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Lower Thrust Engine Options Based on the Small Nuclear Rocket Engine Design

Bruce G. Schnitzler[1]
Idaho National Laboratory, Idaho Falls, Idaho, 83415

Stanley K. Borowski[2]
NASA Glenn Research Center, Cleveland, Ohio, 44135

and

James E. Fittje[3]
QinetiQ North American at NASA Glenn Research Center, Cleveland, Ohio, 44135

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. 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. Future mission applications may require or benefit from moderately larger higher thrust engines. Options for engine designs in the 25,000-lb$_f$ thrust range were described in a recent (2009) Joint Propulsion Conference paper. Moderately lower thrust engines may also have important roles. In particular, lower thrust engine designs demonstrating the critical technologies that are directly extensible to other thrust levels are attractive from a ground testing perspective. Recent activities have included extending the SNRE engine design into the lower thrust range. Results are presented for not-yet optimized lower thrust SNRE-based engine options.

[1] Space Nuclear System Division, 2525 N. Freemont Avenue, Idaho Falls, ID 83415-3870, AIAA Senior Member.
[2] DSS Branch Chief & Technical Leader, NTP Systems, 21000 Brookpark Road, MS:86-4, AIAA Associate Fellow.
[3] Aerospace Engineer, 21000 Brookpark Road, MS:GES-AOS, AIAA Senior Member.

Nomenclature

DRA	=	Design Reference Architecture
ENDF/B	=	Evaluated Nuclear Data File
k-eff	=	effective multiplication factor
K	=	temperature (Kelvin)
lb_f	=	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
NTP	=	Nuclear Thermal Propulsion
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. In NASA's recent Mars Design Reference Architecture (DRA) 5.0 study[1], nuclear thermal propulsion (NTP) was again selected over chemical propulsion as the preferred in-space transportation system option for the human exploration of Mars because of its high thrust and high specific impulse (~900 s) capability, increased tolerance to payload mass growth and architecture changes, and lower total initial mass in low Earth orbit. The recently announced national space policy[2] supports the development and use of space nuclear power systems where such systems safely enable or significantly enhance space exploration or operational capabilities.

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. 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[3,4]. Past papers have addressed neutronics modeling of the SNRE reactor core[5], enrichment zoning options[6] for the SNRE, the SNRE reference stage[7], integrated thermal-fluid-structural analysis of reactor core interior components[8], engine system level modeling and analyses[9], and an extension of the SNRE design into the 25,000 lb_f thrust range[10].

Moderately lower thrust engines may also have important roles. Robotic science missions could benefit directly from smaller nuclear engines, even when NTP is not considered enabling for the particular mission or class of missions. Smaller nuclear engines are also more attractive for an in-space nuclear propulsion technology demonstrator prior to larger scale use for cargo and crewed exploration missions. The lower thrust engine designs could then be used to demonstrate critical technologies that are directly extensible to higher thrust levels. In the ideal case, the hexagonal fuel elements and the hexagonal tie tube elements employed in the ~16,000 lb_f SNRE, the 25,000 lb_f engine, and the lower thrust engine designs would be identical. At the minimum, the cross-sections for the two element types should be identical and critical performance parameters such as maximum fuel temperature should be identical or conservatively higher in the demonstrator. Material compositions should be identical or similar and demonstrated to be conservative. For example, different ^{235}U enrichments might be used at identical or similar total uranium content in the fuel matrix. Different length elements for the different thrust level engines could still be considered.

The following two sections contain a description of the SNRE engine design features allowing extension of the basic design to other thrust ranges, and a description of the options considered and results obtained during the previous study to extend the design into the 25,000-lb_f thrust range.

II. Small Nuclear Rocket Engine Description

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 lb_f 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 lb_f 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[11] and successfully tested in the Nuclear Furnace 1 test reactor.[12] 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 fuel element geometry cross-section is shown in Fig. 1 and the tie tube element geometry cross-section is shown in Fig. 2.

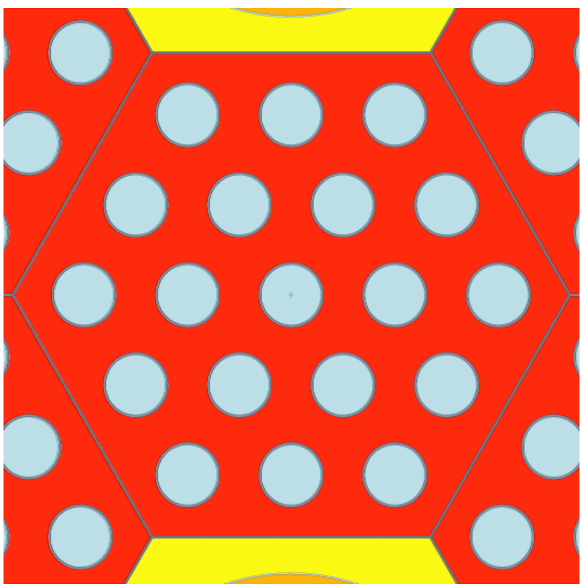

Figure 1. Fuel element cross section.

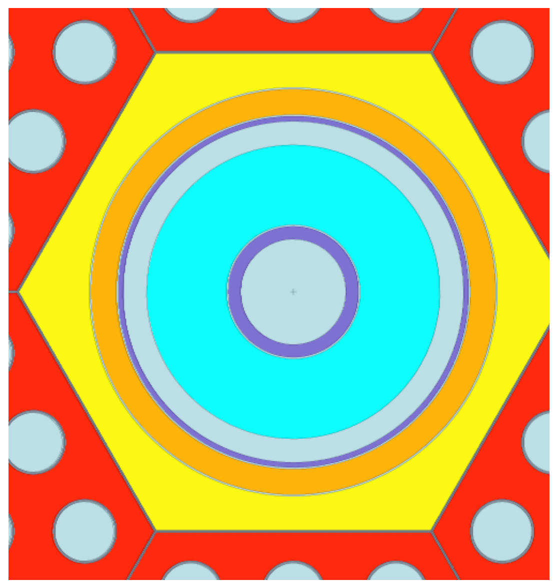

Figure 2. Tie tube element cross section.

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. 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 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[9] but were omitted in the SNRE reference engine models[5], in the 25,000-lb_f thrust engine models[10], and in the models used for evaluations of the lower thrust engine designs reported here.

A lower tie tube plenum, support plate, and upper tie tube plenum are located immediately forward of the active core region. Radiation shielding is provided by a borated zirconium hydride shield assembly located just forward of the upper tie tube plenum. An optional annular brim shield is positioned just forward of the drum actuator zone. Additional geometry information and material compositions are described in earlier SNRE papers[5,7] and in the Nuclear Engine Definition Study (NEDS) Preliminary reports[3,4].

Components outside the active core region are common to the SNRE, the 25-klb$_f$, and the lower thrust designs. All SNRE radial component thicknesses are preserved except for the beryllium reflector thickness. The geometry and dimensions of the twelve control cylinders are also maintained except for the absorber plate thickness. Beryllium reflector thickness is adjusted as needed in the designs to maintain adequate engine reactivity. Absorber plate thickness is adjusted as needed to maintain adequate reactivity control swing.

Overall engine model cross-sections are illustrated in a later section. Different interior core patterns are employed in the engine designs. The different interior arrangements of hexagonal fuel elements and hexagonal tie tube elements are also illustrated in a later section.

III. 25,000-lb$_f$ Thrust Engine Options

Two relatively straightforward options were considered for extending the SNRE-based engine design into the 25,000-lb$_f$ 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. Performance characteristics for two of the previously reported[10] 25,000-lb$_f$ engine options 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.

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		SNRE	SNRE	SNRE	Sparse	Sparse
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

All four engines 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**.**

IV. Lower Thrust Engine Options

The SNRE contained 564 hexagonal fuel elements and was designed to operate at 354 MW_{th} producing 16,125 lb_f thrust. Simple power scaling indicates an operating power of 110 MW_{th} for a 5,000 lb_f engine design. Assuming comparable fuel element performance could be obtained, simple scaling also indicates 175 fuel elements would provide adequate thermal energy for a 5,000 lb_f thrust design. Core reactivity considerations are much more constraining in small engine designs. Some improvements in the SNRE design could result in a lower number of fuel elements and possibly in a smaller engine. However, it does not appear feasible to obtain adequate reactivity in a practical engine design using only 175 fuel elements in the SNRE configuration.

In NERVA-derived engine designs, the reactor cores are made up of hexagonal fuel elements and hexagonal structural (tie tube) elements. 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 moderator sleeve to raise neutronic reactivity. Corner elements are removed and complete and partial hexagonal "filler" elements are utilized to complete an approximately cylindrical core.

Two different fuel element and tie tube element patterns have been employed in previous engine designs. Both element types are 1.905 cm (0.75 in) across the hexagonal element flats. The pattern typically used in larger engine designs and identified here as the "sparse" element pattern results in a fuel element to tie tube element ratio of about 3 to 1. The pattern employed in the SNRE design results in a fuel element to tie tube element ratio of about 2 to 1. Additional reactivity gains may be possible by employing an entirely new pattern identified here as the "dense" element pattern resulting in a fuel element to tie tube element ratio of about 1 to 1. The three element patterns are illustrated in Figures 3 – 5 below.

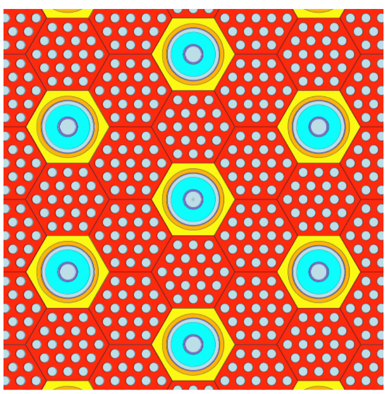

Figure 3. Sparse fuel element and tie tube element pattern.

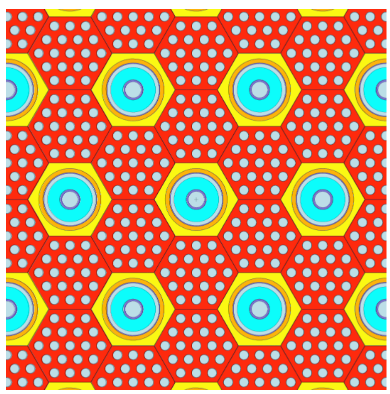

Figure 4. SNRE fuel element and tie tube element pattern.

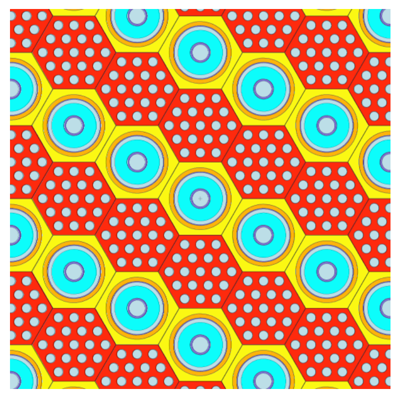

Figure 5. Dense fuel element and tie tube element pattern.

Initial feasibility evaluations were performed to assess the magnitude of core reactivity changes resulting from simply using the three different fuel element and tie tube patterns in an otherwise identical engine model. The MCNP Monte Carlo transport code[13] and an existing model[5] of the SNRE engine were utilized. All SNRE radial and axial components, dimensions, and material compositions described earlier were retained. Cross-section data employed in the MCNP transport calculations are primarily from the Evaluated Nuclear Data File[14,15] (ENDF/B) Version V and VI.

During these initial evaluations, only regular hexagonal arrays were considered. A regular array consisting of a central element plus 13 hexagonal rows of elements surrounding the central element is identified as a regular array of 14 hexagonal rows. Regular arrays of 14, 13, 12, and 11 hexagonal rows were evaluated. The three different fuel element and tie tube element patterns were each evaluated for each of the regular arrays.

Results for the twelve configurations examined are shown in Table 2. Cases 3, 6, and 9 with cores based on the dense array pattern indicate configurations with between 204 and 280 fuel elements may have sufficient reactivity margin to be practical.

Table 2. Calculated effective multiplication factors of selected regular hexagon arrays of fuel elements and tie tube elements in the SNRE engine model.

Case	Number of Hexagonal Rows	Hexagonal Array Pattern Type	Calculated k-effective	Number of Fuel Elements	Number of Tie Tube Elements
1	14	Sparse	0.9641	420	127
2	14	SNRE	0.9987	366	181
3	14	Dense	1.0512	280	267
4	13	Sparse	0.9607	342	127
5	13	SNRE	0.9926	312	157
6	13	Dense	1.0328	228	241
7	12	Sparse	0.9579	306	91
8	12	SNRE	0.9871	264	133
9	12	Dense	1.0336	204	193
10	11	Sparse	0.9475	240	91
11	11	SNRE	0.9790	222	109
12	11	Dense	1.0057	160	171

The configurations shown in Table 2 contain beryllium filler elements extending out to the position of the stainless steel wrapper in the original SNRE design and model. The additional filler elements effectively provide additional reflector thickness. The minimum additional reflector thickness ranges from two hexagonal elements (~3.8 cm) in the 14-row array cases to four hexagonal elements (~7.6 cm) in the 12-row array cases. The SNRE outer diameter is ~98.5 cm (~38.8 in). Removal of the filler elements while retaining the same thicknesses of exterior radial components will reduce the overall engine diameter by 7.6 to 15.2 cm (3 to 6 inches).

Reducing the effective reflector thickness and overall engine size will result in engine mass reduction but will also result in significant reactivity loss. Based on the earlier 25,000-lb_f engine evaluations, two important methods of reactivity enhancement are readily available. These are changes in the tie tube ZrH internal moderator geometry and changes in the control drum absorber thickness. Both enhancements were incorporated into the models for Cases 3, 6, and 9 and the effects are shown in Table 3. The effects were evaluated separately and in combination with the majority (~85%) of the reactivity enhancement being due to the increased ZrH for these cases.

Table 3. Calculated effective multiplication factors with selected reactivity enhancements incorporated.

Case	Number of Hexagonal Rows	Hexagonal Array Pattern Type	Calculated k-effective	ZrH Outer Diameter (Inches)	Hf Absorber Thickness (Inches)
3	14	Dense	1.0512	0.460	0.250
3-C	14	Dense	1.0802	0.478	0.075
6	13	Dense	1.0328	0.460	0.250
6-C	13	Dense	1.0599	0.478	0.075
9	12	Dense	1.0336	0.460	0.250
9-C	12	Dense	1.0593	0.478	0.075

The designs with regular hexagonal arrays of 14 rows (Case 3-C), 13 rows (Case 6-C), and 12 rows (Case 9-C) were selected as baseline configurations for additional evaluation. These configurations all now have 0.478-in outer diameter ZrH moderators. The core interiors were modified by removing corner elements from the regular hexagonal arrays. Outer beryllium filler elements were also removed and the dimensions of all radial components reduced. All radial component thicknesses were maintained except for the beryllium reflector thickness. The reflector thickness was increased as needed to maintain an engine k-effective near unity with control drums adjusted to middle-of-range (90-degree) positions.

Parameters for the lower thrust configurations are shown in Table 4 along with data for the SNRE and one of the 25,000-lb_f engines. Overall engine diameter is shown in the fifth column. The 13 hexagonal row configuration is slightly smaller than the SNRE. The diameter of the 14 hexagonal row configuration is 10.8 cm smaller than the SNRE. Because of the reflector thickness needed for criticality, the 12 hexagonal row configuration is almost as large as the 25,000-lb_f engine. Relative sizes are illustrated in Figure 6 for the three lower thrust engine configurations.

Full swing control drum worths are shown in the last column of Table 4. A full swing worth of ~8.9 dollars had been judged adequate[3,4] for the SNRE. All low thrust configurations either have adequate control swing or adequate reactivity margin to support small changes in the drum design to achieve adequate control swing.

Table 4. Reactor parameters for several engine configurations based on the SNRE design.

Configuration	Number of Fuel Elements	Number of Tie Tube Elements	Reflector Thickness (cm)	Engine Diameter (cm)	Hf Absorper Thickness (cm)	Full Swing Drum Worth ($)
SNRE	564	241	14.7	98.5	0.190	~11.2
25-klbf	864	283	14.7	110.0	0.190	~9.1
14 Hex Row	260	251	14.7	87.7	0.190	~10.3
14 Hex Row	260	251	14.7	87.7	0.635	~11.7
13 Hex Row	216	217	21.6	97.6	0.190	~8.7
13 Hex Row	216	217	21.6	97.6	0.635	~9.6
12 Hex Row	184	177	27.9	106.5	0.190	~7.8
12 Hex Row	184	177	27.9	106.5	0.635	~8.3

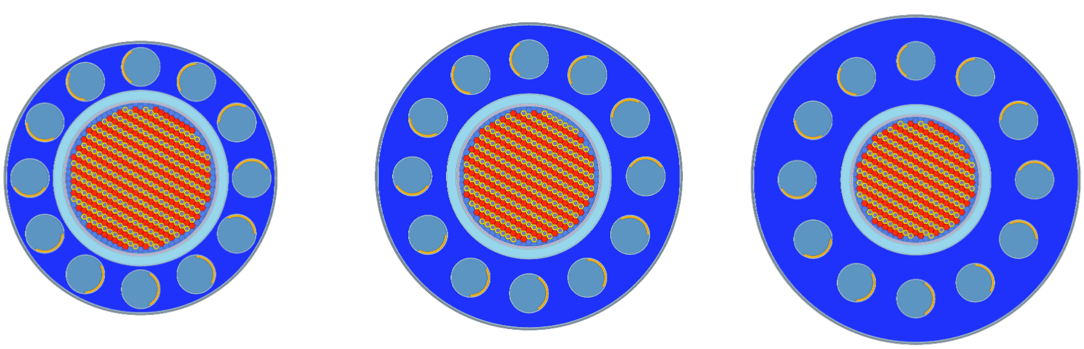

Figure 6. Cross sections near core mid-plane for three lower thrust engines based on the SNRE design (same scale for all three concepts).

Engine performance was evaluated using the Nuclear Engine System Simulation (NESS) code[9]. 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. Performance characteristics are shown in Table 5 for the lower thrust engine options being evaluated in this study. A maximum fuel temperature of 2860 K, a chamber pressure of 1000 psia, and a nozzle expansion ratio of 300:1 are common for the three options and yield approximately the same calculated chamber inlet temperature and specific impulse. Engine trust levels range form 7,420 lb_f to 5,300 lb_f with engine thrust-to-weight ranging from 1.87 to 1.10.

Data for the SNRE and from one of the earlier 25,000-lb_f thrust engine options are included for comparison. Engine thrust-to-weight values for the SNRE and 25,000-lb_f engine differ slightly from the values shown in Table 1. Differences are due primarily to improved mass estimates for some non-reactor engine components such as piping and to reducing the number of engine gimbals from three to one.

Table 5. Performance characteristics of lower thrust engine designs based on the SNRE.

Performance Characteristic	25,000-lbf Option	SNRE Baseline	14 Hex Row Option	13 Hex Row Option	12 Hex Row Option
Reactor					
Active Fuel Length (cm)	89.0	89.0	89.0	89.0	89.0
Reflector Thickness (cm)	14.7	14.7	14.7	21.6	27.9
Engine Diameter (cm)	110.0	98.5	87.7	97.6	106.5
Element Pattern Type	Sparse	SNRE	Dense	Dense	Dense
Number of Fuel Elements	864	564	260	216	184
Number of Tie Tube Elements	283	241	251	217	177
Fuel Fissile Loading (g U/cm^3)	0.45	0.60	0.60	0.60	0.60
Maximum Fuel Temperature (K)	2860	2860	2860	2860	2860
Margin to Fuel Melt (K)	110	40	40	40	40
Component Masses					
Reactor (lbm)	5166	4190	3158	3509	4172
Pressure Vessel (lbm)	667	329	538	495	467
Nozzle (lbm)	332	332	117	100	86
Turbomachinery & Piping (lbm)	248	187	91	75	67
Gimbal (lbm)	133	95	57	31	28
Engine Total	6546	5133	3961	4210	4820
Engine System					
Thrust (klb_f)	25.1	16.4	7.42	6.00	5.30
Chamber Inlet Temperature (K)	2731	2695	2736	2738	2734
Chamber Pressure (psia)	1000	450	1000	1000	1000
Nozzle Expansion Ratio	300:1	100:1	300:1	300:1	300:1
Specific Impulse (s)	894	875	894	894	893
Engine Thrust-to-Weight	3.82	3.20	1.87	1.43	1.10

V. Conclusion

Lower thrust engine options based on the Small Nuclear Rocket Engine design are possible using an entirely new hexagonal element pattern resulting in a fuel element to tie tube element ratio of about 1 to 1. Fuel performance and engine specific impulse comparable to the SNRE and the 25,000-lb_f class engines may be achieved in engine designs with thrust levels as low as 5,000 lb_f, but the lower thrust designs require relatively thick reflectors to maintain a critical configuration and have low thrust-to-weight.

A design capable of providing a thrust level of 7,420 lb_f is more practical. The engine thrust-to-weight is only about 1.87, but this lower thrust engine design could be used to demonstrate critical technologies that are directly extensible to higher thrust levels. Except for the fissile loading, the fuel elements and tie tube elements are exactly as those used in the 25,000-lb_f design.

The design is not optimized and some performance improvement may be possible. In particular, increasing the active fuel length slightly may allow a thinner reflector and reduce overall engine mass.

Acknowledgments

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