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Enhanced Low-Enriched Uranium Fuel Element for the Advanced Test Reactor

M.A. Pope, M.D. DeHart, S.R. Morrell, R.K. Jamison, E.C. Nef, and D.W. Nigg
Idaho National Laboratory
2525 N. Fremont Avenue, Idaho Falls, Idaho, 83415, USA

ABSTRACT

Under the current US Department of Energy (DOE) policy and planning scenario, the Advanced Test Reactor (ATR) and its associated critical facility (ATRC) will be reconfigured to operate on low-enriched uranium (LEU) fuel. This effort has produced a conceptual design for an Enhanced LEU Fuel (ELF) element. This fuel features monolithic U-10Mo fuel foils and aluminum cladding separated by a thin zirconium barrier. As with previous iterations of the ELF design, radial power peaking is managed using different U-10Mo foil thicknesses in different plates of the element. The lead fuel element design, ELF Mk1A, features only three fuel meat thicknesses, a reduction from the previous iterations meant to simplify manufacturing. Evaluation of the ELF Mk1A fuel design against reactor performance requirements is ongoing, as are investigations of the impact of manufacturing uncertainty on safety margins. The element design has been evaluated in what are expected to be the most demanding design basis accident scenarios and has met all initial thermal-hydraulic criteria.

1. Introduction

The Advanced Test Reactor (ATR), located at Idaho National Laboratory (INL), is one of only a few high-power research reactors of its general type in the world. Its capabilities support a variety of missions involving accelerated testing of nuclear fuel and other materials in a very high neutron flux environment, medical and industrial isotope production, and several other specialized applications. Figure 1 shows a cross-sectional view of the ATR core. Along with its companion critical mockup, the ATR Critical Facility (ATRC), the ATR is one of the key nuclear engineering research and testing facilities within the US Department of Energy (DOE) National Laboratory Complex. Under the current long-term DOE policy and planning scenario, both the ATR and the ATRC will be reconfigured at an appropriate time to operate with low-enriched uranium (LEU) fuel. This will be accomplished under the auspices of the Reduced Enrichment for Research and Test Reactors (RERTR) Program of the Global Threat Reduction Initiative (GTRI), administered by the DOE National Nuclear Security Administration (NNSA). This paper presents a description of the lead candidate LEU fuel element for ATR. Results of various calculations are also presented.

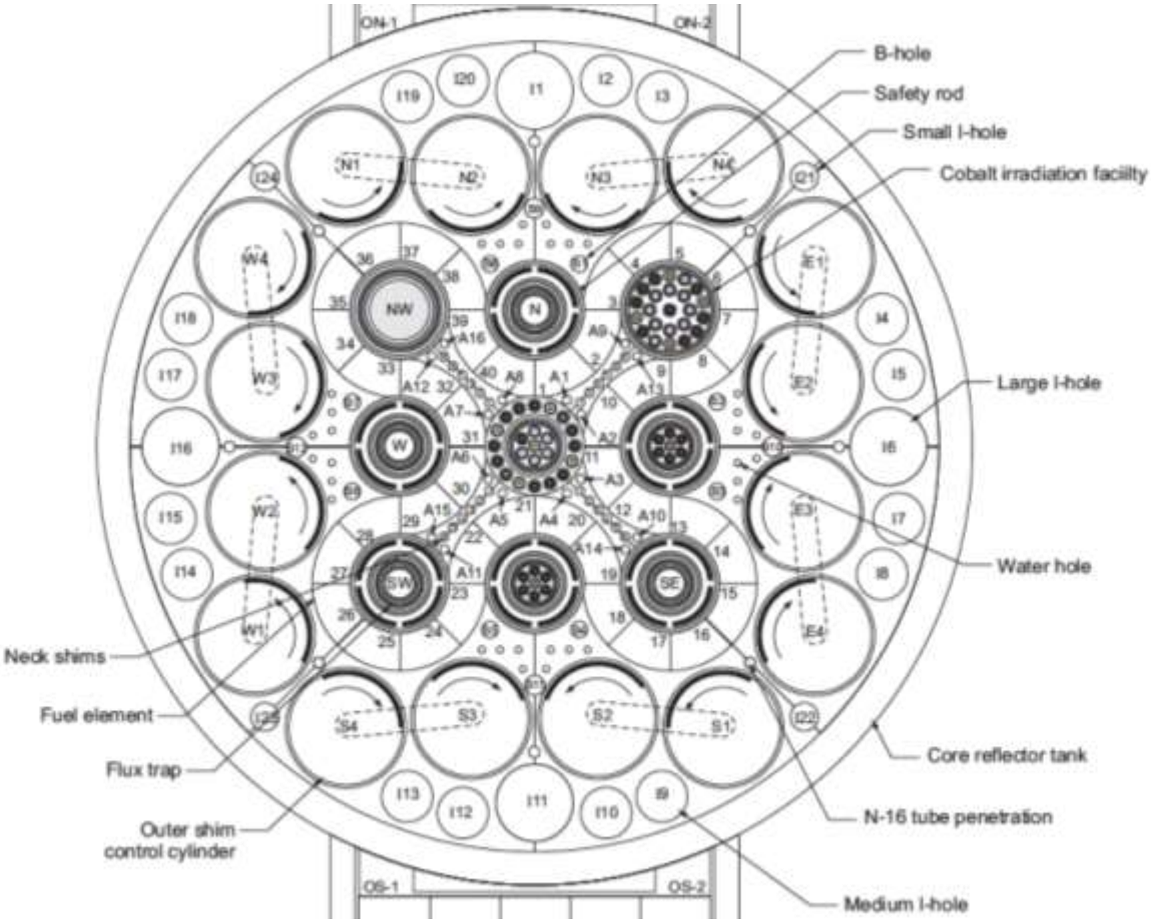

Fig 1. Cross-sectional view of the ATR core.

2. ELF Mk 1A Fuel

A conceptual LEU fuel design has been developed for the ATR called the Enhanced LEU Fuel (ELF) element featuring monolithic U-10Mo fuel foils and aluminum cladding separated by a thin zirconium barrier. [1,2] This design accomplishes radial power peaking control through adjusted fuel meat thicknesses and no use of burnable poison in the fuel elements. Two variations on this Enhanced LEU Fuel (ELF) element have been designed, called ELF Mk 1A and ELF Mk 1B. ELF Mk 1A uses three unique fuel meat thicknesses while ELF Mk 1B uses five unique fuel meat thicknesses to further flatten radial power peaking (at the cost of two additional fuel thicknesses). Both the Mk 1A and Mk 1B fuel designs have been evaluated against key driving accident scenarios anticipated to be bounding with regard to regulatory approval and that both designs met all thermal hydraulic (TH) criteria. This document presents physics analysis of ELF Mk 1A only. A description of the element is provided followed by some key comparisons to the current high-enriched uranium (HEU) fuel in a representative core loading scenario. Because the two ELF designs have nearly identical fuel loadings, none of these results are expected to differ appreciably between them. Table 1 shows fuel meat thicknesses for the Mk 1A fuel and Fig. 2 illustrates the fuel meat variation. The thickest fuel meat is 16 mils (0.04064 cm) thick and the thinnest fuel meat is 8 mils (0.02032 cm) thick. This variation in thickness compensates for the tendency for peripheral plates to have peaked power as a result of moderation outside the element and shielding of the interior plates. Thus thinning the fuel meat of the peripheral plates is analogous to the boron included in peripheral plates (1-4 and 16-19) of the current ATR fuel.

Table 1. ELF Mk 1A fuel meat thicknesses.

Parameter		**(cm)**	**(mils)**
Fuel Meat Thickness by Plate #	1	0.02032	8
	2	0.03302	13
	3	0.03302	13
	4	0.04064	16
	5	0.04064	16
	6	0.04064	16
	7	0.04064	16
	8	0.04064	16
	9	0.04064	16
	10	0.04064	16
	11	0.04064	16
	12	0.04064	16
	13	0.04064	16
	14	0.04064	16
	15	0.04064	16
	16	0.03302	13
	17	0.02032	8
	18	0.02032	8
	19	0.02032	8
Number of unique thicknesses		3	
^{235}U mass per element (g)		1648	

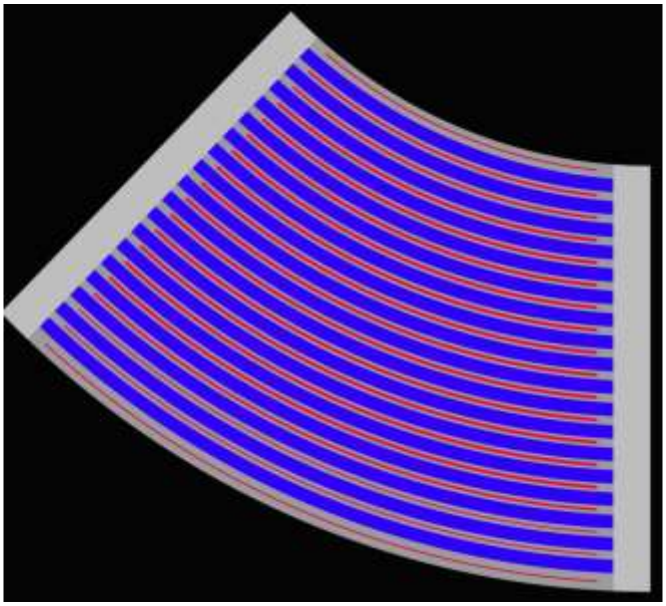

Fig. 2. Cross-section of ELF Mk 1A fuel element with fuel meat thicknesses shown in red.

3. Reactor Modeling Approach

The calculations reported herein were performed using Serpent Version 2.1.15 (July 31, 2013). [3] This is a pre-release *beta* version of this software package; however, all source code and the executable are controlled at INL. All calculations were performed using ENDF/B-VII.0 cross sections as distributed with the Serpent 1.1.7 package via the Radiation Safety Information Computational Center (RSICC) [4]. The only exception to this was the beryllium metal scattering date, which came from ENDF-V. The base model used for these calculations is based on the 94-CIC benchmark described in [5]. Neck shims are small absorber rods used to compensate for reactivity loss during depletion. The model used in this work had two neck-shims withdrawn (22 inserted) as was originally used in the 94-CIC benchmark unless otherwise stated. Outer Shim Control Cylinders (OSCCs) are rotating drums at the core periphery with a surface partially covered with hafnium. These drums are rotated during depletion to 1) maintain lobe power splits, and 2) to compensate for reactivity loss during depletion without significantly disrupting the axial power shape. These were maintained at an 80° rotation unless otherwise stated.

4. Cycle Length Calculations

In order to compare the cycle length capability of the ELF Mk 1A fuel to the current HEU fuel, the representative loading in Figure 3 was used. This was aimed at demonstrating that the same or greater cycle length could be achieved with the new fuel using a loading typical of ATR cores. It was concluded that for the same representative loading, the ELF Mk 1A (LEU) fuel had more reactivity than the HEU fuel. The difference was approximately \$3 additional at beginning of cycle (BOC) and \$1 at end-of-cycle (EOC). The reason for the large additional excess reactivity at BOC is the lack of burnable poisons in the ELF Mk 1A element. This additional holddown is addressed in Section 5. The \$1 additional reactivity at EOC suggests that alternative loadings could be used with ELF fuel wherein fewer fresh elements are used while achieving the same cycle length as with HEU. Here, this hypothesis was tested using Serpent depletion calculations. Two alternative loading configurations are presented here giving the same EOC reactivity as the HEU core. One, here referred to as “ELF Mk 1A (loading 2)” replaces fresh elements in locations 19 and 22 with twice-burned elements. The other, referred to as “ELF Mk 1A (loading 3)” replaces fresh elements in locations 12, 19, 22, and 29 with once-burned elements. Figure 4 shows k_{eff} v. burnup in days for the representative depletion with HEU with ELF Mk 1A (LEU) fuels. The two alternative loadings are also shown in the plot.

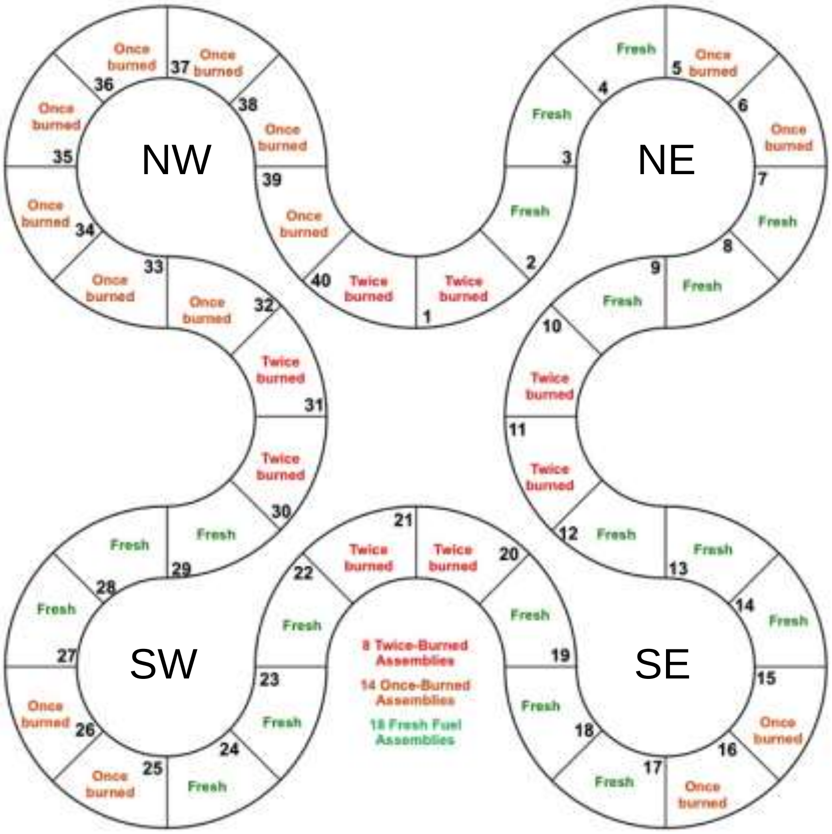

Fig. 3. Representative core loading diagram.

Both of these alternative ELF Mk 1A loadings give approximately $2 higher reactivity than HEU at BOC and the same reactivity as HEU at EOC. This suggests that these alternative loadings may allow ELF Mk 1A fuel to achieve the same cycle length as HEU fuel with 2 to 4 fewer fresh elements loaded per cycle. It should be noted, however, that neck shims are not withdrawn during this simulated depletion. This means that differences in neck shim worth between HEU and LEU are not accounted for here. Any reduction in worth of neck shims or OSCCs from changing to LEU fuel must be compensated for by additional hold-down at BOC. It will be shown in Section 6 that neck shim worth is diminished somewhat with the change to LEU fuel, and so additional consideration must be made for compensating for this.

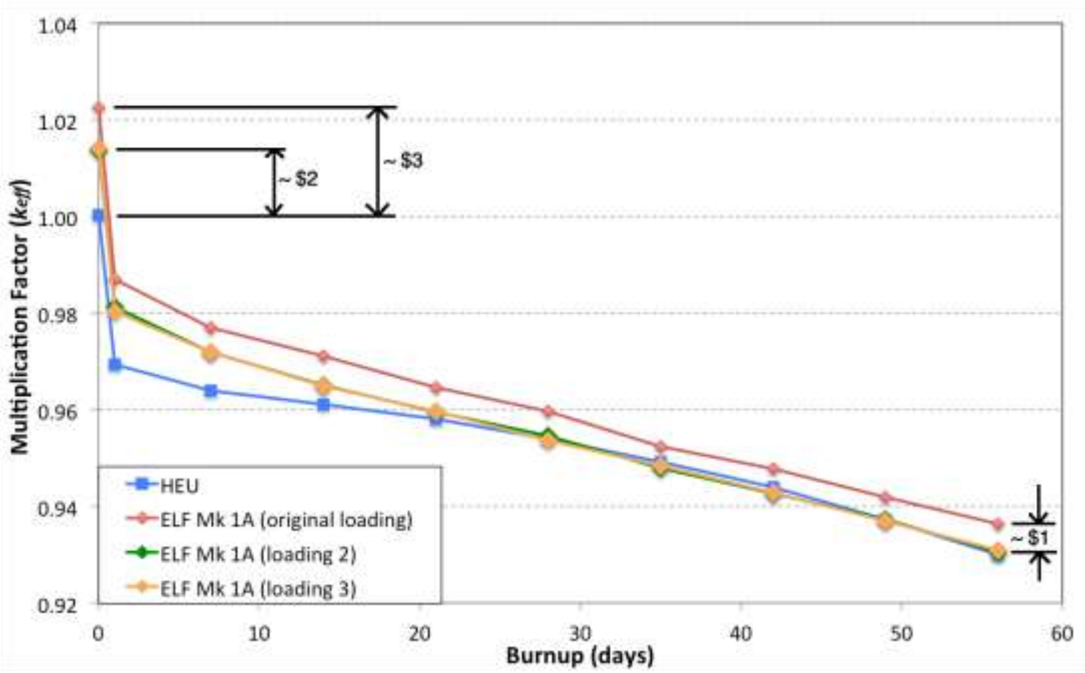

Fig. 4. Multiplication factor v. burnup for HEU and ELF Mk 1A with three different loadings.

5. Burnable Poison Rods in Small B Positions

Because ELF Mk 1A fuel has higher initial reactivity than the current HEU fuel, and it does not have burnable poison in the fuel element, additional reactivity hold-down must be achieved through either manipulation of OSCCs or by addition of burnable poison external to the fuel elements. Here, a burnable poison rod is conceptualized for insertion into small B positions. The selection of Gd_2O_3 for the burnable absorber was based on a balancing of high worth and ability to burn out in less than one cycle. A schematic of the pin is shown in Fig. 5 and the dimensions are given in Table 2. This concept uses a 0.005 cm thick shell of Gd_2O_3 with aluminum cladding inside and out. A central coolant channel is specified for this analysis. The aluminum would be required to lend some structural support because this burnable absorber would also need to serve the function of the B Hole Retainer (INL drawing no. 403205). The function of the B Hole Retainer is to hold a section of beryllium reflector in place in the event that it cracks during a cycle. It is used in sections of reflector at high neutron fluence toward the end of the beryllium lifetime. Further design and analysis should be performed in order to produce a viable design serving both of these functions. This is only a feasibility study meant to evaluate the reactivity worth that can be achieved while assuming that the structural function can be served.

Table 3 shows the reactivity worth of a B-position absorber pin in each of the small B locations, and in all of them simultaneously. These pins have between -\$0.16 and -\$0.41 of reactivity worth, depending on location. Because the power is concentrated in the southern lobes, the B positions adjacent to the SE and SW lobes have higher worth than those adjacent to the NE and NW lobes. The worth absorber pins in all 8 small B-holes simultaneously is -\$2.37.

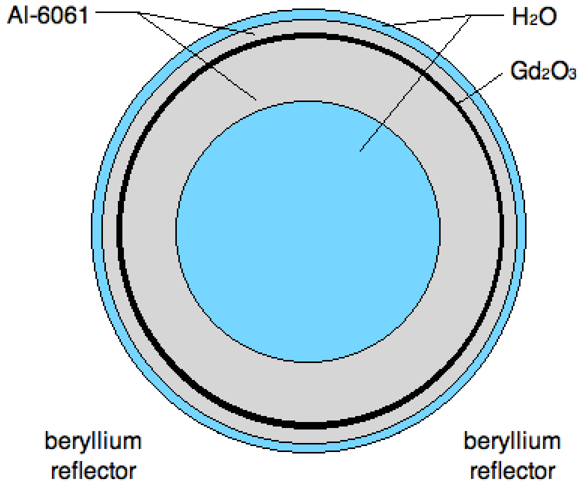

Figure 5. Diagram of B-hole poison pin.

Table 2. Parameters of B-hole absorber poison pin.

Component Surface	**Radius (cm)**
Small B Position	1.11
Pin Outer	1.060
Gd_2O_3 Outer	0.850
Gd_2O_3 Inner	0.845
Inner Coolant Channel	0.500

Table 3. Results from Analysis of Gd_2O_3 absorbers in Small B Positions.

Gd_2O_3 Absorber Locations	**Lobe Adjacent**	**k_{eff}***	**Worth ($)****
None	—	1.02175	—
B1	NE	1.02033	-0.20
B2	NE	1.01987	-0.26
B3	SE	1.01920	-0.35
B4	SE	1.01879	-0.41
B5	SW	1.01886	-0.40
B6	SW	1.01964	-0.29
B7	NW	1.02029	-0.20
B8	NW	1.02060	-0.16
All small B positions	All	1.00494	-2.37

* ± 0.00009

** ± $0.02

The burnable poison pin design evaluated above was used in depletion analyses of the cores with modified loadings presented in Section 4 The purpose of this is to demonstrate that the burnable poisons proposed here burn out in less than one cycle. This analysis is performed with all but two neck shims inserted and the OSCCs rotated to 80º. Figure 6 shows k_{eff} v. burnup for the HEU representative depletion along with the two LEU alternative loadings with burnable poisons in 6 of the 8 small B locations (B2-B7). This shows that by 20 days, the poisons are depleted and the reactivity at EOC is similar to that of HEU. Again, it should be noted that the difference in reactivity worth of neck shims are treated separately in Section 6. This analyses must be taken into consideration for a more complete understanding of the additional reactivity hold-down requirements of converting to ELF Mk 1A fuel.

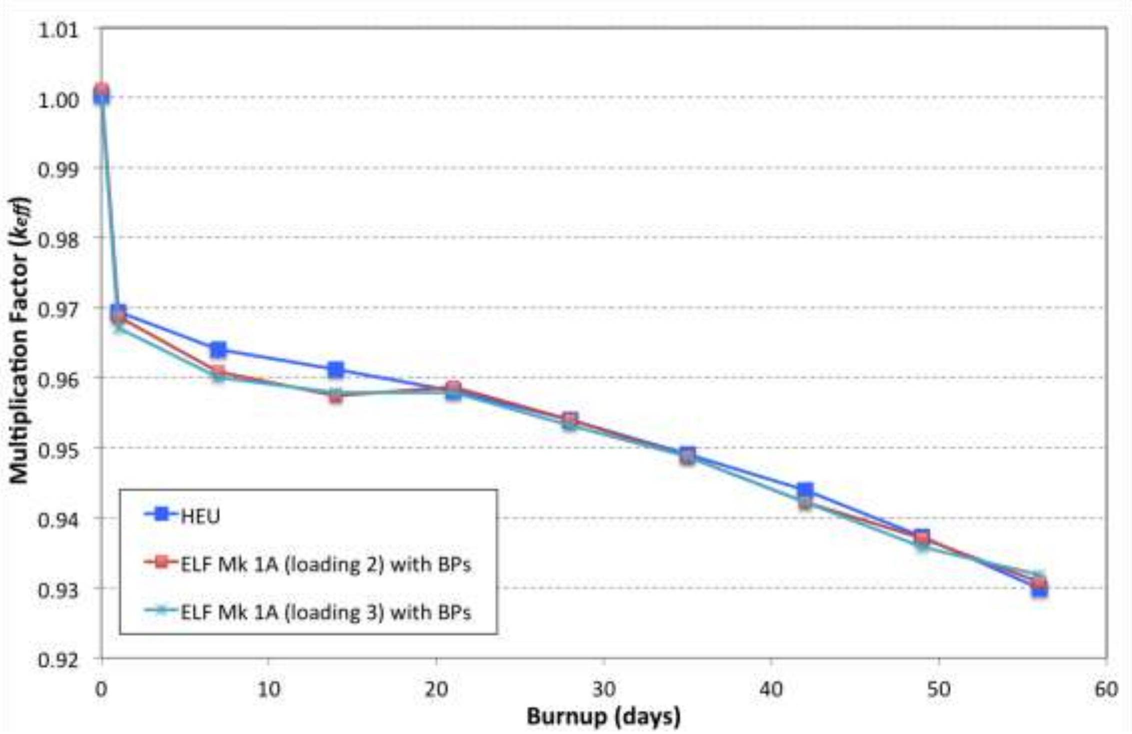

Figure 6. Multiplication factor v. burnup for HEU and ELF Mk 1A with two alternative loadings and burnable absorber pins in positions B2-B7.

6. Neck Shim Worth Comparisons

Comparisons were performed between neck shim worth in HEU and ELF Mk 1A (LEU) fueled cores. The representative loadings were used and all neck shims were inserted in the nominal case. Neck shims were then withdrawn individually and the reactivity increase was recorded as the neck shim worth. For this analysis, the two regulating rods were treated the same as ordinary neck shims. Each time a neck shim was withdrawn, it was reinserted for calculation of subsequent neck shim rods. Therefore, only one was modeled as withdrawn at any given time. Then all neck shims were withdrawn simultaneously giving their collective worth. Table 4 shows neck shim worths in the HEU and ELF Mk 1A (LEU) loaded cores.

Table 4. Neck shim worth in HEU and ELF Mk 1A cores.

Neck Shim(s) Withdrawn	**HEU** (β_{eff} = 0.00701)			**LEU** (β_{eff} = 0.00692)			**Δ Worth* (LEU – HEU)** in pcm (± 17 pcm)
	k_{eff} (± 8E-5)	Worth (pcm)	Worth ($)	k_{eff} (± 6E-5)	Worth (pcm)	Worth ($)	
None	0.99654	NA	NA	1.01790	NA	NA	NA
SW1	0.99842	189	0.27	1.01930	135	0.19	-54
SW2	0.99830	176	0.25	1.01930	135	0.19	-41
SW3	0.99822	169	0.24	1.01965	169	0.24	0
SW4	0.99819	166	0.24	1.01944	148	0.21	-17
SW5	0.99856	203	0.29	1.01964	168	0.24	-35
SW6	0.99869	215	0.31	1.02002	204	0.29	-11
SE1	0.99831	178	0.25	1.01954	158	0.23	-20
SE2	0.99816	162	0.23	1.01947	151	0.22	-11
SE3	0.99830	176	0.25	1.01943	147	0.21	-29
SE4	0.99819	166	0.24	1.01957	161	0.23	-5
SE5	0.99837	183	0.26	1.01966	170	0.24	-14
SE6	0.99873	220	0.31	1.02008	210	0.30	-10
NW1	0.99794	141	0.20	1.01914	120	0.17	-21
NW2	0.99802	149	0.21	1.01899	105	0.15	-43
NW3	0.99768	115	0.16	1.01892	98	0.14	-16
NW4	0.99802	149	0.21	1.01883	90	0.13	-59
NW5	0.99768	114	0.16	1.01890	96	0.14	-18
NW6	0.99791	138	0.20	1.01899	105	0.15	-32
NE1	0.99803	150	0.21	1.01918	123	0.18	-26
NE2	0.99776	123	0.17	1.01900	106	0.15	-17
NE3	0.99774	121	0.17	1.01916	121	0.18	1
NE4	0.99777	123	0.18	1.01910	116	0.17	-7
NE5	0.99776	122	0.17	1.01938	143	0.21	21
NE6	0.99791	137	0.20	1.01963	167	0.24	30
Average	NA	158	0.22	NA	139	0.20	-18
All Neck Shims Withdrawn	1.04674	4812	6.86	1.06439	4291	6.20	-521

* Negative values indicate that neck shim has lower worth with LEU than with HEU fuel.

The worth of nearly all neck shims either remained the same (within statistical uncertainty of the Serpent calculations) or diminished upon changing from HEU to ELF Mk 1A (LEU) fuel. At BOC in ATR, nearly all neck shims are inserted (all but two regulating rods) and at EOC, nearly all neck shims are withdrawn (again all but two regulating rods). The worth of all neck shims inserted was found to be about 521 pcm (~ $0.75) less in the LEU fuel than with HEU.

The representative core depletions from earlier sections of this paper assume all but two neck shims are inserted for the duration. This means that at the end of cycle, approximately $0.75 of reactivity must be credited to the HEU fuel in this comparison. Thus, in Figure 2, when the representative loading of ELF Mk 1A fuel has approximately $1 additional reactivity at EOC compared to HEU, it can be considered to be nearly the same reactivity for the purposes of this analysis. Therefore, a loading intermediate to the original representative loading and the alternatives (although closer to the original representative loading) may be a viable option. Considering the neck shim value, then, the additional holddown required for ELF Mk 1A fuel is estimated to be approximately $2.75 for an equivalent cycle length to that of a typical HEU core. In Section 5 it was shown that if all eight small B positions could be occupied by the proposed burnable poison, this would give -$2.37 of additional holddown at BOC. If OSCCs can be rotated inward (lower numerical rotation) at BOC than normally done, some of this additional holddown could be accommodated, reducing the burden on external burnable poisons and occupying fewer test positions.

7. Outer Shim Control Cylinder Worth

Comparisons were also performed between OSCC worth in HEU and ELF Mk 1A fueled cores. The representative loadings were used at BOC and all OSCC banks were rotated simultaneously from 0° to 180° in 10° increments. Table 5 shows results of this study with a comparison of worths of OSCC rotation using 180° as a baseline. This shows that the difference in OSCC worth between HEU and ELF Mk 1A (LEU) is less than 100 pcm for most rotations sampled. This is not anticipated to present a major challenge to operational practices.

Table 5. Worth of simultaneous rotation of OSCCs in HEU and ELF Mk 1A cores.

OSCC Rotation (degrees)	**HEU** (β_{eff} = 0.00701)			**LEU** (β_{eff} = 0.00692)			**Δ (LEU – HEU)** in pcm (± 15 pcm)
	k_{eff} (± 8E-5)	Worth (pcm)	Worth ($)	k_{eff} (± 6E-5)	Worth (pcm)	Worth ($)	
0	0.94355	-10451	-14.90	0.96353	-10336	-14.93	115
10	0.94535	-10250	-14.61	0.96544	-10132	-14.64	118
20	0.94876	-9870	-14.07	0.96865	-9788	-14.14	82
30	0.95389	-9303	-13.26	0.97376	-9246	-13.36	57
40	0.96060	-8570	-12.22	0.98078	-8512	-12.30	59
50	0.96952	-7613	-10.86	0.98940	-7623	-11.01	-10
60	0.97961	-6550	-9.34	0.99968	-6583	-9.51	-33
70	0.99024	-5454	-7.78	1.01051	-5512	-7.96	-57
80	1.00091	-4378	-6.24	1.02141	-4456	-6.44	-78
90	1.01100	-3381	-4.82	1.03192	-3458	-5.00	-77
100	1.02019	-2490	-3.55	1.04145	-2572	-3.72	-82
110	1.02821	-1725	-2.46	1.04978	-1810	-2.61	-84
120	1.03471	-1114	-1.59	1.05679	-1178	-1.70	-63
130	1.03982	-639	-0.91	1.06233	-684	-0.99	-45
140	1.04350	-300	-0.43	1.06646	-320	-0.46	-20
150	1.04601	-70	-0.10	1.06930	-71	-0.10	0
160	1.04724	42	0.06	1.07069	51	0.07	9
170	1.04744	60	0.09	1.07082	62	0.09	2
180	1.04678	0	0.00	1.07011	0	0.00	0

8. Conclusions

The conceptual design of the ELF Mk 1A fuel for the ATR was presented. Calculations were performed to further characterize the performance of this fuel and compare its performance to the current HEU fuel. The reactivity to be held down at BOC for ELF Mk 1A fuel is estimated to be approximately $2.75 greater than with HEU for a typical cycle. This is a combined effect of the absence of burnable poison in the ELF fuel and the reduced neck shim worth in LEU fuel compared to HEU. Burnable poison rods were conceptualized for use in the small B positions containing Gd_2O_3 absorber. These were shown to provide $2.37 of negative reactivity at BOC and to burn out in less than half of a cycle. Neck shims were found to be worth, on average, slightly less in the LEU core than in the HEU core. The worth of all neck shims simultaneously was calculated to be $0.75 less in the LEU core than in the HEU core. The worth of OSCCs is approximately the same between HEU and ELF Mk 1A (LEU) fuels in the representative loading evaluated. This was evaluated by rotating all banks simultaneously. Evaluations of performance of the ELF Mk 1A fuel in more realistic operational scenarios are ongoing.

9. References

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