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Enrichment Zoning Options for the Small Nuclear Rocket Engine (SNRE)

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Enrichment Zoning Options for the Small Nuclear Rocket Engine (SNRE)

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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. In NASA's recent Mars Design Reference Architecture (DRA) 5.0 study (NASA-SP-2009-566, July 2009), nuclear thermal propulsion (NTP) was again selected over chemical propulsion as the preferred in-space transportation system option 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. 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 development of highly detailed MCNP Monte Carlo transport models of the SNRE and other small engine designs. Preliminary core configurations typically employ fuel elements with fixed fuel composition and fissile material enrichment. Uniform fuel loadings result in undesirable radial power and temperature profiles in the engines. 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. For the SNRE, element enrichment zoning provided very flat radial power profiles with 552 of the 564 fuel elements within 5% of the average element power. Results for this and alternate enrichment zoning options for the SNRE are compared.

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
NTP	=	nuclear thermal propulsion
SNRE	=	Small Nuclear Rocket Engine

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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], the SNRE reference stage[6], integrated thermal-fluid-structural analysis of reactor core interior components[7], engine system level modeling and analyses[8], and an extension of the SNRE design into the 25,000 lbf thrust range[9].

Most nuclear thermal propulsion engine designs utilize uranium fuel enriched to 93 wt% ^{235}U. 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. An iterative process is usually needed to achieve acceptable power flattening while minimizing both reactivity loss and engine mass.

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 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 tie tube element geometry cross section is shown in Fig. 1. The fuel element geometry and the tie tube and fuel element pattern in the interior of the reactor core are shown in Fig. 2.

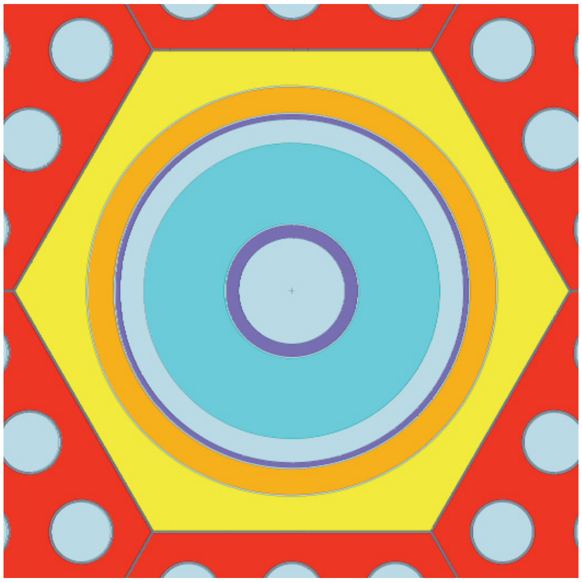

Figure 1. Tie tube element cross section.

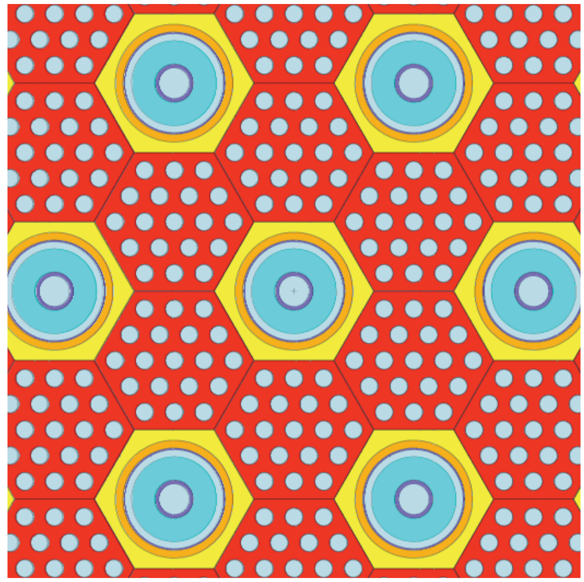

Figure 2. Fuel element and tie tube element pattern in core interior.

The reactor core cross section at the axial mid-plane is illustrated in Fig. 3. These cross sections are from a geometric model described in a later section. In this figure, the interior details of the tie tube elements and the propellant channels in the fuel elements are omitted for clarity. The tie tube elements are shown as yellow hexagons with an inner green circle and fuel elements are shown as open red hexagons. Beryllium filler elements are shown in light blue. Peripheral core components include a stainless steel membrane, a beryllium barrel located between the filler elements and the beryllium reflector, and an aluminum alloy pressure vessel. Reactivity control is provided by twelve cylindrical control drums located in the radial reflector. The rotating drums contain neutron absorber plates over a 120-degree sector of their outer surface. The SNRE design utilized boron-copper for the absorber plates, but the design was not complete. Based on modern test reactor experience, absorber plates of 0.635-cm thick hafnium were assumed. Prior to enrichment zoning, the calculated control swing of about 11.2 dollars exceeds the 8.9 dollars judged adequate for the SNRE design. The drum positions illustrated in Fig. 3 are at the middle-of-range or 90-degree positions.

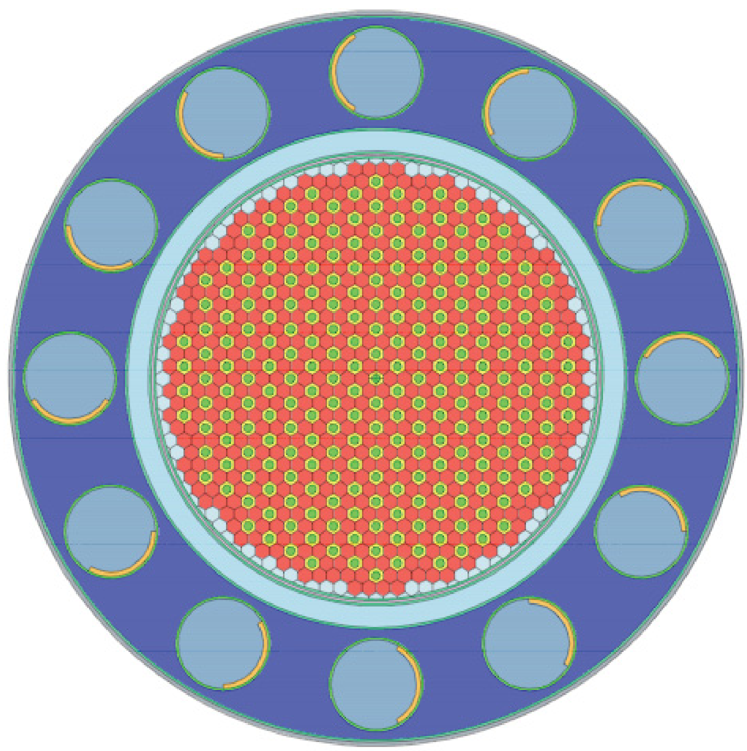

Figure 3. SNRE MCNP model cross section at core mid-plane.

III. Analysis Methods

All transport evaluations reported here were performed using the MCNP Monte Carlo transport code[12]. Cross section data employed in the MCNP transport calculations are primarily from the Evaluated Nuclear Data File[13,14] (ENDF/B) Versions V and VI. The ENDF/B cross section evaluations for some materials of interest, in particular the zirconium and hafnium isotopes, do not include photon yield data. The ENDF/B evaluations were employed for estimating core reactivity and alternate Lawrence Livermore evaluations[15] for some materials substituted for energy deposition evaluations.

A. MCNP Models and Methods

The MCNP model includes the reactor core and the radial components outward through the pressure vessel wall. Geometry and material data for the external components are documented in Table 6 of Ref. 5. The model extends axially from the aft end of the active fuel forward through the internal shields. The pressure vessel forward dome and the regions aft of the active fuel, including the nozzle, were not modeled. The hydrogen tank and miscellaneous hardware components, such as the turbine, hydrogen propellant turbopump, and propellant piping, were not modeled. Although the omitted components will clearly impact external radiation fields, all analyses and results described here are focused on the reactor interior.

The core interior model consists of 564 fuel elements, 241 tie tube elements, and 120 complete or partial beryllium filler elements. Each element is constructed using six exterior surfaces making up the faces of the hexagonal element plus the aft and forward surfaces. Each element contains a “homogenized” material composition established by volume weighting the material compositions of each of the element components. The homogenized compositions for each element type are identical prior to enrichment zoning. This core interior model corresponds to the “Homogenized Discrete” model described in Ref. 5.

Both fission density and energy deposition tally types are available from the MCNP neutron and photon transport evaluations. Although fission events are the energy source and the intent is to adjust local fission density by changing the uranium enrichment, energy deposition rates are more directly related to temperature distributions in the core. Energy deposition rates averaged over each element are used here as the basis for enrichment adjustments.

Local energy deposition peaking can be quantified in terms of a heating rate ratio for fuel element n defined as H_n = (total heating in element n) x (total number of fuel elements) / (total heating in all elements). A similar heating rate ratio is defined for the tie tube elements.

B. EZONER Utility Module

The MCNP-calculated element-by-element energy deposition rates are exported to a FORTRAN utility module. Output from the EZONER utility module exercised in an edit-only mode includes the heating rate ratio for each element and an element list ranked by the heating rate ratio. The utility is exercised a second time to perform the enrichment adjustments. Two methods are available to perform enrichment adjustments. The desired enrichment can be input for each element or the new enrichment can be calculated based on input heating rate ratio limits. For example, the enrichment for any element with a heating rate ration in the range 0.96 to 0.98 can be adjusted upward by 3 wt% ^{235}U while the enrichment for any element with a heating rate ratio in the range 1.20 to 1.30 can be adjusted downward by, say, 20 wt% ^{235}U. The number of heating rate ranges is arbitrary and the enrichment delta for each range is arbitrary.

The material composition description for an MCNP homogenized fuel element model includes the initial (beginning-of-life) fuel isotopes plus structural material isotopes. Fission product isotopes and heavy metal isotopes are also included to support fuel depletion evaluations. The current fuel composition model contains 8 structural material isotopes, 50 fission product isotopes, and 43 heavy metal isotopes for a total of 101 isotopes in the fuel composition. With 564 fuel elements, material concentrations for 56,964 isotopes must be tracked. A fuel element model is usually subdivided into axial zones for depletion analyses. Assuming 7 axial zones per element means 398,748 isotopic concentrations must be tracked. Managing the composition data is automated in the EZONER utility. The MCNP fuel models are exported to the EZONER utility and new fuel descriptions generated following the enrichment adjustment.

Fuel element heating rates do not respond in a strictly linear manner with changes in enrichment. Heating rates in a particular element depend not only on the element itself but also on neighboring elements. Heating rates are strongly influenced by nearby elements with the influence weakening for more distant elements. Several iterations may be required to obtain optimum flattening.

IV. Results

The initial SNRE benchmark evaluations reported in Ref. 5 employed a uniform fuel loading of 0.60 g/cm^3 uranium with a uniform enrichment of 93 wt% ^{235}U. The undesirable thermal energy deposition distributions resulting from this uniform loading are illustrated in Fig. 4. Calculated relative heating rate ratios prior to fuel zoning and with all control drums at the middle of range (90-degree) positions are shown. Element hexagons are color coded with red, light blue, and green representing fuel elements and orange, yellow, and violet represent tie tube elements. Beryllium filler elements and partial elements at the core periphery are dark blue.

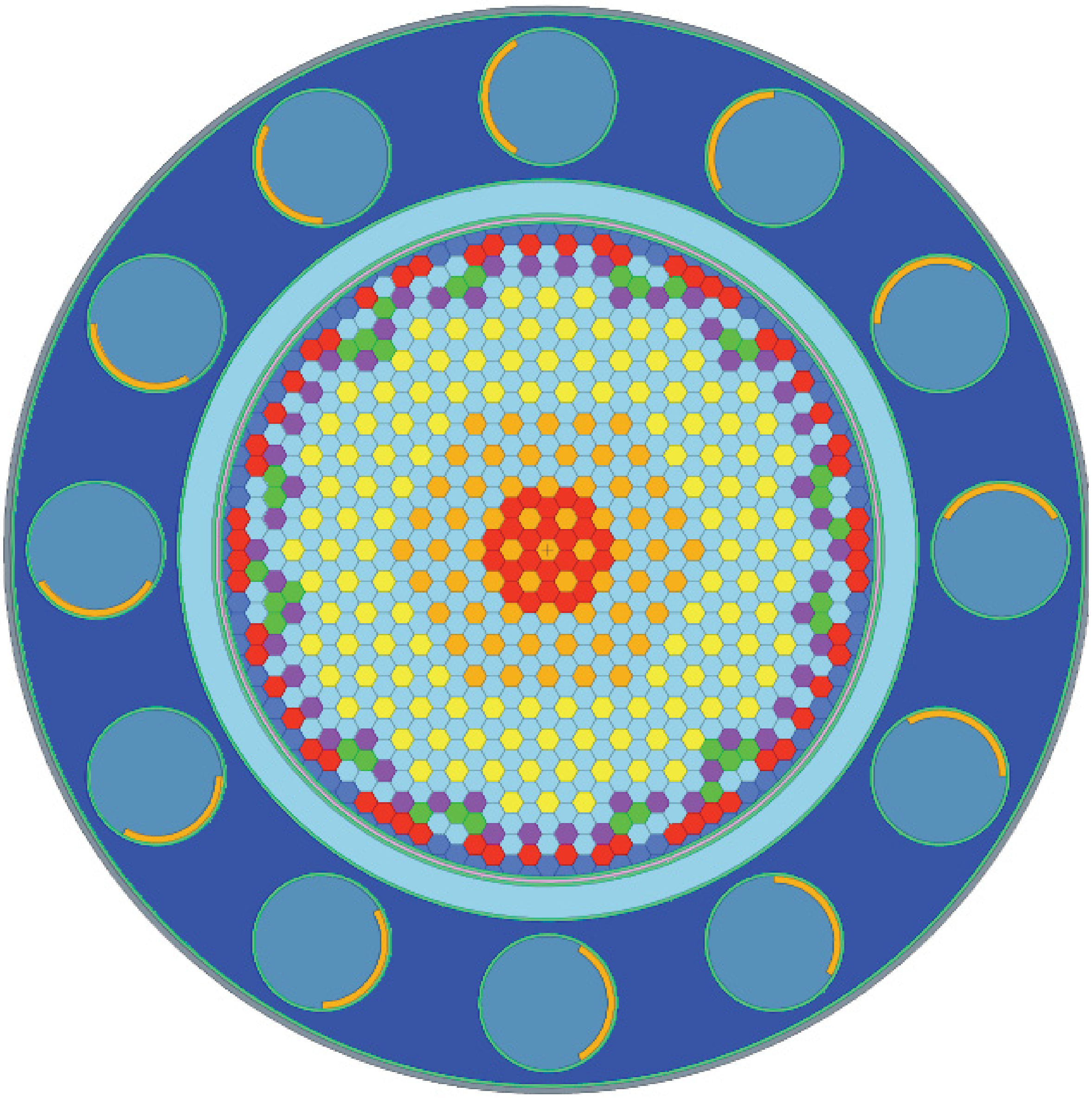

Figure 4. Relative heating in SNRE core with uniform 93 wt% enrichment and all control drums at middle-of-range (90-degree) positions.

Fuel elements operating within $\pm$10% of the average fuel element power are shown in light blue. Fuel elements operating at greater than 110% of the average fuel element power are shown in red. Fuel elements operating at less than 90% of the average fuel element power are shown in green. Tie tube elements within $\pm$10% of the average tie tube element energy deposition are shown in yellow. Warmer (>110%) and cooler (<90%) tie tube elements are shown in orange and violet, respectively.

Fuel element heating is peaked slightly (about 112%) at the center of the core and more sharply at the core periphery near the beryllium barrel and reflector. The maximum fuel peaking at the core periphery is about 130%. The core heating pattern is quite symmetric with minor perturbations produced by the control drum absorbers.

Engine performance can be improved by some combination of propellant flow control at the fuel element level and by varying the fuel composition. The fissile ^{235}U density is a function of both the ^{235}U enrichment and the total uranium loading in the fuel. Optimum engine performance will likely be obtained through application of all three methods. For these evaluations, the 0.60 g/cm^3 uranium loading is held constant and no element inlet orifice flow control is assumed. Only ^{235}U enrichment changes are considered.

The ultimate in power flattening could presumably be obtained by constraining only the upper enrichment limit and allowing an arbitrary number of enrichments. This limiting case could result in a unique enrichment for each of the 564 fuel elements. In practice, enrichments for each fuel position must be selected from a limited number of fixed enrichments. Both the number of enrichments and the enrichment values must be selected.

A. Arbitrary Number of Fuel Enrichment Groups

Prior to enrichment zoning, the heating rate ratio varies from a maximum of 1.293 at the core periphery to a minimum of 0.864, also near the core periphery. Power flattening obtained with successive enrichment zoning iterations is shown in Table 1. The initial configuration with all 93 wt% ^{235}U is designated as Iteration 0. There are 24 fuel elements with heating rate ratios in the range 1.20 to 1.30 and 31 elements with heating rate ratios below 0.90. An arbitrary number of fuel enrichment groups is allowed in the iteration process but the enrichment groups are constrained to be in 1 wt% ^{235}U increments. After the first iteration the maximum heating rate ratio is less than 1.10 and 552 of the fuel elements have heating rate ratios between 0.90 and 1.10. After the second iteration, all heating rate ratios are between 0.90 and 1.05 and the 220 elements with heating rate ratios less than 0.99 are at the maximum 93 wt% enrichment. Successive iterations continue to reduce the heating rate ratio range limits but are more effective at depressing high heating rates than elevating low heating rates.

After Iteration 8, 480 of the 564 fuel elements are within 1% of the average heating rate. There are 12 elements in the range 1.01 to 1.02 and the maximum heating rate ratio is 1.012. All 72 elements with heating rate ratios less than 0.99 are at the maximum enrichment. Enrichments range from 93 wt% to 57 wt%. This range contains 37 enrichment groups with 1% enrichment increments. There are no elements in 6 of the groups leaving 31 populated groups. Seven of the groups contain 6 or fewer elements allowing an option to reduce to 24 groups. This case was not examined.

Table 1. SNRE power flattening with an arbitrary number of enrichment groups.

Fuel Element Heating Rate Ratio Range		Enrichment Zoning Iteration Number								
		0*	1	2	3	4	5	6	7	8
		Number of Fuel Elements in Heating Rate Ratio Group								
1.20	1.30	24	0	0	0	0	0	0	0	0
1.10	1.20	60	0	0	0	0	0	0	0	0
1.05	1.10	72	106	0	0	0	0	0	0	0
1.03	1.05	30	118	103	3	0	0	0	0	0
1.02	1.03	29	34	145	119	17	0	0	0	0
1.01	1.02	1	12	62	175	249	184	97	58	12
1.00	1.01	24	29	12	70	119	217	318	380	418
0.99	1.00	19	13	32	24	27	56	60	43	62
0.98	0.99	23	24	31	37	60	27	17	35	30
0.97	0.98	12	39	44	49	20	37	36	12	16
0.95	0.97	58	87	87	51	60	31	24	24	14
0.90	0.95	181	90	48	48	12	12	12	12	12
0.80	0.90	31	12	0	0	0	0	0	0	0
0.95	1.05	196	356	516	528	552	552	552	552	552
0.90	1.10	449	552	564	564	564	564	564	564	564

* All 93 wt% enrichment prior to first iteration

B. Two Enrichment Groups

Four cases with two enrichment groups are considered using 93 wt% in combination with 80 wt%, 75 wt%, 70 wt%, or 60 wt% enrichment. With only two enrichment groups, one iteration usually yields the best enrichment distribution and only marginal power flattening can be achieved. The combination of 93 wt% and 75 wt% provides the best flattening among these four cases. There are 406 elements with heating rate ratios between 0.95 and 1.05 and 540 elements with ratios between 0.90 and 1.10. There are 24 elements with heating rate ratios greater than 1.10 and the maximum ratio is 1.147.

C. Three Enrichment Groups

Four cases with three fuel enrichment groups are considered using 93 wt% in combination with two other enrichments. The first two cases used fixed enrichment increments. Power flattening results are shown in Table 2. In the first case with 7 wt% increments, the 24 elements with heat ratios above 1.10 could not be reduced with the lowest group (79 wt%). Increasing the delta to 10 wt% improved the power flattening, but 18 elements remained with heat rate ratios above 1.10.

Case 3 utilized enrichments of 93 wt%, 80 wt%, and 70 wt%. After 5 iterations, 494 of the 564 elements are within 5% of the average heating rate and 557 are with 10% of the average heating rate. The 7 elements with heat ratios above 1.10 are at 70 wt% and marginal improvement could be expected from additional iterations.

For Case 4 the lowest group enrichment is reduced to 67 wt% in an attempt to reduce heating in the high heat rate ratio elements. After 5 iterations heating rate ratios in all 564 of the fuel elements are within 10% of the average heating rate. Although the total heating rate ratio band width is reduced, the larger enrichment delta between the two lower groups forces many elements from the 0.95 to 1.05 band into the 0.90 to 1.10 band.

Element movement from the 5% group to the 10% group is not necessarily detrimental to engine performance since the high heat rate ratios have been lowered.

Table 2. SNRE power flattening with three enrichment groups.

Fuel Element Heating Rate Ratio Range		Enrichment Zoning Iteration Number: 0*	1	2	3	4	5
		Number of Fuel Elements in Heating Rate Ratio Group					
Enrichments of 93 wt%, 86 wt%, and 79 wt%							
1.10	1.30	84	36	24	24	-	-
1.05	1.10	72	82	42	42	-	-
1.00	1.05	84	133	208	204	-	-
0.95	1.00	112	172	187	192	-	-
0.90	0.95	181	129	94	94	-	-
0.80	0.90	31	12	9	8	-	-
0.95	1.05	196	305	395	396	-	-
0.90	1.10	449	516	531	532	-	-
Enrichments of 93 wt%, 83 wt%, and 73 wt%							
1.10	1.30	84	12	17	18	-	-
1.05	1.10	72	96	55	39	-	-
1.00	1.05	84	148	169	191	-	-
0.95	1.00	112	200	274	280	-	-
0.90	0.95	181	100	4	36	-	-
0.80	0.90	31	8	0	0	-	-
0.95	1.05	196	348	443	471	-	-
0.90	1.10	449	544	547	546	-	-
Enrichments of 93 wt%, 80 wt%, and 70 wt%							
1.10	1.30	84	12	6	6	6	7
1.05	1.10	72	87	69	55	48	44
1.00	1.05	84	163	169	173	202	204
0.95	1.00	112	221	275	302	278	290
0.90	0.95	181	76	45	28	30	19
0.80	0.90	31	5	0	0	0	0
0.95	1.05	196	384	444	475	480	494
0.90	1.10	449	547	558	558	558	557
Enrichments of 93 wt%, 80 wt%, and 67 wt%							
1.10	1.30	84	6	0	1	0	0
1.05	1.10	72	85	91	96	77	77
1.00	1.05	84	175	171	158	172	165
0.95	1.00	112	219	229	256	262	288
0.90	0.95	181	79	72	53	53	34
0.80	0.90	31	0	1	0	0	0
0.95	1.05	196	394	400	414	434	453
0.90	1.10	449	558	563	563	564	564

* All 93 wt% enrichment prior to first iteration

D. Four Enrichment Groups

Two cases with four enrichment groups are considered. Power flattening results for these cases are shown in Table 3. The first case utilized an enrichment increment of 7 wt%. After 3 iterations there are 6 elements with heat rate ratios greater than 1.10. Additional iterations result in additional elements in this high heat rate ratio group. This can be misleading since the maximum heat rate ratio remains about 1.14 for Iterations 3 through 6 while the number of elements continues to diminish in the lower performance group with heat ratios in the range 0.90 to 0.95.

The second case utilized a larger enrichment increment of 10 wt%. After the first iteration heat rate ratios for all 564 elements are within 10% of the average heat rate. After four iterations, heat rate ratios for 517 of the 564 elements are within 5% of the average heat rate. The maximum heat rate ratio after four iterations is 1.064. This iteration also yields the lowest number of elements in the lower performance group with heat ratios in the range 0.90 to 0.95.

Table 3. SNRE power flattening with four enrichment groups.

Fuel Element Heating Rate Ratio Range		Enrichment Zoning Iteration Number							
		0*	1	2	3	4	5	6	7
		Number of Fuel Elements in Heating Rate Ratio Group							
Enrichments of 93 wt%, 86 wt%, 79 wt%, and 72 wt%									
1.10	1.30	84	6	6	6	7	12	12	17
1.05	1.10	72	91	61	56	44	26	23	7
1.00	1.05	84	180	220	206	221	225	233	243
0.95	1.00	112	185	184	223	242	260	258	261
0.90	0.95	181	92	88	72	50	41	38	36
0.80	0.90	31	10	5	1	0	0	0	0
0.95	1.05	196	365	404	429	463	485	491	504
0.90	1.10	449	548	553	557	557	552	552	547
Enrichments of 93 wt%, 83 wt%, 73 wt%, and 63 wt%									
1.10	1.30	84	0	0	0	0	0	-	-
1.05	1.10	72	75	68	44	32	44	-	-
1.00	1.05	84	181	194	232	221	213	-	-
0.95	1.00	112	263	266	266	296	289	-	-
0.90	0.95	181	45	36	22	15	18	-	-
0.80	0.90	31	0	0	0	0	0	-	-
0.95	1.05	196	444	460	498	517	502	-	-
0.90	1.10	449	564	564	564	564	564	-	-

* All 93 wt% enrichment prior to first iteration

V. Conclusion

Enrichment zoning is one of three primary methods of reducing undesirable radial power and temperature profiles in the engine. Even when applied as the sole method, enrichment zoning is quire effective at achieving exceptionally flat energy deposition profiles assuming of order twenty enrichment groups can be used. Two enrichment groups provide only marginal power flattening. Although not optimum, as few as three or four enrichment groups provide considerable flattening and may be adequate when combined with orifice inlet flow control at the fuel element level. Results from additional engine system performance evaluations such as reported in Ref. 8 are needed to incorporate inlet flow control and to assess the impact of using a minimum number of enrichment groups.

Acknowledgments

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