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Key Metrics for HFIR HEU and LEU Models

Germina Ilas
Ben Betzler
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October 25, 2016

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OAK RIDGE NATIONAL LABORATORY
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Reactor and Nuclear Systems Division
Research Reactors Division

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OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831-6283
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CONTENTS

LIST OF FIGURES

LIST OF TABLES

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ABSTRACT

This report compares key metrics for two fuel design models of the High Flux Isotope Reactor (HFIR). The first model represents the highly enriched uranium (HEU) fuel currently in use at HFIR, and the second model considers a low-enriched uranium (LEU) interim design fuel. Except for the fuel region, the two models are consistent and both include an experiment loading that is representative of HFIR's current operation.

The considered key metrics are

- the neutron flux at the cold source moderator vessel,
- the mass of ^{252}Cf produced in the flux trap target region as function of cycle time,
- the fast neutron flux at locations of interest for material irradiation experiments, and
- the reactor cycle length.

These key metrics are a small subset of the overall HFIR performance and safety metrics. They were defined as a means of capturing data essential for HFIR's primary missions, for use in optimization studies assessing the impact of HFIR's conversion from HEU fuel to different types of LEU fuel designs.

1. INTRODUCTION

The High Flux Isotope Reactor (HFIR) is a high-flux pressurized light water-cooled and -moderated flux-trap type research reactor operated at Oak Ridge National Laboratory (ORNL). HFIR is one of the major neutron research facilities at ORNL, supporting neutron scattering experiments, materials irradiation research, and isotope production. The reactor is operated at 85 MWth power and is fueled with highly enriched uranium (HEU) dispersion fuel (U_3O_8-Al), with a nominal enrichment of 93 wt% ^{235}U. Efforts are ongoing to design a low-enriched uranium (LEU) fuel with 19.75 wt% ^{235}U enrichment that would allow a safe, reliable, affordable conversion of HFIR from HEU to LEU fuel. The LEU fuel under consideration is a high-density U-Mo alloy [1].

One of the goals of the HFIR fuel conversion program is to "ensure that the ability of the reactor to perform its scientific mission is not significantly diminished" [1]. To compare the performance of HFIR HEU and LEU cores and assess various LEU fuel design alternatives, a simple yet broad set of key performance metrics is required. These metrics, used for relative comparisons, are intended to represent the multifaceted missions of HFIR—neutron scattering, isotope production, and materials irradiation—and to be relatively straightforward to calculate. Absolute performance estimation and benchmarking to HFIR's actual performance will be conducted separately and in more detail.

The parametrization of the considered key metrics, which is described in Section 2 of this report, includes

- the neutron flux at the cold source moderator vessel,
- the ^{252}Cf produced in the flux trap target region,
- the fast neutron flux at locations of interest for material irradiation experiments, and
- the reactor cycle length.

The models used to calculate these key metrics are documented in detail in previous publications [2–4]. This report presents a comparison of these key metrics, which were determined for two three-dimensional (3-D) high-fidelity HFIR models. The first model [2] considers HEU fuel, an experiment loading representative of HFIR's current operation, and a reactor power of 85 MW. The second model [3] considers an LEU interim design fuel [1] with a reactor power of 100 MW. Except for the fuel region, the two models are consistent and both include an explicit representation [2–4] of the HFIR's fuel plate involute geometry.

The results of the key metrics comparison are presented and discussed in Section 3 of this report, followed by concluding remarks in Section 4.

2. KEY METRICS DESCRIPTION

Evaluation of the key performance metrics has been performed based on the parametrization described herein. For each of the key metrics, the following are provided: the calculated parameters, the location in the reactor, the day during the reactor cycle at which the parameters are calculated, and the units used to report the calculated data.

2.1 FLUX AT THE COLD SOURCE MODERATOR VESSEL

The following parameters are calculated for the cold source moderator vessel, where fluxes are expressed in units of n/cm^2s) (absolute flux value) and n/cm^2s MW (flux per unit power), and E_n stands for neutron energy:

- neutron flux for cold neutrons for the energy bins ($E_n < 0.103978$ eV) listed in Table 2.1
- neutron flux in three energy groups:
  - thermal ($E_n < 0.625$ eV),
  - epithermal (0.625 eV $< E_n <$ 100 keV),
  - fast (100 keV $< E_n <$ 20 MeV),
- total neutron flux ($E_n <$ 20 MeV)
- neutron flux ratios:
  - thermal/total, epithermal/total, fast/total,
  - group flux/total (group energy as shown in Table 2.1).

Table 2.1. Energy bins to tally neutron flux at low energies

Wavelength (Å)	Energy (meV)
0.887	103.978
2.860	10.001
5.020	3.246
7.510	1.450
10.000	0.818
11.930	0.575
15.860	0.325
20.000	0.205
28.600	0.100

The neutron fluxes are reported at beginning of cycle (BOC), end of cycle (EOC), and middle of cycle (MOC). The magnitude of the cold flux is expected to increase from BOC through EOC as the control elements that separate the beryllium reflector from the fuel elements region are withdrawn during the reactor cycle. This results in increased streaming of neutrons from the fuel into the reflector. The cold source moderator vessel region where the fluxes are calculated consists of three cells in the HFIR model that was developed for use with the Monte Carlo N Particle (MCNP) [5] code: 86011, 86051, and 86091. The material considered in these three cells is hydrogen at a temperature of 20 K.

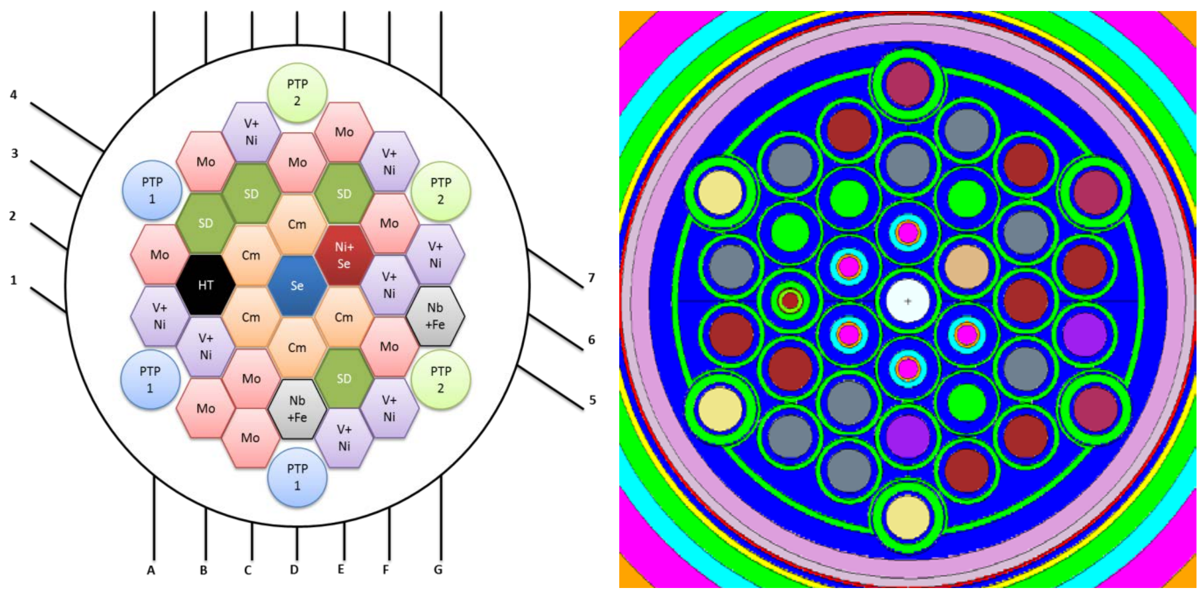
It was assumed that hydrogen in the cold source moderator vessel is 99.8% para-hydrogen and 0.2% ortho-hydrogen, as applicable to liquid hydrogen [6]. This assumption impacts the thermal scattering data used in the MCNP neutron transport simulations. The spin state (ortho or para) of the hydrogen atoms is relevant for cold neutrons because for neutron energies below 30 meV, the total neutron cross sections for the ortho and para states are significantly different, with the cross section for the ortho state being larger than the cross section for the para state [7]. The thermal scattering libraries used with MCNP for hydrogen at 20K were *hortho.10t* and *hpara.10t*.

The selected energy bins in Table 2.1 are relevant for studies previously reported for the HFIR cold source design [7]. The table also shows the corresponding cold neutron wavelengths.

2.2 CALIFORNIUM-252 PRODUCTION

The calculated parameter is the total mass of ^{252}Cf (in grams) produced in all targets used for ^{252}Cf production (see Fig. 2.1). These targets are located at five sites in the flux trap target region and are labeled *Cm* in Fig. 2.1 because the initial feedstock material is curium oxide. In addition to the target position map at the core midplane, this figure includes a cross section of the MCNP model showing the representation of this map.

Data are reported at EOC and at the end of each day of the irradiation cycle. The ^{252}Cf production target is assumed to have the isotopic composition as specified in the HEU representative model [2].



(a) (b)

Fig. 2.1 Cross section of flux trap target region at the core midplane: target position map (a) and HFIR representative model (b) [2].

2.3 FAST FLUX IN FLUX TRAP AND REFLECTOR

The following parameters are calculated, where fluxes are expressed both in units of n/cm^{2}s (absolute flux value) and n/cm^{2}s MW (flux per unit power), and E_n is the neutron energy:

- fast neutron flux (100 keV < E_n < 20 MeV) and total neutron flux (E_n < 20 MeV), and
- fast-to-total neutron flux ratio.

The fluxes are calculated for the union of the materials irradiation targets located at 26 sites in the flux trap, labeled *Mo*, *V+Ni*, *Nb+Fe*, *PTP 1*, and *PTP 2* in Fig. 2.1. This union covers the following cells in the MCNP model [2]: 411, 421, 431, 441, 471, 481, 491, 541, 551, 591, 611, 661, 671, 681, 691, 711, 721, 731, 741, 811, 812, 813, 814, 815, 816, 821, 822, 823, 824, 825, 826, 831, 832, 833, 834, 835, 836, 843, 844, 845, 846, 853, 854, 855, 856, 863, 864, 865, and 866.

In the reflector, the fluxes are calculated for the union of the beryllium plugs in the 8 large removable beryllium (RB) locations (Fig. 2.2). This union covers the following cells in the MCNP model [2]: 6301, 6302, 6303, 6351, 6352, 6353, 6501, 6502, 6503, 6551, 6552, 6553, 6701, 6702, 6703, 6751, 6752, 6753, 6901, 6902, 6903, 6951, 6952, and 6953.

The calculated parameters are reported at BOC, MOC, and EOC.

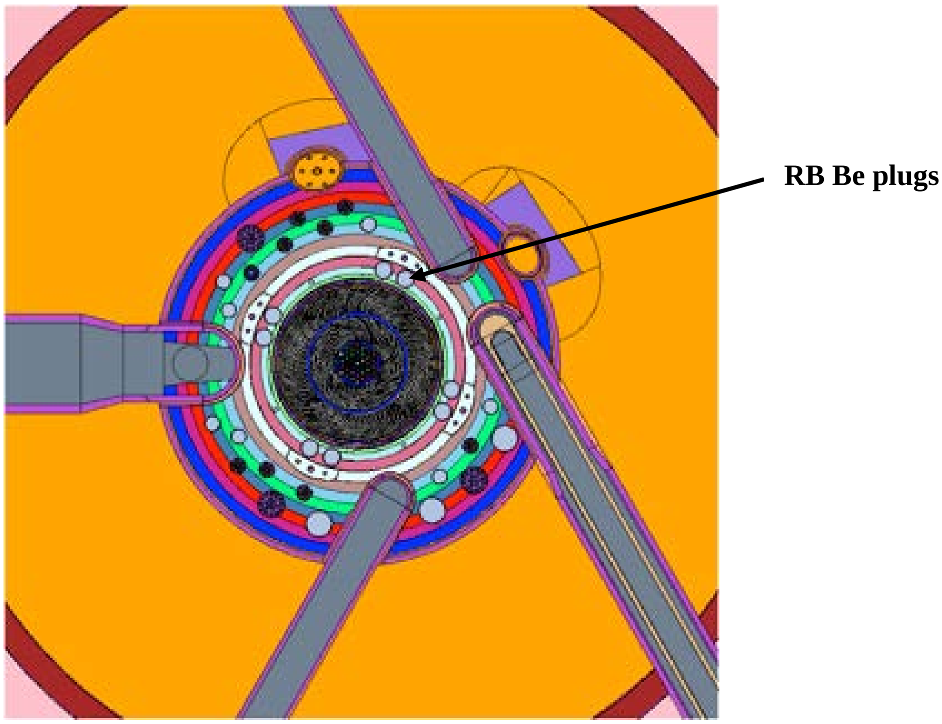


Fig. 2.2 Cross section of the HFIR model at the core midplane.

2.4 CYCLE LENGTH

The cycle length was calculated based on time-dependent depletion simulations that model the time-dependent symmetric movement of control elements to ensure criticality at each state point. It represents the time span between BOC and EOC.

The EOC is determined as the time point at which both of the following criteria are met:

- control elements are fully withdrawn (relative positions of control elements are specified in the MCNP model by translation cards; an absolute value of 68.58 cm in these translation cards indicates fully withdrawn control elements), and

- effective multiplication factor k_{eff} (or eigenvalue) at EOC is within 50 pcm (or 0.0005) of the critical value of 1.0.

Cycle length is expressed in days, with a precision of 0.5 days. This precision is considered adequate for EOC estimations in HFIR depletion simulations [2,3].

3. RESULTS

3.1 FLUX AT THE COLD SOURCE MODERATOR VESSEL

3.1.1 Low-energy flux

The calculated flux in the low energy range (less than 104 meV considered here) is presented in Tables 3.1, 3.2, and 3.3 for the BOC, EOC, and MOC state points. Each of these tables includes the flux and the flux per unit power for the HEU and LEU cores, as well as the LEU to HEU flux ratio, for each of the nine energy bins specified in Table 2.1. The EOC time was 26 days [2] for the HEU core and 34 days [3] for the LEU core, as further discussed in Section 3.4. The MOC state point was set as 14 days for the HEU and 18 days for the LEU core [2,3].

As seen in Tables 3.1–3.2, the flux increases from BOC to EOC for both HEU and LEU cores. For the HEU core, the fluxes at MOC in all considered energy bins are ~13–14% greater than the corresponding fluxes at BOC, whereas the fluxes at EOC are ~20% greater than the fluxes at BOC. For the LEU core, the fluxes at MOC in all considered tally bins are ~16% greater than the corresponding fluxes at BOC, whereas the fluxes at EOC are ~21% greater than the fluxes at BOC.

The flux per unit power in all energy bins and at all state points for LEU is always smaller than for HEU, with LEU/HEU ratios varying between 0.88 and 0.90, depending on the time point. The variation with wavelength of the flux per unit power for the HEU and LEU cores at EOC is illustrated in Fig. 3.1.

The absolute flux values for LEU are ~4-6% greater than for HEU, depending on the energy bin and time point considered. Note that the total system power, which is used for normalizing the flux calculated with MCNP, is 100 MW for LEU and 85 MW for HEU. The power was increased for the LEU core to conserve the overall flux performance in the reactor after conversion from HEU to LEU [1]. The differences between LEU and HEU fluxes at the location discussed here (cold source moderator vessel) are consistent with the observed hardening of the neutron spectrum in the beryllium reflector and beam tube regions when the fuel is changed from HEU to LEU.

Figure 3.2 illustrates the ratio of group fluxes (energy bins as seen in Table 2.1) to the total flux (integrated over the 0–20 MeV energy range) for HEU and LEU cores at EOC. The values of these ratios at BOC, MOC, and EOC are presented in Table 3.4.

Table 3.5 presents the cumulative flux distribution F_k, calculated as:

$$F_k = \sum_{g=1}^{k} \frac{\varphi_g}{\varphi_{total}} \quad (1)$$

where g is neutron group index (1 to 9, ordered from low to high energies), k is distribution bin (1 to 9), and φ stands for neutron flux. This distribution, illustrated in Fig. 3.3 for the EOC state point, provides a measure of the fraction of the total neutron flux that corresponds to a cold neutron wavelength that is greater than a given value. For example, for the LEU core at EOC, 1.3% of the total neutron flux corresponds to neutron energies smaller than 0.8181 meV and wavelengths greater than 10 Å, and 77.3% of the neutron flux corresponds to neutron energies smaller than 104 meV and wavelengths greater than 0.887 Å.

Table 3.1. Low energy flux at the cold source moderator vessel at BOC

Energy[a] (meV)	Wavelength (Angstrom)	HFIR HEU core			HFIR LEU core			LEU/HEU flux ratio		
		Flux n/(cm^{2}s)	**Flux per unit power** n/(cm^{2}s MW)	σ_{rel}[b] (%)	**Flux** n/(cm^{2}s)	**Flux per unit power** n/(cm^{2}s MW)	σ_{rel} (%)	**Flux ratio**	σ[c]	**Flux per unit power ratio**
0.1000	28.600	1.088E+11	1.280E+09	0.26	1.128E+11	1.123E+09	0.27	1.037	0.004	0.882
0.2045	20.000	3.561E+11	4.189E+09	0.22	3.698E+11	3.677E+09	0.24	1.039	0.003	0.883
0.3252	15.860	7.137E+11	8.396E+09	0.21	7.408E+11	7.385E+09	0.22	1.038	0.003	0.882
0.5748	11.930	2.309E+12	2.716E+10	0.20	2.394E+12	2.389E+10	0.21	1.037	0.003	0.881
0.8181	10.000	3.373E+12	3.968E+10	0.20	3.499E+12	3.492E+10	0.21	1.037	0.003	0.882
1.4500	7.511	1.202E+13	1.414E+11	0.21	1.246E+13	1.244E+11	0.21	1.037	0.005	0.881
3.2460	5.020	4.473E+13	5.262E+11	0.19	4.637E+13	4.628E+11	0.20	1.037	0.003	0.881
10.0000	2.860	1.238E+14	1.457E+12	0.19	1.284E+14	1.282E+12	0.20	1.037	0.003	0.881
104.0000	0.887	2.159E+14	2.540E+12	0.17	2.241E+14	2.237E+12	0.18	1.038	0.003	0.882

[a] Upper energy bin.
[b] Relative standard deviation (1σ) for the flux tally (in percent).
[c] Standard deviation (1σ) for the flux ratio.

Table 3.2. Low energy flux at the cold source moderator vessel at EOC

Energy[a] (meV)	Wavelength (Angstrom)	HFIR HEU core			HFIR LEU core			LEU/HEU flux ratio		
		Flux n/(cm^{2}s)	**Flux per unit power** n/(cm^{2}s MW)	σ_{rel}[b] (%)	**Flux** n/(cm^{2}s)	**Flux per unit power** n/(cm^{2}s MW)	σ_{rel} (%)	**Flux ratio**	σ[c]	**Flux per unit power ratio**
0.1000	28.600	1.304E+11	1.534E+09	0.23	1.363E+11	1.363E+09	0.24	1.045	0.003	0.888
0.2045	20.000	4.258E+11	5.009E+09	0.20	4.462E+11	4.462E+09	0.21	1.048	0.003	0.891
0.3252	15.860	8.540E+11	1.005E+10	0.19	8.960E+11	8.960E+09	0.20	1.049	0.003	0.892
0.5748	11.930	2.763E+12	3.251E+10	0.18	2.897E+12	2.897E+10	0.19	1.048	0.003	0.891
0.8181	10.000	4.038E+12	4.750E+10	0.18	4.238E+12	4.238E+10	0.19	1.050	0.003	0.892
1.4500	7.511	1.439E+13	1.693E+11	0.18	1.510E+13	1.510E+11	0.19	1.049	0.003	0.892
3.2460	5.020	5.353E+13	6.297E+11	0.17	5.617E+13	5.617E+11	0.18	1.049	0.003	0.892
10.0000	2.860	1.483E+14	1.745E+12	0.17	1.556E+14	1.556E+12	0.18	1.050	0.003	0.892
104.0000	0.887	2.591E+14	3.048E+12	0.16	2.714E+14	2.714E+12	0.17	1.047	0.002	0.890

[a] Upper energy bin.
[b] Relative standard deviation (1σ) for the flux tally.
[c] Standard deviation (1σ) for the flux ratio.

Table 3.3. Low energy flux at the cold source moderator vessel at MOC

Energy[a] (meV)	Wavelength (Angstrom)	HFIR HEU core			HFIR LEU core			LEU/HEU flux ratio		
		Flux n/(cm^{2}s)	**Flux per unit power** n/(cm^{2}s MW)	σ_{rel}[b] (%)	**Flux** n/(cm^{2}s)	**Flux per unit power** n/(cm^{2}s MW)	σ_{rel} (%)	**Flux ratio**	σ[c]	**Flux per unit power ratio**
0.1000	28.600	1.232E+11	1.449E+09	0.24	1.305E+11	1.305E+09	0.25	1.060	0.004	0.901
0.2045	20.000	4.035E+11	4.747E+09	0.21	4.275E+11	4.275E+09	0.22	1.060	0.003	0.901
0.3252	15.860	8.098E+11	9.527E+09	0.20	8.552E+11	8.552E+09	0.21	1.056	0.003	0.898
0.5748	11.930	2.621E+12	3.084E+10	0.19	2.771E+12	2.771E+10	0.20	1.057	0.003	0.899
0.8181	10.000	3.829E+12	4.505E+10	0.18	4.056E+12	4.056E+10	0.19	1.059	0.003	0.900
1.4500	7.511	1.364E+13	1.604E+11	0.18	1.444E+13	1.444E+11	0.19	1.059	0.003	0.900
3.2460	5.020	5.072E+13	5.968E+11	0.18	5.378E+13	5.378E+11	0.19	1.060	0.003	0.901
10.0000	2.860	1.406E+14	1.654E+12	0.18	1.490E+14	1.490E+12	0.19	1.060	0.003	0.901
104.0000	0.887	2.456E+14	2.889E+12	0.16	2.598E+14	2.598E+12	0.17	1.058	0.002	0.899

[a] Upper energy bin.
[b] Relative standard deviation (1σ) for the flux tally.
[c] Standard deviation (1σ) for the flux ratio.

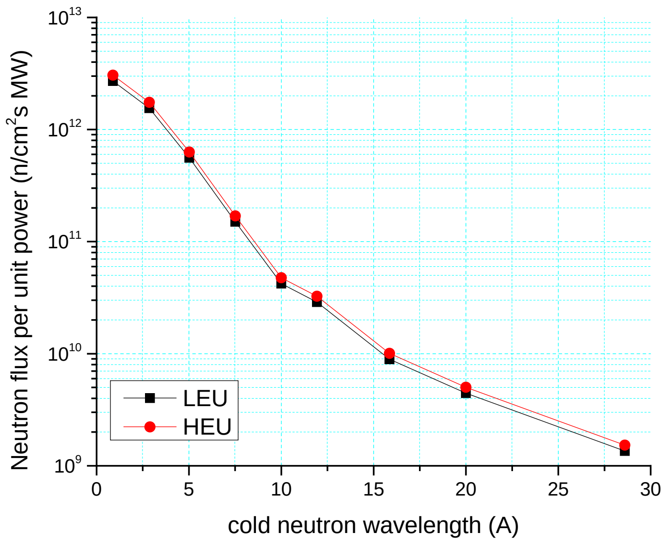


Fig. 3.1 Cold neutron flux per unit power at EOC.

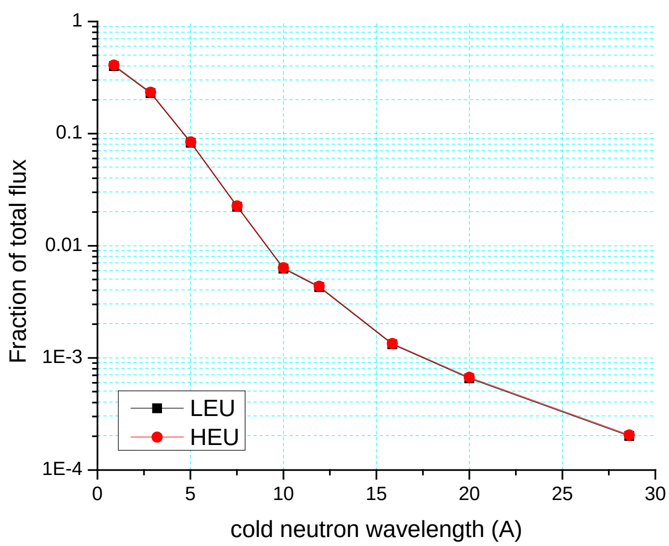


Fig. 3.2 Cold neutron flux to total flux ratio at EOC.

Table 3.4. Low energy flux to total flux ratio at the cold source moderator vessel

Energy[a] (meV)	**Wavelength** (Angstrom)	**LEU group flux/total flux ratio**[b] BOC	MOC	EOC	**HEU group flux/total flux ratio**[b] BOC	MOC	EOC
0.1000	28.600	1.95E-04	1.99E-04	2.01E-04	1.97E-04	2.01E-04	2.05E-04
0.2045	20.000	6.38E-04	6.51E-04	6.58E-04	6.44E-04	6.60E-04	6.71E-04
0.3252	15.860	1.28E-03	1.30E-03	1.32E-03	1.29E-03	1.32E-03	1.35E-03
0.5748	11.930	4.13E-03	4.22E-03	4.27E-03	4.18E-03	4.28E-03	4.35E-03
0.8181	10.000	6.04E-03	6.18E-03	6.25E-03	6.10E-03	6.26E-03	6.36E-03
1.4500	7.511	2.15E-02	2.20E-02	2.23E-02	2.17E-02	2.23E-02	2.27E-02
3.2460	5.020	8.00E-02	8.19E-02	8.28E-02	8.09E-02	8.29E-02	8.43E-02
10.0000	2.860	2.22E-01	2.27E-01	2.30E-01	2.24E-01	2.30E-01	2.34E-01
104.0000	0.887	3.87E-01	3.96E-01	4.00E-01	3.91E-01	4.01E-01	4.08E-01

[a] Upper energy bin.

[b] Calculated as ratio of the flux in each energy bin and total flux in the cold source moderator vessel. The total flux values are listed in Table 3.6 for HEU and LEU at BOC, MOC, and EOC. Relative standard deviation (1σ) for the HEU and LEU flux/total flux ratios are less than 0.3% in all cases.

Table 3.5. Low energy flux distribution at the cold source moderator vessel

Energy[a] (meV)	**Wavelength** (Angstrom)	**HEU flux fraction**[b] BOC	MOC	EOC	**LEU flux fraction**[b] BOC	MOC	EOC
0.1000	28.600	1.95E-04	1.99E-04	2.01E-04	1.97E-04	2.01E-04	2.05E-04
0.2045	20.000	8.33E-04	8.50E-04	8.59E-04	8.41E-04	8.61E-04	8.76E-04
0.3252	15.860	2.11E-03	2.15E-03	2.18E-03	2.13E-03	2.18E-03	2.22E-03
0.5748	11.930	6.24E-03	6.37E-03	6.45E-03	6.31E-03	6.47E-03	6.57E-03
0.8181	10.000	1.23E-02	1.25E-02	1.27E-02	1.24E-02	1.27E-02	1.29E-02
1.4500	7.511	3.38E-02	3.45E-02	3.50E-02	3.42E-02	3.50E-02	3.56E-02
3.2460	5.020	1.14E-01	1.16E-01	1.18E-01	1.15E-01	1.18E-01	1.20E-01
10.0000	2.860	3.35E-01	3.43E-01	3.47E-01	3.39E-01	3.48E-01	3.53E-01
104.0000	0.887	7.22E-01	7.39E-01	7.48E-01	7.30E-01	7.49E-01	7.62E-01

[a] Upper energy bin.

[b] Calculated as shown in Eq. (1).

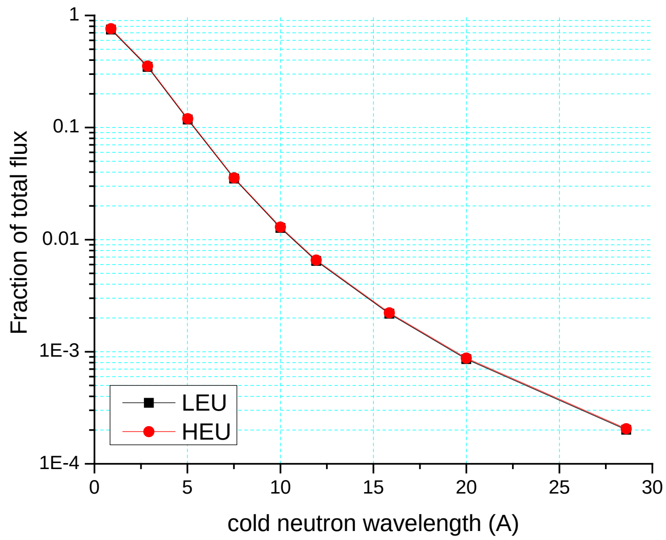


Fig. 3.3 Cold neutron cumulative flux distribution at EOC.

3.1.2 Three-group and total flux

The calculated three-group fluxes and the total flux at the cold source moderator vessel for the LEU and HEU cores at BOC, MOC, and EOC are presented in Table 3.6. These fluxes are included here to provide the total flux that was used to calculate the relative ratios discussed in Section 3.1.1 and to enable a comparison of the fluxes in the low-energy range (see Table 2.1) with fluxes on a coarser energy grid.

Table 3.6. Three-group[a] and total flux data for HEU and LEU cores

	Day	Thermal flux	σ_{rel}[b]	Epithermal flux	σ_{rel}	Fast flux	σ_{rel}	Total flux	σ_{rel}	Thermal/ Total	σ[c]	Fast/ Total	σ
BOC													
LEU	0	4.451E+14	0.0019	9.514E+13	0.0029	3.923E+13	0.0046	5.794E+14	0.0017	0.768	0.002	0.068	<0.001
HEU	0	4.282E+14	0.0018	8.766E+13	0.0029	3.674E+13	0.0045	5.526E+14	0.0016	0.775	0.002	0.066	<0.001
LEU/HEU		**1.039**	0.0026	**1.085**	0.0041	**1.068**	0.0064	**1.048**	0.0023	**0.991**	0.003	**1.018**	0.007
MOC													
LEU	18	5.146E+14	0.0017	1.007E+14	0.0029	4.149E+13	0.0045	6.568E+14	0.0016	0.783	0.002	0.063	<0.001
HEU	14	4.847E+14	0.0016	8.934E+13	0.0028	3.769E+13	0.0044	6.118E+14	0.0015	0.792	0.002	0.062	<0.001
LEU/HEU		**1.062**	0.0023	**1.127**	0.0040	**1.101**	0.0063	**1.074**	0.0022	**0.989**	0.003	**1.025**	0.007
EOC													
LEU	34	5.366E+14	0.0017	1.001E+14	0.0029	4.133E+13	0.0045	6.780E+14	0.0016	0.791	0.002	0.061	<0.001
HEU	26	5.104E+14	0.0016	8.796E+13	0.0028	3.661E+13	0.0045	6.349E+14	0.0015	0.804	0.002	0.058	<0.001
LEU/HEU		**1.051**	0.0023	**1.138**	0.0040	**1.129**	0.0064	**1.068**	0.0022	**0.985**	0.003	**1.057**	0.007

[a] Energy groups are: thermal (En < 0.625 eV), epithermal (0.625 eV < En < 100 keV, and fast (100 keV < En < 20 MeV); En stands for neutron energy.

[b] Relative standard deviation (1σ) for the flux tally was provided by MCNP; relative standard deviation for flux ratio was calculated based on relative standard deviations for flux tallies.

[c] Standard deviation (1σ) calculated for the flux ratio.

3.2 CALIFORNIUM-252 PRODUCTION

The variation with cycle time of the ^{252}Cf mass produced in the five targets located in the flux trap (see Fig. 2.1) is listed in Table 3.7 and illustrated in Fig. 3.4. Figure 3.4 shows the ^{252}Cf mass variation using both linear and log scales to facilitate a direct comparison of the HEU and LEU values at all times within the reactor cycle.

Table 3.7. ^{252}Cf mass vs irradiation time for HEU and LEU cores

HEU core		LEU core	
Time (d)	**^{252}Cf (g)**	**Time (d)**	**^{252}Cf (g)**
0	0	0	0
1	2.136E-06	1	2.712E-06
2	3.222E-05	2	3.899E-05
3	1.404E-04	3	1.676E-04
4	3.759E-04	4	4.429E-04
5	7.708E-04	5	8.976E-04
6	1.344E-03	6	1.553E-03
7	2.100E-03	7	2.415E-03
8	3.046E-03	8	3.470E-03
9	4.156E-03	9	4.716E-03
10	5.438E-03	10	6.138E-03
11	6.864E-03	11	7.713E-03
12	8.410E-03	12	9.431E-03
13	1.008E-02	13	1.127E-02
14	1.183E-02	14	1.322E-02
15	1.367E-02	15	1.525E-02
16	1.558E-02	16	1.734E-02
17	1.754E-02	17	1.949E-02
18	1.955E-02	18	2.169E-02
19	2.158E-02	19	2.392E-02
20	2.363E-02	20	2.618E-02
21	2.571E-02	21	2.846E-02
22	2.780E-02	22	3.074E-02
23	2.988E-02	23	3.302E-02
24	3.196E-02	24	3.531E-02
25	3.403E-02	25	3.757E-02
26	**3.608E-02**	26	3.983E-02
		27	4.208E-02
		28	4.433E-02
		29	4.657E-02
		30	4.877E-02
		31	5.098E-02
		32	5.316E-02
		33	5.533E-02
		34	**5.748E-02**

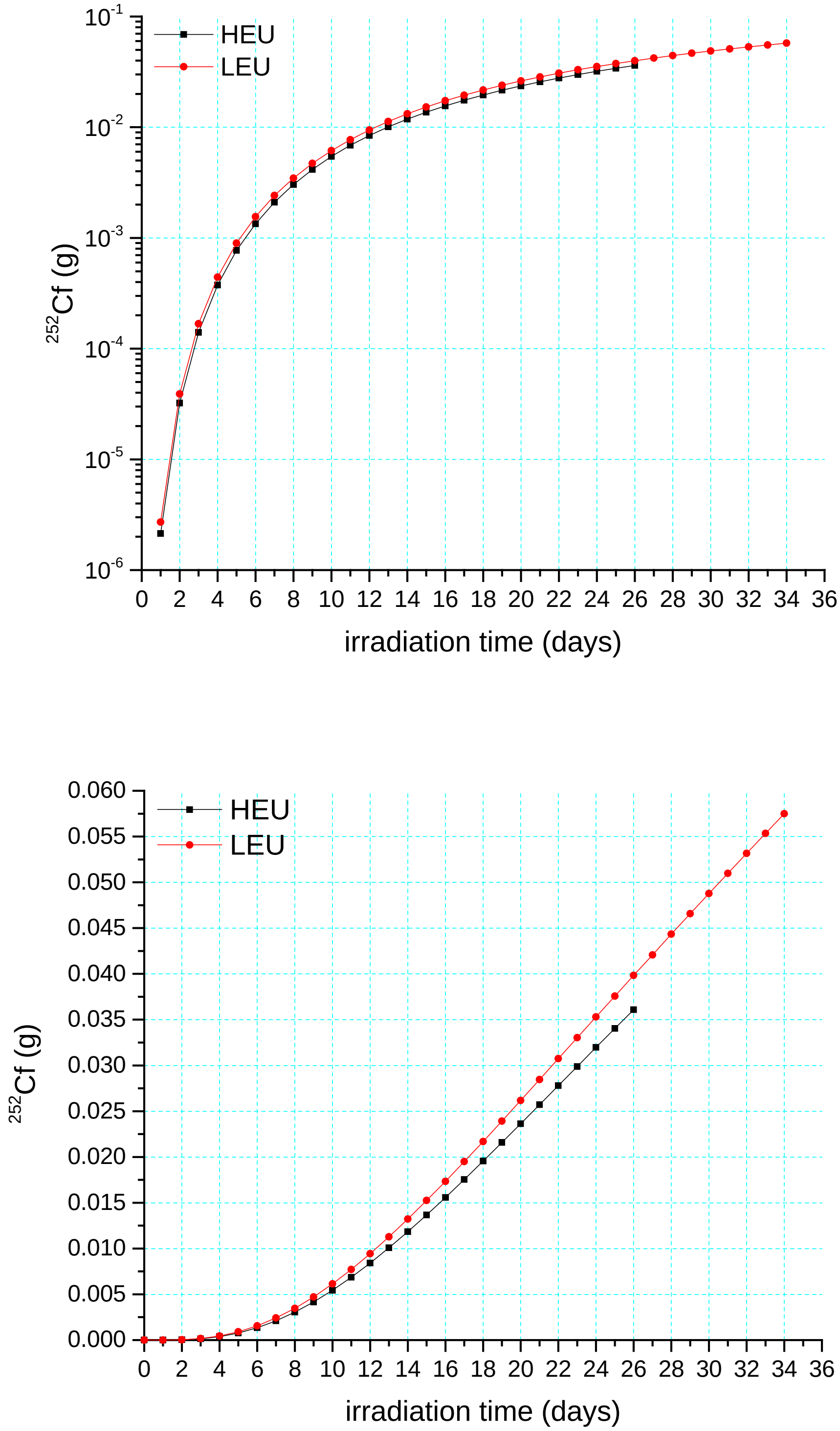


Fig. 3.4 ^{252}Cf mass vs irradiation time for HEU and LEU cores (log and linear scales).

The mass of ^{252}Cf at EOC is 36.08 mg for the HEU core at 85 MW and 57.48 mg for the LEU core at 100 MW. Therefore, there is ~60% more ^{252}Cf produced in the LEU core than in the HEU core for one reactor cycle. However, the total irradiation time is much longer in the LEU case (34 days) than in the HEU case (26 days). Based on the mass variation with irradiation time, the same mass of ^{252}Cf that is produced in the 26-day HEU cycle at 85 MW power could be obtained at an irradiation time of ~25 days with the LEU core at 100 MW power.

The comparison presented in this report is intended for relative comparisons between the LEU and the HEU cores only. Accuracy of the HFIR HEU model in predicting the ^{252}Cf production will be established in an upcoming validation study that will use actual HFIR ^{252}Cf production data.

3.3 FAST FLUX IN FLUX TRAP AND REFLECTOR

The fast flux metrics for the considered irradiation locations (see Section 2.3) and the three considered state points (BOC, MOC, and EOC) are presented in Table 3.8 for the flux trap locations and in Table 3.9 for the reflector locations.

The fast neutron flux (n/cm^{2}s) for the LEU core at 100 MW is greater than that of the HEU core at 85 MW in both flux trap and reflector locations and at all considered state points. The magnitude of the difference between LEU and HEU cores varies within the reactor cycle in the range of ~14–18% for the flux trap and ~7–12% for the reflector.

The fast neutron flux per unit power (n/cm^{2}s MW) for the LEU core in the flux trap at BOC is practically the same (values within ~0.4%) as for the HEU core, but it is slightly smaller at MOC (by ~3%) and EOC (by ~1%). For the reflector locations, the fast flux per unit power for the LEU core is smaller than for the HEU core at all times during the cycle; the difference is ~9% at BOC and ~4% at EOC.

The fast-to-total flux ratio for the LEU core is greater than for the HEU core at both flux trap and reflector locations and at all considered state points. The fast-to-total flux ratios calculated for the LEU core are greater than those for the HEU core by ~8–12% for the flux trap and ~4–10% for the reflector locations, depending on the time point.

Table 3.10 presents cycle-average flux data, with the average calculated based on the flux values at BOC, MOC, and EOC. Though a rigorous cycle-average calculation should include all state points between BOC and EOC (27 for HEU and 35 for LEU), the approximate averages shown here provide a reasonable measure of the relative difference between HEU and LEU cycles.

The data in Table 3.10 show that on average, the LEU fast flux (n/cm^{2}s) at 100 MW is greater than the HEU fast flux at 85 MW by ~15% in the flux trap and ~10% in the reflector. The LEU fast flux per unit power (n/cm^{2}s MW) is smaller than the HEU fast flux per unit power by ~2% in the flux trap and ~6% in the reflector, on average. The fast-to-total LEU flux ratio is greater than the corresponding HEU value by ~10% on average in the flux trap and ~6% in the reflector.

Table 3.8. Fast neutron flux metrics for flux trap locations[a]

	day	Fast neutron flux n/(cm^{2}s)	Fast neutron flux n/(cm^{2}s MW)	Total neutron flux n/(cm^{2}s)	Total neutron flux n/(cm^{2}s MW)	Fast/total flux ratio
BOC						
HEU	0	1.142E+15	1.343E+13	3.771E+15	4.436E+13	0.303
LEU	0	1.348E+15	1.348E+13	4.127E+15	4.127E+13	0.327
LEU/HEU		**1.181**	**1.004**	**1.094**	**0.930**	**1.079**
MOC						
HEU	14	1.095E+15	1.288E+13	3.770E+15	4.435E+13	0.290
LEU	18	1.245E+15	1.245E+13	3.922E+15	3.922E+13	0.317
LEU/HEU		**1.137**	**0.966**	**1.041**	**0.884**	**1.091**
EOC						
HEU	26	9.857E+14	1.160E+13	3.544E+15	4.170E+13	0.278
LEU	34	1.146E+15	1.146E+13	3.676E+15	3.676E+13	0.312
LEU/HEU		**1.162**	**0.988**	**1.037**	**0.882**	**1.121**

[a] The relative statistical uncertainties (1 standard deviation) in the flux values and ratio values are smaller than 0.1%.

Table 3.9. Fast neutron flux metrics for reflector locations[a]

	day	Fast neutron flux n/(cm^{2}s)	Fast neutron flux n/(cm^{2}s MW)	Total neutron flux n/(cm^{2}s)	Total neutron flux n/(cm^{2}s MW)	Fast/total flux ratio
BOC						
HEU	0	2.799E+14	3.293E+12	1.296E+15	1.525E+13	0.216
LEU	0	2.984E+14	2.984E+12	1.327E+15	1.327E+13	0.225
LEU/HEU		**1.066**	**0.906**	**1.023**	**0.870**	**1.042**
MOC						
HEU	14	2.886E+14	3.395E+12	1.529E+15	1.798E+13	0.189
LEU	18	3.209E+14	3.209E+12	1.610E+15	1.610E+13	0.199
LEU/HEU		**1.112**	**0.945**	**1.053**	**0.895**	**1.056**
EOC						
HEU	26	2.975E+14	3.500E+12	1.753E+15	2.062E+13	0.170
LEU	34	3.343E+14	3.343E+12	1.788E+15	1.788E+13	0.187
LEU/HEU		**1.124**	**0.955**	**1.020**	**0.867**	**1.101**

[a] The relative statistical uncertainties (1 standard deviation) in the flux values and ratio values are smaller than 0.1%.

Table 3.10. Cycle-average fast neutron flux metrics for flux trap and reflector locations

	Fast neutron flux		Total neutron flux		Fast/total flux ratio
	n/(cm^{2}s)	n/(cm^{2}s MW)	n/(cm^{2}s)	n/(cm^{2}s MW)	
Flux trap					
HEU	1.082E+15	1.273E+13	3.718E+15	4.374E+13	0.291
LEU	1.249E+15	1.249E+13	3.919E+15	3.919E+13	0.319
LEU/HEU	**1.154**	**0.981**	**1.054**	**0.896**	**1.095**
Reflector					
HEU	2.883E+14	3.392E+12	1.518E+15	1.786E+13	0.190
LEU	3.181E+14	3.181E+12	1.577E+15	1.577E+13	0.202
LEU/HEU	**1.103**	**0.938**	**1.039**	**0.883**	**1.062**

3.4 CYCLE LENGTH

The cycle length was estimated to be 26 days for the HEU representative model [2] and 34 days for the LEU representative model with interim design fuel [3]. The eigenvalue at EOC is 0.99976 (1σ = 0.00013) for the HEU core [2] and 0.99950 (1σ = 0.00015) for the LEU core [3]. The symmetrical control element withdrawal curves in the HEU and LEU models are illustrated in Fig. 3.5. The 68.58 cm position corresponds to fully withdrawn control elements.

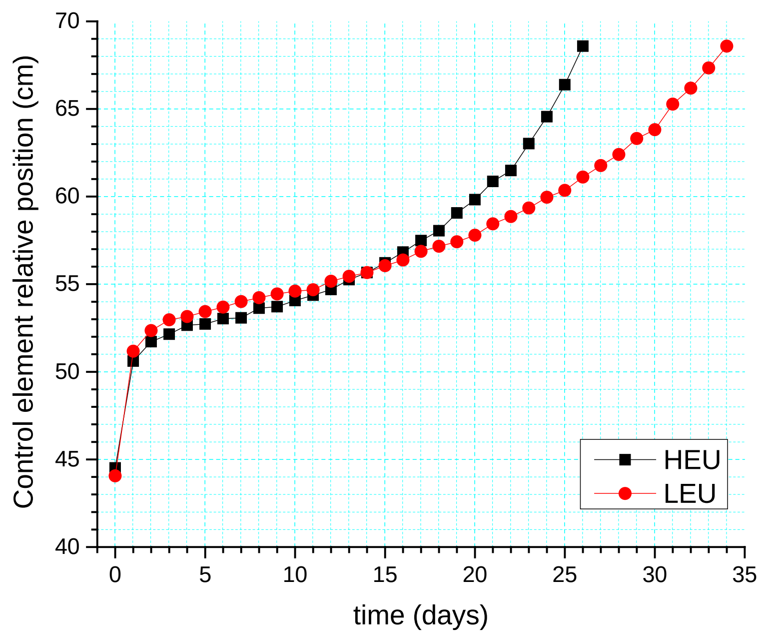


Fig. 3.5 Control element withdrawal curves for the HEU and LEU cores.

4. CONCLUSIONS

This report documents selected key performance metrics for the HFIR HEU core at 85 MW operating power and an LEU core with an interim design fuel that would operate at 100 MW power. The purpose is to estimate the relative impact due to change of fuel from HEU to LEU on metrics relevant to the neutron scattering, isotope production, and material irradiation missions of HFIR. The HEU and LEU models used for this assessment are consistent. Both models include an explicit representation of the HFIR's fuel plate involute geometry and an experiment loading that is representative of HFIR's current operation, with the fuel region being the only difference between the models.

The considered key metrics include

- neutron flux at the cold source moderator vessel,
- ^{252}Cf production in the flux trap target region,
- fast neutron flux at locations of interest for material irradiation experiments, and
- reactor cycle length.

These metrics are relatively easy to calculate and can serve for preliminary assessment of the impact on reactor performance of various LEU fuel designs. When changing the fuel from HEU to LEU, the reactor cycle length increases by ~31%, from 26 days to 34 days, for the considered LEU fuel design and fuel load. Assuming that the same number of six cycles per year is used for the HEU and LEU cores, it would result in ~31% additional time available per year for experiments with the LEU core. Even with only six cycles of LEU operation versus seven cycles of HEU operation, the operating time would increase by 12%.

The neutron fluxes in the cold source moderator vessel were calculated in nine low-energy groups from 0 to 104 meV to cover the neutron wavelength range of interest to cold neutron scattering experiments. For each of these energy groups, the LEU fluxes (n/cm^{2}s) are ~3–6% greater than the HEU fluxes depending on the considered energy bin and time point during the reactor cycle. However, the flux per unit power (n/cm^{2}s MW) in all nine energy bins and at all time points is smaller for LEU than for HEU, with LEU/HEU flux ratios varying between 0.88 and 0.90, depending on the time point and energy bin. Given that the LEU cycle is much longer than the HEU cycle, the fluence is greater for the LEU than for the HEU core, for the LEU fuel design and fuel load considered here.

The calculated ratios of the low-energy fluxes in each of the considered nine energy bins to the total flux (0–20 MeV) in the cold moderator vessel provide a measure of the fraction of total flux that corresponds to a given cold neutron wavelength range. For the LEU and HEU cores at EOC, neutrons with wavelengths less than 10 Å are ~1.3% of the total neutron flux, while neutrons with wavelengths greater than 0.887 Å make up 77.3% and 78.7%, respectively, of all neutrons at this core location.

The mass of ^{252}Cf calculated in one HEU cycle is 36.08 mg, while 57.48 mg were calculated in one cycle for the considered LEU core. Therefore, the LEU 34-day cycle produces ~60% more ^{252}Cf than the HEU 26-day cycle. The ^{252}Cf mass variation with irradiation time for the HEU and LEU cores indicates that the mass of ^{252}Cf that is produced in the 26-day HEU cycle would correspond to a total irradiation time of ~25 days with the LEU core. This comparison applies only to the LEU power level and fuel configuration as considered here and would differ for other LEU configurations (as function of power, fuel load, fuel design, etc.).

The fast neutron flux (n/cm^{2}s) for the LEU core is greater than that of the HEU core in both flux trap and reflector material irradiation locations and at all considered time points, by ~14–18% for the flux trap and

~7–12% for the reflector, depending on the time within the reactor cycle. However, the fast neutron flux per unit power (n/cm^{2}s MW) is smaller for the LEU core than for the HEU core. The magnitude of this effect is lower for the flux trap (< 3%) than for the reflector region (between 4–9% depending on the time within the reactor cycle). However, the fast neutron fluence for the LEU core is higher than for the HEU core given the much longer LEU cycle length for the LEU fuel and load considered here.

Comparison of the key metrics in this report shows that the change of fuel from HEU to LEU would not adversely affect the reactor performance that is reflected by these metrics. However, the conclusions of this assessment are valid only for the LEU fuel design, initial load, and core power considered here. They will not be directly applicable for other, different LEU core configurations, for which a new assessment of the key metrics will be required.

5. REFERENCES

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