires high performance propulsion systems to support missions beyond low Earth orbit. A robust space exploration program will include robotic outer planet and crewed missions to a variety of destinations including the moon, near Earth objects, and eventually Mars. Past studies, in particular those in support of both the Strategic Defense Initiative (SDI) and the Space Exploration Initiative (SEI), have shown nuclear thermal propulsion systems provide superior performance for high mass high propulsive delta-V missions.

Past activities at the NASA Glenn Research Center have included upgrading and modernizing nuclear thermal propulsion system models and analysis methods. Initial efforts were focused on benchmarking methods and models against the Small Nuclear Rocket Engine (SNRE) and stage configuration documented in the Nuclear Engine Definition Study (NEDS) Preliminary reports[1,2]. Recent papers addressed neutronics modeling of the SNRE reactor core[3], the SNRE reference stage[4], integrated thermal-fluid-structural analysis of reactor core interior components[5] and engine system level modeling and analyses[6].

The SNRE was a nominal 16,000-lbf thrust engine originally intended for unmanned applications with relatively short engine operations and the engine and stage design were constrained to fit within the payload volume of the then planned space shuttle. Future mission applications may require or benefit from moderately larger higher thrust engines. The recent NASA Design Reference Architecture (DRA) 5.0 Study re-examined mission, payload, and transportation system requirements for a human Mars landing mission in the post-2030 timeframe. Nuclear thermal propulsion was again identified as the preferred in-space transportation system[7]. Another paper[8] to be presented at this meeting describes an NTR space transportation option for DRA 5.0 utilizing 25,000-lbf thrust engines.

Both thermal neutron spectrum and fast neutron spectrum reactors had been considered during the 1955-1973 nuclear thermal rocket technology development effort. A 25,000-lbf class engine had been tested[9] in 1968 during the Rover/NERVA Program. The combination of the limited documentation available for the Pewee engine and the recent Glenn Research Center experience in benchmarking analytical methods encouraged consideration of higher thrust engines based on growth versions of the SNRE. The SNRE is described in the following section.

II. Small Nuclear Rocket Engine Description

The primary reasons for selecting the SNRE for analysis were the maturity of the engine design, the engine size and thrust level, and the quality of the available documentation. The SNRE is the last engine design studied by the Los Alamos National Laboratory during the Rover Program and incorporates lessons learned throughout the very successful technology development program. Although the program was terminated prior to completion of the design, available preliminary design results provide reasonably good documentation, especially for the reactor core. The SNRE also provides a valuable small engine analytic benchmark for propulsion systems in a lower thrust range of potential interest.

Design requirements for the small engine included the ability to operate at either of two full power conditions. Full power operating conditions for a single-mission injection mode are one-hour engine life at 367 MWth yielding 16,406 lbf thrust with a specific impulse of 875 seconds. Full power conditions for operation in a reusable mission mode are two-hour engine life at 354 MWth yielding 16,125 lbf thrust with a specific impulse of 860 seconds. Engine specific impulse is a function of several parameters including propellant molecular weight, propellant temperature, and nozzle expansion ratio. The SNRE nozzle expansion ratio of 100:1 was established primarily by the requirement that the stage be carried into Earth orbit by the then planned space shuttle. Hydrogen propellant chamber temperatures are 2696 K and 2633 K, respectively, for the two operating modes.

The engine utilizes hexagonal fuel elements and hexagonal structural support or “tie tube” elements. Both element types are 1.905 cm (0.750 in) across the flats and 89 cm (35 in) in length. The fuel composition is the (U,Zr)C-graphite “composite” described by Taub[10] and successfully tested in the Nuclear Furnace 1 test reactor.[11] The reference SNRE engine design was based on composite fuel with a (U,Zr)C solid solution content of 35% by volume. In the initial design effort, evaluations were first performed with a uniform uranium loading of 0.64 g/cm^3. Element uranium loadings were then selectively reduced in the higher power elements to flatten the radial fission profile across the core. The regeneratively cooled tie tube elements provide structural support for the fuel elements, provide a source of energy to drive the turbomachinery, and incorporate a zirconium hydride moderator sleeve to raise neutronic reactivity in the small engine size. The core contains 564 fuel elements and 241 tie tube elements. Additional complete and partial hexagonal elements of beryllium “filler” elements are utilized to complete an approximately cylindrical core. The fuel element geometry cross section is shown in Fig. 1 and the tie tube element geometry cross section is shown in Fig. 2.

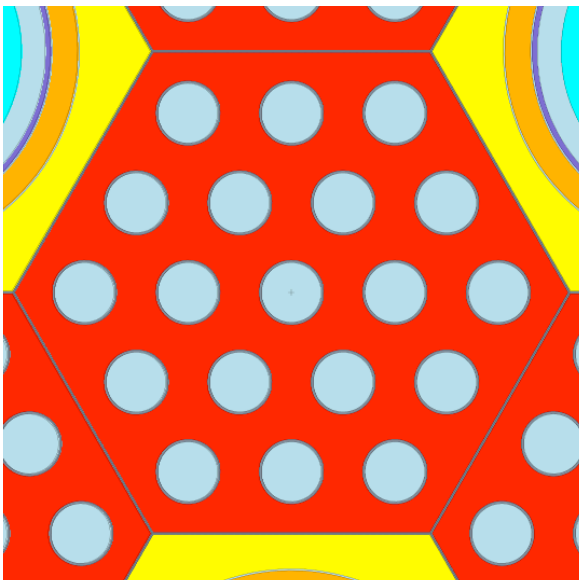

Figure 1. Fuel element cross section.

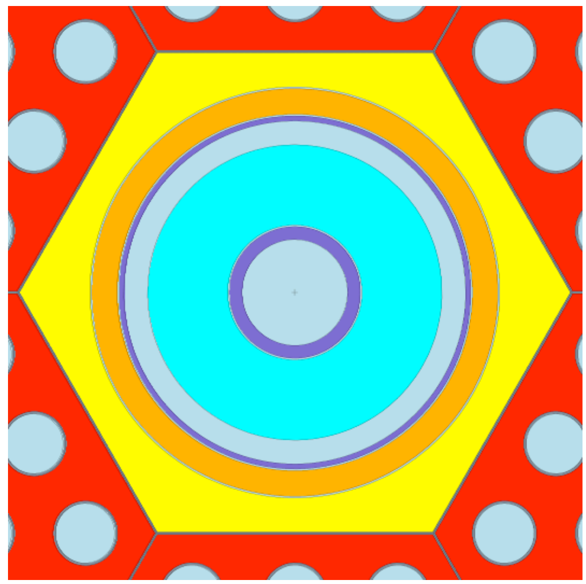

Figure 2. Tie tube element cross section.

A thin (nominally 0.1 mm) metal wrapper is incorporated for hydrogen flow control and for structural support. Additional radial components are a 2.8575 cm (1.125 in) beryllium barrel, a 14.732 cm (5.80 in) beryllium reflector, and a 0.5588 cm (0.22 in) aluminum pressure vessel. The reflector contains twelve cylindrical control assemblies. Each control assembly contains an absorber plate extending over a 120-degree sector of the rotating control cylinder.

The hot ends of the tie tube elements extend approximately 4 cm beyond the active fuel region into a hot end support assembly. The two concentric Inconel-718 tubes are connected in the assembly and the assembly includes insulating components and an Inconel-718 end cap. The assembly also incorporates six small support arches extending outward from the tie tube tip and supporting the six neighboring fuel elements. Hot end details were incorporated into the SNRE reference stage model[4] but were omitted in the SNRE reference engine models[3].

Regions immediately forward of the active fuel are the tie tube hydrogen inlet plenum, a support plate, the tie tube outlet plenum, and an internal shield of zirconium hydride containing 0.5 weight percent natural boron. Control drum actuators are located in the annular region forward of the beryllium reflector. An optional brim shield can be included immediately forward of the drum actuator region. The brim shield is also borated zirconium hydride, but is only one-half the thickness of the internal shield. A forward dome encloses the reactor pressure vessel. The dome is an ellipsoidal end cap but truncated to help shorten the overall stage length. The reference engine model[3] is truncated at the forward surface of the internal shield.

III. Engine Design Methodology

Credible engine design and analysis requires considerable effort. Reactor neutronic performance, the combined thermal-fluid-structural performance of reactor interior components, and engine system level performance must be considered. An effective design and analysis sequence is to first establish a preliminary core configuration that meets the fundamental neutronic performance requirements of criticality and adequate control swing. Results from neutronic analyses of the reactor core can then be utilized to provide neutron and gamma energy deposition rates as input to integrated thermal-fluid-structural analyses of the core interior components. Once acceptable neutronic and thermal performance is achieved, overall engine system performance can be evaluated. The above sequence is typically an iterative process.

Preliminary core configurations typically employ fuel elements with fixed fuel composition and fissile material enrichment. Uniform fuel loading usually results in undesirable radial power and temperature profiles in the engine. Engine performance can be improved by some combination of propellant flow control at the fuel element level and by varying the fuel composition. Enrichment zoning at the fuel element level with lower enrichments in the higher power elements at the core center and on the core periphery is particularly effective. Power flattening by enrichment zoning typically results in more uniform propellant exit temperatures and improved engine performance at the cost of some reactivity loss. Compensation for the reactivity loss is possible by several methods. Again, an iterative process is usually needed.

Another important step in the design and analysis sequence is to evaluate fissile depletion and fission product buildup during engine operation. Engine operating times are usually short with low reactivity loss. Reactivity losses due to depletion can be accommodated by control drum rotation, but drum rotation also results in core power distribution changes that can lower engine performance.

Interest in a 25,000-lbf thrust class engine encouraged consideration of a simpler analysis methodology to provide preliminary performance estimates. The SNRE benchmark efforts provide guidance and justification for such a simpler approach. Lessons learned from the SNRE evaluations and the methodology employed for the results presented in this paper are addressed in the following sections.

A. Lessons Learned from SNRE Evaluations

Initial neutronic evaluations for the SNRE evaluations had been performed using the MCNP Monte Carlo transport code[12] and an MCNP geometric model based on the engine description provided in Section II. Three particular aspects are noted: the ZrH internal moderator dimensions, the fuel composition, and the control absorber configuration. Dimensions of the tie tube ZrH internal moderator were identical to those identified for the SNRE reference design.

The reference SNRE engine design was based on composite fuel with a (U,Zr)C solid solution content of 35% by volume. In the initial design effort, evaluations were first performed with a uniform uranium loading of 0.64 g/cm^3 and a constant U-235 enrichment of 93 wt%. Element uranium loadings were then selectively reduced in the higher power elements to flatten the radial fission profile across the core. The SNRE benchmarking evaluations[3] had been performed starting with a slightly lower uranium loading of 0.60 g/cm^3 and a constant U-235 enrichment of 93 wt%. Power flattening was then accomplished by retaining a constant total uranium loading and reducing the U-235 enrichment in the higher power elements. This alternate method of power flattening was selected to minimize element-to-element variations in composite fuel coefficients of thermal expansion.

The SNRE design featured twelve control drums with boron-copper control plates but the drum design was not complete. Results from two-dimensional (r,θ) calculations had indicated a control drum worth of approximately 8.9 dollars and this was judged adequate. For the MCNP models, absorber plates of 0.635-cm thick hafnium were assumed. The hafnium segment has an inner radius of 5.3975 cm (2.125 in) and extends over a 120-degree sector. Somewhat fortuitously, this assumed preliminary control drum configuration yielded a reactor eigenvalue near unity (k-eff = 1.0016) with the control drums set at the middle of their rotation range. Although the calculated control swing of approximately 11.2 dollars was more than adequate, the preliminary drum design was retained until enrichment zoning evaluations were completed.

As previously noted, the U-235 enrichment was reduced in the higher power elements to flatten radial power distribution in the engine. After enrichment zoning, fuel element powers in 551 of the 564 elements were within 1% of the average. Fuel element powers in the remaining 13 elements ranged from 96.6% to 99% of the average. The lower total U-235 loading resulted in a reactivity loss of approximately 4.1 dollars.

A number of options were available to recover the reactivity loss. The options selected were a change in the ZrH internal moderator geometry and a change in the control drum design. The outer diameter of the ZrH internal moderator was increased from 0.460-in to 0.478-in. Results of sensitivity to ZrH dimension changes in the range from 0.454-in to 0.466-in outer diameter were reported in Ref. 2. Tie tube thermal performance for the 0.478-in outer diameter case is also expected to be acceptable, but has not been evaluated. The control drum absorber plate was reduced to 0.075-in thick hafnium. The combination of these two changes resulted in a reactivity gain of approximately 4.2 dollars. The resulting control drum swing is approximately 9.5 dollars.

These results support the development of initial engine models based on a constant U-235 enrichment of 93 wt%, 0.460-in outer diameter ZrH moderators, control drums with 0.25-in thick hafnium absorber plates, control drums set at the middle of their rotation range, and targeting an engine eigenvalue of unity. It is reasonable to expect the nominal reactivity loss due to enrichment zoning for power flattening can be recovered by small ZrH moderator dimension increases and decreases in the hafnium absorber plate thickness.

B. Design Approach

Two relatively straightforward options were considered for extending the SNRE-based engine design into the 25,000-lbf thrust range. The first option was to simply extend the reactor core active fuel length while retaining all other components identical to the SNRE engine. The second option was to retain the SNRE core length but expand the effective core radius by adding additional hexagonal fuel and tie tube elements. Simple scaling based on needed thermal power was utilized to obtain preliminary estimates of core length for the axial growth versions and preliminary estimates of the number of additional fuel and tie tube elements for the radial growth versions. This approach was used to obtain good starting points for the iterative design approach outlined in Section III.

1. Axial Growth Versions

The 16,406-lbf SNRE engine operating power was 367 MWth. Simple scaling implies the operating power required for a 25,000-lbf thrust engine will be approximately 550 MWth. Maintaining the same linear power density in the active fuel would dictate a 53.3-in active fuel length. During the Rover/NERVA Program a 52-in long hexagonal fuel element had emerged as a standard and this length was selected for the axial growth version.

Lengthening the SNRE reactor core to 52 inches and retaining a uranium loading of 0.60 g/cm^3 with a constant U-235 enrichment of 93 wt% yielded a reactor k-eff of 1.0799 with the control drums set at the middle of their rotation range. Two performance enhancing options to take credit for this significant excess reactivity are reducing the beryllium reflector thickness and reducing the uranium fissile loading. Decreasing the reflector thickness and control cylinder dimensions reduces engine mass and improves the engine thrust-to-weight. Reducing the 5.80-in thick reflector to a 2.80-in thick reflector yielded a reactor k-eff of 1.0297 and considerable mass savings. Unfortunately, the smaller control cylinders did not provide an adequate reactivity control swing. Although control cylinder redesign or additional control cylinders could presumably provide adequate control swing, this option was not pursued.

Reducing the uranium loading in the (U,Zr)C solid solution composite fuel not only lowers core reactivity but also raises the composite fuel melting point. Credit for the higher melting point can be taken either as additional margin to fuel melting or as increased hydrogen propellant temperature. Reducing uranium loading to 0.25 g/cm^3 yielded a reactor k-eff of 1.0114 and reducing to 0.20 g/cm^3 yielded a reactor k-eff of 0.9922. The 0.25 g/cm^3 loading was adopted for the axial growth version engine.

2. Radial Growth Versions

The average fuel element power in the 35-in long SNRE design was approximately 0.65 MWth. Maintaining the same fuel element power in a radial growth version would dictate approximately 860 fuel elements for a 25,000-lbf thrust engine operating at 550 MWth.

The SNRE design incorporated a fuel element and tie tube element pattern in the core interior that differed from the pattern typically used for larger engines. Core reactivity limitations tended to be more constraining in small engine designs. Given a proposed engine design with a fixed number of fuel elements, the core reactivity could be raised by incorporating additional tie tube elements. The more reactive fuel element and tie tube element pattern, used in the SNRE design and identified here by the term "dense" pattern, provided additional reactivity at the expense of a larger effective core radius. The pattern typically used for larger engines and identified here by the term "sparce" pattern, results in a lower effective core radius and is preferred if adequate reactivity is available. The dense fuel element and tie tube element pattern is illustrated in Fig. 3 and the sparce pattern is shown in Fig. 4.

An important feature common to both patterns is that each tie tube is surrounded by, and provides mechanical support for, six fuel elements. With the dense pattern, each fuel element has three adjacent fuel elements and three adjacent tie tube elements making up the six surrounding elements. With the sparce pattern, each fuel element has two adjacent tie tubes and four adjacent fuel elements making up the surrounding six elements.

Other features of the pattern differences can be illustrated by noting the tie tubes at the centers of both the Fig. 3 and Fig. 4 cross sections. In the Fig. 3 dense pattern, a line directed outward from the central tie tube through any of the six hexagonal surfaces passes through two fuel elements before entering the next tie tube. In the Fig. 4 sparce pattern, the line passes through only one fuel element before entering the next tie tube. In the Fig. 4 sparce pattern, alternating rows are made up of only fuel elements with no tie tubes.

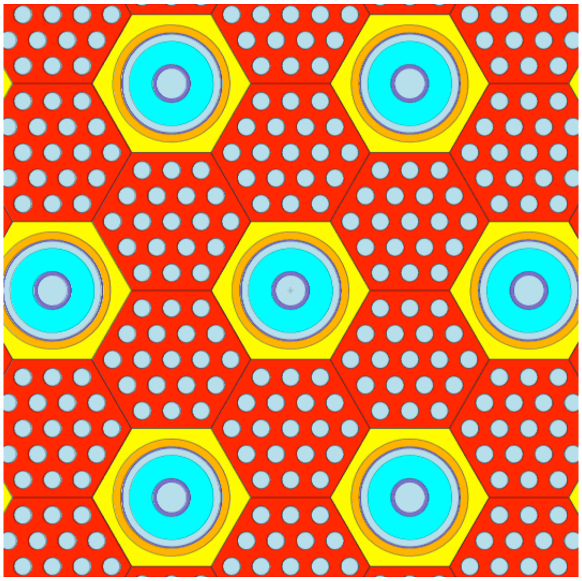

Figure 3. Dense fuel element and tie tube element pattern in core interior.

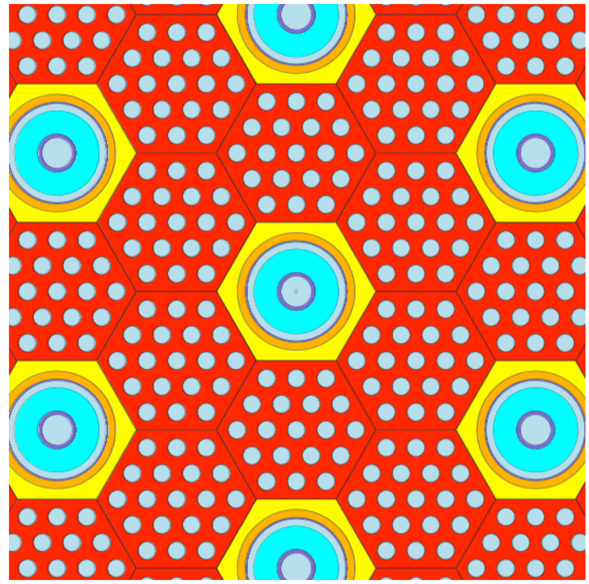

Figure 4. Sparce fuel element and tie tube element pattern in core interior.

The sparce pattern was selected for the radial growth engine. An initial core configuration was developed containing 864 fuel elements, 283 tie tube elements, and 138 complete or partial beryllium filler elements. All radial components outside the active core region were similar to the SNRE design. The radial thickness of each component was preserved. The reactor cross section at the core axial mid-plane is illustrated in Fig. 5.

Initial MCNP neutronics evaluation assuming a constant uranium loading of 0.60 g/cm^3 and a flat U-235 enrichment of 93 wt% yielded a reactor k-eff of 1.0348 with the control drums set at the middle of their rotation range.

As noted previously for the axial growth version, two options are available to take credit for the excess reactivity. Reducing the reflector thickness was not evaluated. Reducing uranium loading to 0.45 g/cm3 yielded a k-eff of 1.0067.

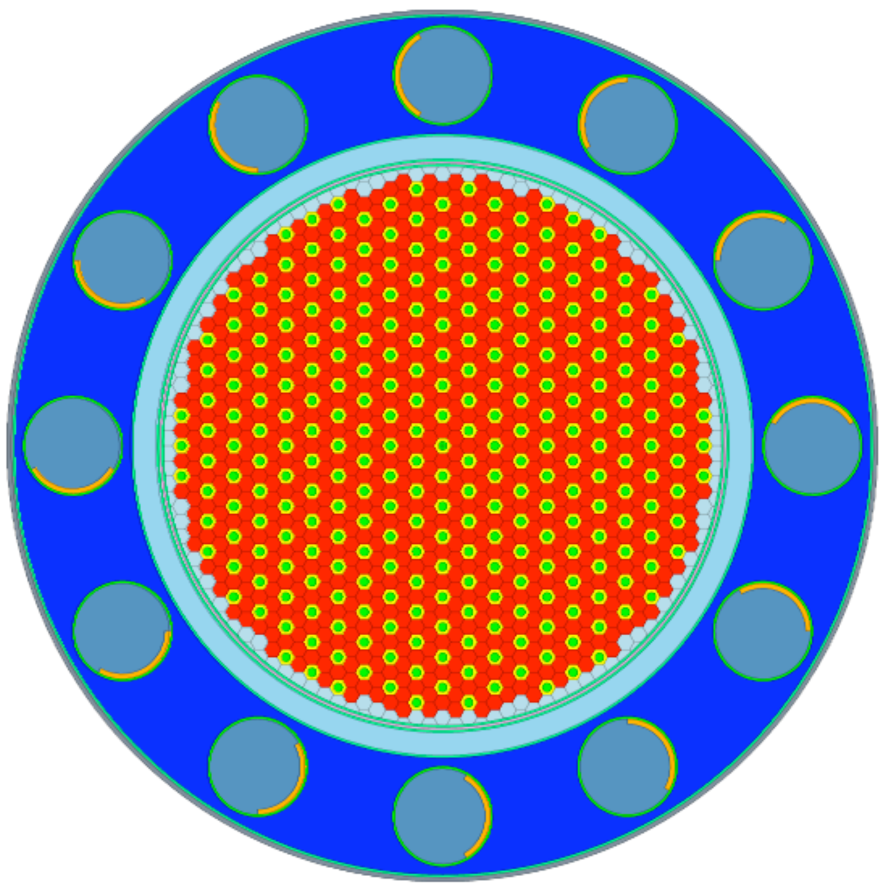

Figure 5. Engine cross section at reactor core mid-plane.

C. System Level Analyses

Engine performance was evaluated using the Nuclear Engine System Simulation (NESS) code[6]. The NESS code contains an option to calculate a suitable fuel element propellant orificing pattern to minimize fuel element temperature peaking, maintain the peak fuel temperature below a specified limit, and maximize the mixed mean propellant exit temperature. This option may be exercised at any point during the enrichment zoning process. Comparisons of system level performance before and after enrichment zoning were previously reported[6] for the SNRE design. Identical specific impulse and comparable engine thrust were achievable before and after enrichment zoning. Radial power peaking prior to enrichment zoning results in somewhat higher pump discharge pressure requirements and marginally higher engine system masses.

IV. Results

Performance characteristics for two of the 25,000-lbf engine options evaluated in this study are shown in Table 1. Characteristics baselined in the Mars DRA 5.0 Study and for the SNRE design are included for comparison.

Both axial growth and radial growth engine options were evaluated at two different operating conditions identified as "nominal" and "enhanced" in Table 1. The 2860 K maximum fuel temperature assumed for the SNRE baseline was imposed for the nominal operating condition cases. For the enhanced operating condition cases, the same 40 K margin to fuel melting as assumed for the SNRE was imposed allowing somewhat higher fuel operating temperatures.

All four engine options meet the 25,000-lbf thrust goal. The axial growth version operating with a maximum fuel temperature constrained to 3010 K delivers 25,100 lbf of thrust with an Isp of 941 seconds at an engine thrust-to-weight of 3.50. The radial growth version operating with a maximum fuel temperature constrained to 2930 K produces 25,100 lbf of thrust with an Isp of 913 seconds at an engine thrust-to-weight of 3.60.

Table 1. Performance characteristics of 25,000-lbf engines based on growth versions of the SNRE design.

Performance Characteristic	DRM 5.0 Baseline	SNRE Baseline	Axial Growth Option Nominal	Axial Growth Option Enhanced	Radial Growth Option Nominal	Radial Growth Option Enhanced
Engine System						
Thrust (klb$_f$)	25	16.4	25.1	25.1	25.1	25.1
Chamber Inlet Temperature (K)	~ 2650 - 2700	2695	2790	2940	2731	2807
Chamber Pressure (psia)	1000	450	1000	1000	1000	1000
Nozzle Expansion Ratio	300:1	100:1	300:1	300:1	300:1	300:1
Specific Impulse (s)	~ 900 - 910	875	906	941	894	913
Engine Thrust-to-Weight	3.43	2.92	3.49	3.50	3.59	3.60
Reactor						
Active Fuel Length (cm)		89.0	132.0	132.0	89.0	89.0
Effective Core Radius (cm)		29.5	29.5	29.5	35.2	35.2
Engine Radius (cm)		49.3	49.3	49.3	55.0	55.0
Element Fuel/Tie Tube Pattern Type		Dense	Dense	Dense	Sparce	Sparce
Number of Fuel Elements		564	564	564	864	864
Number of Tie Tube Elements		241	241	241	283	283
Fuel Fissile Loading (g U per cm^3)		0.60	0.25	0.25	0.45	0.45
Maximum Enrichment (wt% U-235)		93	93	93	93	93
Maximum Fuel Temperature (K)		2860	2860	3010	2860	2930
Margin to Fuel Melt (K)		40	190	40	110	40

V. Conclusion

Lessons learned from previous analyses using the SNRE as a computational benchmark provide confidence in the methods employed to scale the engine design to moderately higher thrust levels. Two relatively simple growth versions of the SNRE design to the 25,000-lbf thrust level are shown to provide performance that meets or exceeds the performance characteristics baselined in the Mars DRA 5.0 study. The designs are not yet optimized and additional performance improvements are a reasonable expectation.

Acknowledgments

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