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Transition Core Calculations for LEU Conversion of NBSR

D. J. Diamond, A. Varuttamensi, and L.-Y. Cheng
Nuclear Science and Technology Department
Brookhaven National Laboratory
33 No. Renaissance Rd.
Upton, NY 11973 USA

ABSTRACT

The National Institute of Standards and Technology operates a 20 MW reactor for neutron-based research. The heavy-water moderated and cooled reactor is fueled with high-enriched uranium (HEU) but a program to convert the reactor to low-enriched uranium (LEU) fuel is underway. It is not possible to simply replace a core containing HEU fuel in an equilibrium burnup state with a core consisting of fresh LEU fuel elements. This would lead to violations of Technical Specifications on excess reactivity and shutdown margin. The alternative approaches being considered maintain the current fuel management scheme whereby four fresh elements are placed in the core every 38.5-day fuel cycle. Variants being considered are to insert either four fresh LEU elements or to insert only two LEU elements along with two HEU elements. The latter scheme takes into account that there may be an inventory of HEU elements that would be worth utilizing. These approaches have been analyzed to show that the transition cycles maintain a large safety margin. However, there are two operational issues that arise. One is a reduction in excess reactivity during the transition that would need to be compensated for; perhaps by shortening one of the transition cycles. Another problem is the reduction in neutron flux available to the experimental program. This paper discusses potential transition schemes and the analysis showing the effect on operations and safety.

1 Introduction

The NIST (National Institute of Standards and Technology) research reactor (aka NBSR) is a heavy water moderated and cooled reactor operating at 20 MW. It provides users with thermal and cold neutron beams to carry out diverse world-class research. It is fueled with high-enriched uranium (HEU) fuel elements but a program is underway to convert the reactor to low-enriched uranium (LEU) fuel [1]. To accomplish this, the fuel meat within each fuel plate will change from U_3O_8 (with fully enriched uranium) in an aluminum powder dispersion to U10Mo metal foil (with

19.75% enriched uranium). The Al cladding material and fuel plate external geometry will remain the same.

It is not possible to simply replace a core containing HEU fuel in an equilibrium burnup state with a core consisting of fresh LEU fuel elements (FEs). This would lead to a core having an excess reactivity and a shutdown margin that violate the reactor's Technical Specifications [2]. Hence, it is necessary to have a transition plan that only reloads a fraction of the core with fresh LEU fuel elements at any given time, or uses a core filled with LEU elements with different enrichments to simulate an equilibrium core. The latter option complicates the fuel fabrication process and since the former approach leads to other benefits, to be discussed below, this is the approach to be taken.

In the following sections a proposed reload plan is discussed. The transition loading patterns must satisfy operational constraints and safety requirements. Hence, analysis done to demonstrate a satisfactory transition is also reported.

2 Transition Core Options

A reload plan must satisfy safety criteria and should minimize operational problems. Since the equilibrium LEU core has been designed with a particular fuel management scheme and with an optimum cycle length, these characteristics should be part of the transition cycles. The fuel management scheme removes four fuel elements every 38.5-day cycle; the remaining fuel is reshuffled, and four fresh elements are added. There are a total of 30 FEs, so two of the fresh elements stay in the core for eight cycles and two for seven cycles. The placement of fuel elements in the core is shown on the grid in Figure 1. The fuel elements are placed symmetrically in the east (E) and west (W) sides of the core and each is designated N-C where N is either "7" or "8", depending on whether it will be in for seven or eight cycles, and C is the cycle it is experiencing. Hence, in grid location D1 the fuel element (8-1W) that will experience eight cycles is in its first cycle on the west side of the core. Also represented on the grid in Figure 1 are the locations of the major cold source (CS), the regulating rod (RR) and irradiation thimbles (<>).

If the four fresh elements are LEU, this would eliminate all HEU fuel and lead to a 100% LEU core in eight cycles. However, that approach ignores the inventory of HEU fuel elements that is likely to be present at the time LEU fuel elements are available for loading. In order to take advantage of that inventory, a slower loading whereby less than four LEU fuel elements are loaded each cycle, is considered more optimum. For example, two fresh LEU and two fresh HEU fuel elements could be loaded each cycle for a period of time until all existing HEU fuel elements are used, after which, only LEU fuel elements would be loaded each cycle.

Another approach that might be considered takes into account that although the LEU fuel qualification will have been endorsed by the U.S. Nuclear Regulatory Commission, it is prudent to do the transition slowly in order to be sure that the production fuel elements provide the expected performance. Prototypic fuel will have been irradiated as part of the fuel qualification program, but none of those tests are expected to use a production NBSR fuel element. Hence, consider the following two-phase transition. The Phase-1 transition [3] is to initially load two LEU fuel elements (to be used for eight cycles) and two HEU fuel elements (to be used for seven cycles). The following seven cycles would each load four HEU fuel elements and then after the two LEU fuel elements are removed after the eighth cycle, two fresh LEU elements would be added in the next cycle along with two HEU elements. This process would proceed until sufficient HEU fuel elements have been utilized and at that point (Phase 2) only four LEU elements would be loaded every cycle.

	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**
					CS								
1				**8-1W**		**7-2W**		**7-2E**		**8-1E**			
2			**8-3W**		**7-5W**		<>		**7-5E**		**8-3E**		
3		**7-3W**		<>		**8-7W**		**8-7E**		<>		**7-3E**	
4	**7-1W**		**8-6W**		**7-7W**		<>		**7-7E**		**8-6E**		**7-1E**
5		**8-4W**		<>		**8-8W**		**8-8E**		<>		**8-4E**	
6			**7-4W**		**7-6W**		RR		**7-6E**		**7-4E**		
7				**8-2W**		**8-5W**		**8-5E**		**8-2E**			

Figure 1. NBSR Core Layout

The Phase-1 and Phase-2 transitions are shown in Figure 2. There are two criteria that will be used to decide whether to continue Phase-1 or move to Phase-2 (“Phase-1 transition to continue?” on Figure 2). The first criterion is the number of HEU fuel elements remaining. For example if there is a two-year supply of HEU FEs available when the conversion first takes place, then there will be approximately 60 available and if 30 are utilized every eight cycles (along with the two LEU elements), then Phase-1 can continue for 16 fuel cycles. This is consistent with the fact that leaving viable HEU elements unused is counter to the principle that conversion should not pose an unreasonable cost burden on the facility.

The second criterion relates to the other motivation for using the Phase-1 approach—it conservatively prepares for uncertainties in supply and performance of the new fuel. In the unlikely event that there is a problem during Phase-1, which necessitates the removal of the LEU fuel, it would not be too difficult to get the reactor operational again with only HEU fuel. The second criterion for moving to Phase-2 is the absence of any data or information that indicates LEU fuel is not performing as expected.

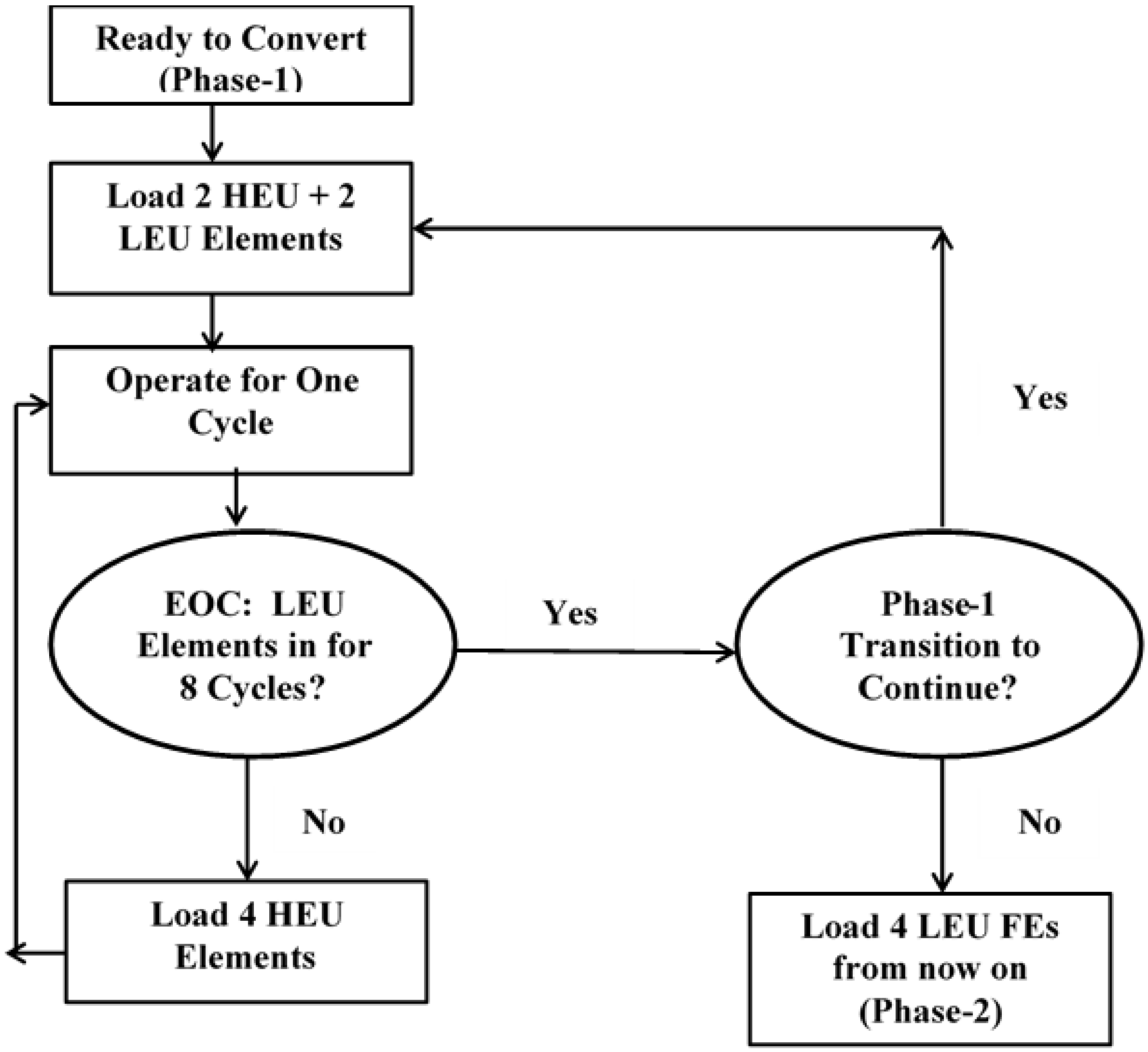

Figure 2. Flow Diagram for Transition from HEU to LEU Fuel

3 Transition Core Properties

An analysis of two Phase-1 cycles (a total of 16 fuel cycles) was carried out and documented [3]. It shows that there are no major neutronic or power distribution issues. However, there will be a decrease in the excess reactivity after loading the LEU fuel elements so that the first cycle will not be able to operate for 38.5 days; it is expected to operate for only 37.4 days. All subsequent cycles are expected to be able to last no less than 38 days and most at least 38.5 days. The calculations of the excess reactivity and shutdown margin show compliance with Technical Specification 3.1.2, Reactivity Limitations [2]. There will be a small decrease in the neutron beam performance, the magnitude of which will change as the LEU elements are moved through the core. Calculations of shim arm critical position at startup; neutron lifetime and delayed neutron fraction; and moderator temperature coefficient of reactivity; showed that these parameters will not change significantly when the LEU is added to the core during the Phase-1 program [2].

The power distribution will change as the LEU elements move through the core. The calculations of the 16 Phase-1 transition cores [3] show that the highest half-element relative power increases to 1.39 at startup conditions, a small difference from the equilibrium LEU core where the highest half-element relative power is 1.35 [1].

A similar analysis was carried out for the Phase-2 transition with the insertion of four LEU fuel elements every cycle until cycle eight (and beyond) when the core is completely loaded with LEU [4]. However, as with Phase-1, there is insufficient excess reactivity during the transition to assure 38.5-day cycles. A solution is to have the first transition cycle with a reduced length (22 days will work) leaving enough excess reactivity so that the remaining cycles can be the standard 38.5-day length. This approach would result in a transition that would not be in violation of Technical Specifications on excess reactivity and shutdown margin.

The analysis carried out for this approach [4] shows that neutronic properties are either not changed significantly or are still considered to be within the required safety envelope. This includes shim arm worth, prompt neutron lifetime, delayed neutron parameters, and moderator temperature and void reactivity coefficients.

The power distribution will change through the Phase-2 transition. Although the fuel loading with HEU fuel is optimized to provide neutrons to peripheral beams, the same approach in the LEU core is compromised by the increase in ^{238}U, which increases parasitic absorption of higher energy neutrons and causes the flux to peak towards the center of the core. The power distribution is calculated for 14 axial and 3 transverse meshes in every fuel plate in every fuel element (42840 mesh boxes). Tables I and II [4] give the hottest spots, stripes (axial integrated power) and half-element powers at startup (SU) and end-of-cycle (EOC) during the eight transition cycles (TCs) and for the equilibrium HEU and LEU cores. The tables also show the particular FE and whether the peak value is in the upper (U) half of the fuel element or the lower (L) half. The hot spots are conservative estimates because they all occur in partially burned elements in which these spots experienced more depletion of ^{235}U than the average fuel material in that half element [5]. The results show an increase in power peaking relative to the Phase-1 results; the maximum half-element relative power is now 1.44 or 7% (1.44/1.35) higher than the LEU equilibrium core value.

In order to see what change in power peaking might lead to an unacceptable decrease in thermal margin, a series of RELAP5 [6] calculations was completed for the startup accident, the most limiting transient wherein reactivity corresponding to the shim arms is inserted at the maximum rate possible. The RELAP5 analysis utilized the model developed for the equilibrium LEU core [1] but with arbitrary scaling of the power in the limiting coolant channels with either the hottest stripe or the hottest spot. The results for the minimum critical heat flux ratio (MCHFR) are in Table III; results for the minimum onset-of-flow-instability ratio show even larger margins.

The MCHFR results show that even with the extreme assumption of a 25% increase in power peaking, the MCHFR does not fall below 1.58. This corresponds to a probability of not reaching critical heat flux of 99%. The statistical hot channel analysis [7], as summarized in Figure 3, shows the probability of not exceeding CHF for a particular MCHFR. When the MCHFR is above 1.4 there is still a 95% probability that CHF will not be reached.

Table I Hottest Spots, Stripes and Half-Element Powers at SU (Phase 2)

	Hottest Spot			Hottest Stripe			Hottest Half FE		
	Rel. Value	FE	Fuel	Rel. Value	FE	Fuel	Rel. Value	FE	Fuel
HEU	2.48	7-2E/L	HEU	1.81	8-3E/L	HEU	1.28	7-5E/L	HEU
TC1	2.42	7-2E/L	HEU	1.78	7-1W/L	LEU	1.26	8-7W/L	HEU
TC2	2.53	7-2E/L	LEU	1.78	8-3E/L	HEU	1.34	8-7E/L	HEU
TC3	2.55	7-3E/L	LEU	1.90	7-3W/L	LEU	1.32	8-7W/L	HEU
TC4	2.59	8-4W/L	LEU	1.92	8-4W/L	LEU	1.32	8-7W/L	HEU
TC5	2.70	7-5W/L	LEU	2.02	7-5W/L	LEU	1.37	7-5W/L	LEU
TC6	2.60	7-5W/L	LEU	1.96	7-5W/L	LEU	1.33	8-6W/L	LEU
TC7	2.63	7-5W/L	LEU	1.92	7-7W/L	HEU	1.44	7-7W/L	LEU
TC8	2.53	7-5W/L	LEU	1.91	7-5W/L	LEU	1.40	8-7W/L	LEU
LEU	2.43	8-3E/L	LEU	1.78	8-3E/L	LEU	1.35	8-7W/L	LEU

Table II Hottest Spots, Stripes and Half-Element Powers at EOC (Phase 2)

	Hottest Spot			Hottest Stripe			Hottest Half FE		
	Rel. Value	FE	Fuel	Rel. Value	FE	Fuel	Rel. Value	FE	Fuel
HEU	2.19	7-1W/U	HEU	1.66	7-2E/U	HEU	1.18	7-2E/U	HEU
TC1	2.26	7-1E/U	LEU	1.64	7-2E/U	HEU	1.14	7-2E/U	HEU
TC2	2.27	7-1E/U	LEU	1.73	7-2E/U	LEU	1.15	7-2E/U	LEU
TC3	2.43	7-3W/L	LEU	1.73	7-3W/L	LEU	1.14	7-3E/U	LEU
TC4	2.42	7-3W/L	LEU	1.67	7-3W/L	LEU	1.12	7-5E/U	HEU
TC5	2.38	7-3W/L	LEU	1.66	7-3W/L	LEU	1.16	7-5E/U	LEU
TC6	2.29	7-3W/L	LEU	1.64	7-3W/L	LEU	1.12	7-5W/U	LEU
TC7	2.28	7-3W/L	LEU	1.63	7-3W/L	LEU	1.16	7-7W/L	LEU
TC8	2.25	8-3W/L	LEU	1.61	7-3W/L	LEU	1.12	8-7W/L	LEU
LEU	2.21	7-3E/U	LEU	1.65	7-2E/U	LEU	1.15	8-7E/U	LEU

Table III MCHFR with Arbitrary Scaling Factors

Scaling Factor	MCHFR with Hot Spot Scaled	MCHFR with Hot Stripe Scaled
1.00	2.07	2.07
1.05	1.96	1.95
1.10	1.86	1.84
1.15	1.77	1.74
1.20	1.69	1.66
1.25	1.62	1.58

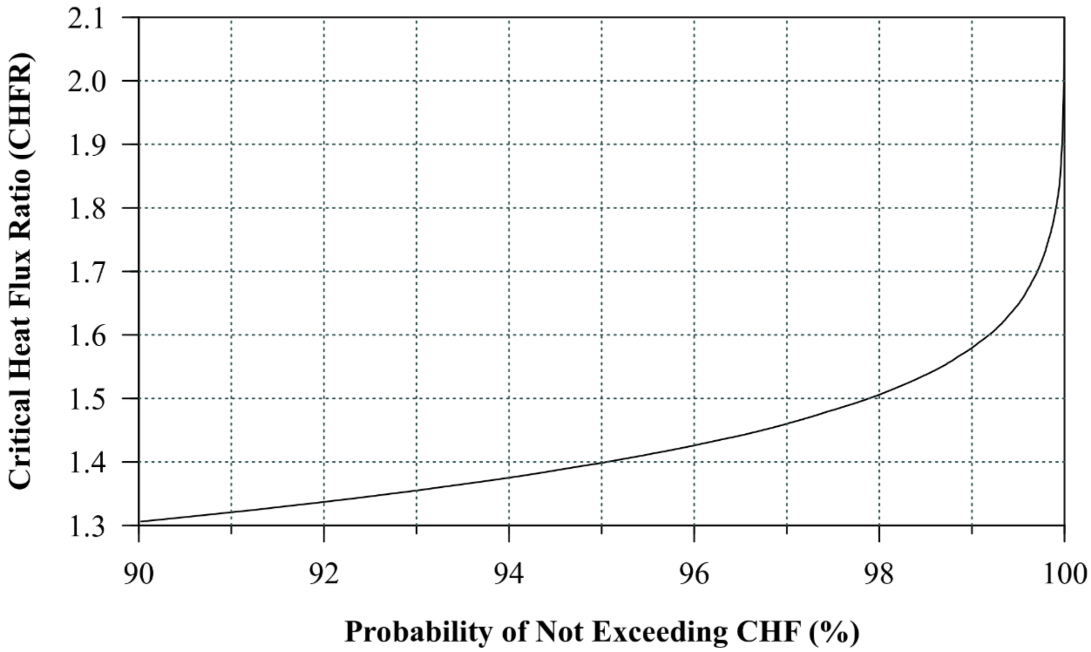

Figure 3. Cumulative Distribution Function for Critical Heat Flux Ratio

4 Summary

Different transition cycles are being considered for conversion of the NBSR from HEU to LEU fuel. The analyses done for two different fuel management schemes show that the assumed transition cores will be able to be operated normally with the exception of having a shorter first cycle to make up for a lack of excess reactivity. They will also be able to operate safely as evidenced by considering changes to parameters like shutdown margin and thermal margin.

5 References

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