OVERVIEW OF HIGH FLUX ISOTOPE REACTOR DESIGN BASES RELEVENT TO POSSIBLE CONVERSION TO LOW-ENRICHED URANIUM

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ABSTRACT

In order to consider the conversion of the High Flux Isotope Reactor (HFIR) from highly enriched uranium (HEU) to low enriched uranium (LEU), a review of the design bases and key operating criteria is being performed in order to develop the scope of the engineering analyses for a fuel conversion study. The aspects of the review are discussed and include: current fuel operating parameters, enrichment-related Safety Analysis Report sections and Technical Safety Requirements, and the record of past fuel performance and current fabrication criteria that would be expected to be matched or applied or would impact the manufacture of LEU fuel. Finally, out-of-reactor issues related to a potential LEU fuel cycle will be discussed. Criteria to bound the engineering analyses are being developed and are presented. A set of reactor performance measures is being developed to quantify the impact on performance for an LEU core design, and this set is presented. The HFIR design, criteria, and performance metrics will form the bases for design analyses of the HFIR core conversion planned to be performed in 2006.

1. Introduction

The U.S. nonproliferation policy "to minimize, and to the extent possible, eliminate the use of highly enriched uranium (HEU) in civil nuclear programs throughout the world" (from http://www.nnsa.doe.gov/na-20/rertr.shtml) has resulted in the conversion (or scheduled conversion) of many of the U.S. research reactors from HEU to low enriched uranium (LEU). However, the potential conversion of the High Flux Isotope Reactor (HFIR) from HEU to LEU presents a considerable challenge because of its high power density and high fuel burn-up. In addition, as an existing reactor, the construction/configuration of the reactor vessel, reflector, target bundle and cooling system along with the requirement for production of extremely high thermal flux combines to place restrictions on the design changes that would be available for consideration in any proposed conversion. A review of the design bases and key operating criteria is being performed in order to develop the scope of the engineering analyses that must be performed for a conversion study. A set of reactor performance measures is being developed to quantify the impact on performance if conversion to LEU were attempted. This paper presents a overview of the topics for which quantitative assumptions are being developed.

2. Reactor description

Ref. 1 provides the following quoted summary description of the HFIR:

> The HFIR is a pressurized light-water-cooled and -moderated, flux-trap type reactor that uses highly enriched ^{235}U as the fuel. The reactor core (shown in Fig. 1)

consists of a series of concentric annular regions, each approximately 61 cm high (fueled height is 51 cm). The center of the core is a 12.70-cm-diam cylindrical hole, referred to as the “flux trap,” which contains 37 vertical experimental target sites.

Fig. 1. Inner and outer HFIR elements

Surrounding the flux trap are two concentric fuel elements separated by a water region. The inner element contains 171 involute-shape fuel plates, and the outer element contains 369 involute-shape fuel plates. The fuel is aluminum-clad, highly enriched uranium oxide distributed along the arc of the involute aluminum plate (U_3O_8-Al cermet).

The inner fuel element contains boron (^{10}B) as a burnable poison, primarily to help shift the power distribution from the inner element to the outer element. The core loading is 9.4 kg of ^{235}U and 2.8 g of ^{10}B. The average core life cycle is (19-26) d at 85 MW (depending on quantity and type of material being irradiated).

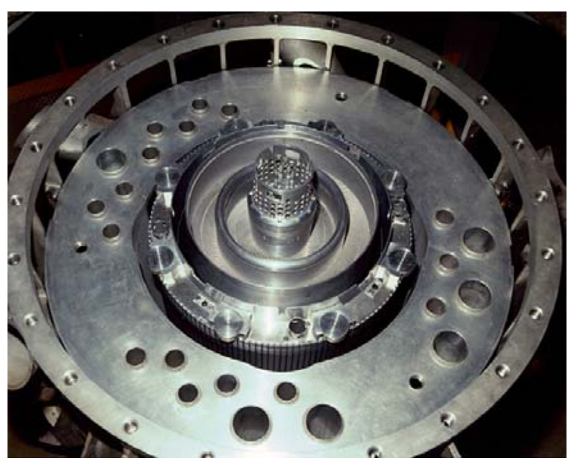

Fig. 2. The HFIR core with the beryllium reflector.

The control plates, in the form of two thin, poison-bearing concentric cylinders, are located in an annular region between the outer fuel element and the beryllium reflector. These plates are driven in opposite directions. Reactivity is increased by downward motion of the inner cylinder, which is used only for shimming and regulation; that is, it has no fast safety function. The outer control cylinder consists of four separate quadrants, each having an independent drive and safety release mechanism. Reactivity is increased as the outer plates are raised. All control plates have three axial regions of different poison content designed to minimize the axial peak-to-average power-density ratio throughout the core lifetime. Any single rod or cylinder is capable of "shutting the reactor down".

The fuel region is surrounded by a concentric ring of beryllium that serves as a reflector and is approximately 30 cm thick. This, in turn, is subdivided into three regions: the removable reflector, the semi-permanent reflector, and the permanent reflector, as shown in Fig. 2. The beryllium is surrounded by a water reflector of effectively infinite thickness. In the axial direction, the reactor is reflected by water.

The reactor core assembly is contained in a 244-cm-diam steel pressure vessel located in a pool of water. The top of the pressure vessel is 518 cm below the pool surface, and the reactor horizontal midplane is 838 cm below the pool surface.

HFIR spent fuel assemblies are stored on-site, in a pool adjacent to the reactor vessel. A few key parameters of HFIR are presented in Table 1. Significant components of the reactor are identified in Fig. 3.

Table 1. Key parameters of HFIR

Reactor power, MW	85	
Active core height, cm	50.8	
Number of fuel elements	2	
Fuel type	U_3O_8—aluminum	
Total ^{235}U loading, kg	9.43	
Enrichment, %	93.1	
Fuel element parameters	***Inner fuel element***	***Outer fuel element***
Number of fuel plates	171	369
^{235}U loading, kg	2.60	6.83
Average fuel uranium density, gU/cm^3	0.776	1.151
^{235}U per plate, g	15.18	18.44
Burnable poison in element (^{10}B), g	2.8	None
Fuel plate thickness, cm	0.127	0.127
Coolant channel between plates, cm	0.127	0.127
Minimum aluminum clad thickness, mm	0.25	0.25
Fuel plate width, cm	8.1	7.3
Fuel cycle length, d	~24	
Cycle 400 length, d	24.6	
Coolant inlet temperature, °F	120	
Coolant outlet temperature, °F	169	
Fuel plate centerline temperature (nominal), °F	323	

3. Components of the HFIR physical plant impacted by change in enrichment

Due to the construction of the reactor, the dimensions of the HFIR fuel elements could not be modified for LEU without prohibitively high cost and outage time to make reactor plant modifications. A criterion of future engineering studies is that there shall be no change to the physical dimensions of the core. However, simply changing the fuel from HEU to LEU, if that were neutronically feasible, will increase the uranium loading to a value that is five times the current uranium content. An inner fuel element has a mass of 47.2 kg, and an outer element has a mass of 91.7 kg. A consequence of changing to LEU would be that the mass of an inner fuel element would increase by at least 22% and that of an outer element by at least 30%. Maintaining an equivalent cycle length for the LEU fuels will almost certainly lead to fuel element mass increases greater than these values**.**

The mass or weight of the HFIR fuel elements directly impacts fuel handling operations during fuel fabrication, transportation of fresh fuel to Oak Ridge, fresh fuel storage, handling operations between the fresh fuel storage and the reactor core, handling operations between the core and spent fuel storage, and finally transportation by shipping cask to the spent fuel storage site. Fuel handling tools, seismic qualification of storage arrays, and other weight-related analyses will have to be performed when an acceptable LEU fuel design has been developed. Fuel handling operations are performed several times a year since HFIR typically is refueled eight times per year.

The physical support structure of the reactor core inside the reactor pressure vessel should be sufficient for the increase in weight accompanying LEU fuel but the increased weight will necessitate a review of the reactor support seismic analyses. Nevertheless, the physical plant would have to be reviewed and qualified for the added weight.

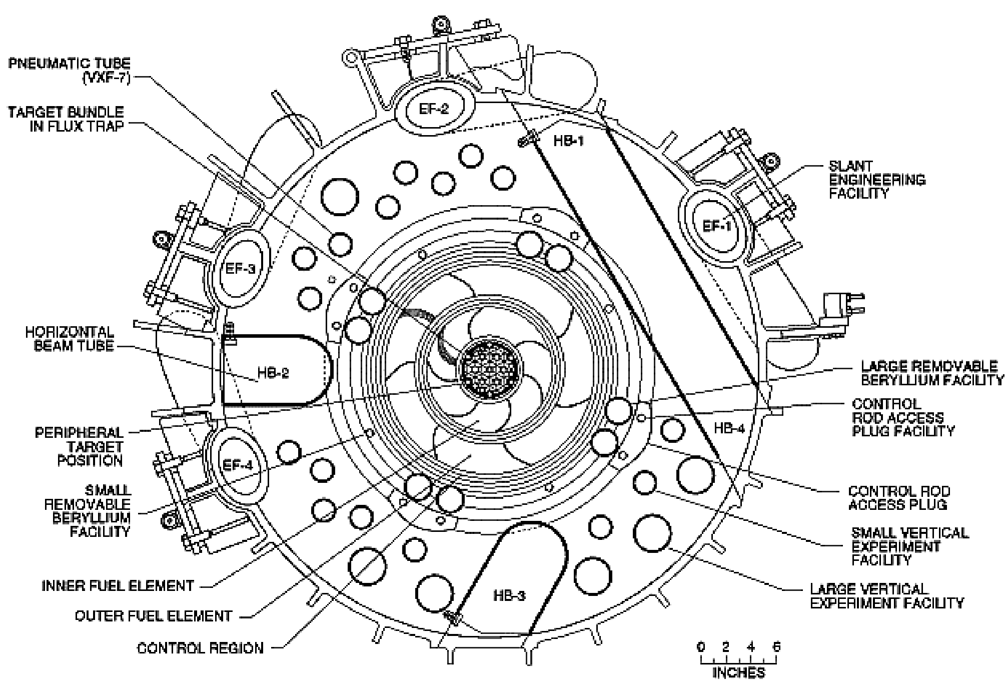

Fig. 3. Cross section of the HFIR reactor core at horizontal midplane.

Irradiated HFIR elements are stored in relatively close-packed, three dimensional arrays at the reactor site until sufficiently decayed for shipment (typically 5-7 years; the minimum storage time is 30 months – the time it takes for decay heat to reach 600 watts). Approximately sixty assemblies (combinations of inner and outer elements) are currently stored at HFIR and anticipated future operation would add eight assemblies per year. The physical support structure of the array should be sufficient for the increase in weight accompanying LEU fuel but would have to be reviewed and qualified. The storage of spent fuel is currently limited to 90 cores because the "loading calculation" for the pool floor did not adequately account for the fuel weight.

Increased ^{235}U content is necessary to compensate for parasitic capture in the fertile fuel and change of enrichment level will mandate new criticality safety analyses for the spent fuel storage array. The current safety approval for the spent fuel storage is based on a series of cadmium-poisoned arrays of fresh, HEU fuel elements (no burn-up credit). New analyses would be required for LEU and it will have to be determined if a change to LEU would require new critical experiments and/or a larger fuel element spacing.

The radiation source term from spent HFIR fuel is the basis for accident source terms for some ORNL hot cell facilities as well as for the HFIR itself. This source term will be different due to the enhanced plutonium and trans-plutonium isotope content of spent LEU fuel as compared to HEU (for comparable energy generation) and due to differing fission product distribution in LEU fuel (a significant number of fissions will occur in plutonium produced from ^{238}U due to the high burn-up of HFIR elements – 200,000 MWD/MTHM for HEU fuel). Changes to the physical plant due to variation in the radiation source term would seem unlikely but modification of safety documentation would extend beyond HFIR to other ORNL facilities.

3. Components of HFIR fuel elements impacted by change in enrichment

The current operating power level for HFIR was set by a required reduction in system pressure due to possible pressure vessel embrittlement. Without changes in the HFIR physical plant (pressure vessel, pumps, etc.), the heat transfer properties of the existing HEU element should remain unchanged for LEU fuel. Heat removal requires large surface area, high surface-to-volume ratio, fuel plates and coolant channels to be as thin as can be fabricated, and a cladding material with excellent thermal conductivity. Consequently, changes to the fuel plate dimensions or fuel element dimensions are not practical for an LEU element.

The fuel meat region inside the clad is the portion of the plate that will change due to conversion to LEU. HFIR fuel plates have a graded fuel distribution, shown in Fig. 4, and an involute shape to maintain constant coolant channel thickness along all portions of the plate surface. The current fuel distribution is constrained by the following:

- minimum fuel plate thickness that can be fabricated,
- properties of fuel and aluminum powders,
- plate edge clad minimum dimension to insure that the fueled region does not extend inside the element sideplates,
- plate end clad dimensions to insure margin-to-boiling at coolant exit,
- minimizing rejection of fuel plates due to variability in the manufacturing process,
- minimizing the peak-to-average power density for the core.

A prior study[2] has identified uranium-molybdenum, either as particles dispersed in aluminum or as a foil, as the fuel to be considered in the upcoming engineering studies. The high uranium loading required for a HFIR LEU fuel can not be achieved with the current U_3O_8 fuel or with the U_3Si_2 fuel used in the conversion low power research reactors to LEU. Criteria for fuel based on this alloy must correspond to the criteria for the current HEU fuel. The actual, numeric values for the various parameters will likely be different than for the current fuel and will be identified in future engineering studies. The fuel distribution and curved plate configurations are unique to HFIR and little applicable data exists.

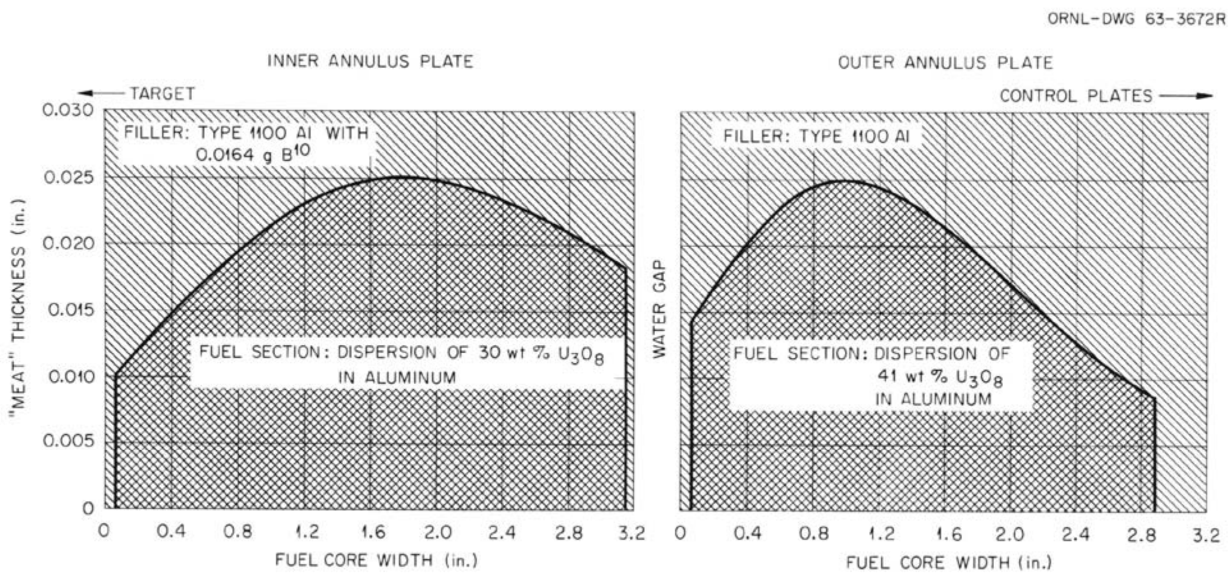

Fig. 4. Fuel and aluminum filler distribution inside inner element and outer element fuel plates

The presence of ^{238}U in LEU will lead to the production of significantly greater quantities of plutonium than exist in current stored, irradiated HEU elements. While the spent LEU elements will have sufficient radiation fields to be self-protecting, the storage of spent elements at HFIR for 5-7 years would result in a large increase in the plutonium inventory at ORNL. Regulatory impacts, if any, of this change will have to be assessed.

4. Changes in the documented safety basis due to conversion to LEU

The steady-state operation of the reactor (reactor physics and thermal hydraulics) is described in Chapter 4 of the HFIR Updated Safety Analysis Report (USAR).[3] Analyses of the reactor power distribution, inlet and outlet coolant temperatures, margin to incipient boiling, hot spot temperatures, clad oxide thickness, etc., will be performed using existing HFIR methodologies and models.[1, 4-7] While it is expected that values different from those in the current safety analysis report will be obtained, the goal for the engineering design studies will be to obtain a design such that the margin of safety is not reduced from that documented in the USAR. Such a philosophy has been successfully followed in recent design changes.[8]

The distribution of fission product isotopes in the spent fuel will be different for LEU than for HEU. The impact of the change in fission product distribution will have to be propagated through the analyses that compose the radiological hazard consequences analyses.

The performance of the reactor under anticipated transients is described in Chapter 15 of the USAR. No new transients are expected to be identified due to a change in fuel material and fuel enrichment but input will be needed from materials specialists to confirm performance of uranium-molybdenum alloy relative to the current fuel that is a mixture of U_3O_8 and aluminum. However, the reactivity worth of the control elements as a function of element position will change when the fuel enrichment is changed and as plutonium is produced during the fuel cycle. When a fuel design has been developed that satisfies steady-state operating criteria, existing methods and models[9] will be used to examine the transient performance of the reactor. As for steady state, the goal for the engineering design studies will be to obtain a design such that the margin of safety is not reduced from that documented in the USAR.

5. Performance of existing fuel fabrication technology

During 40 years of operation (406 fuel cycles each requiring an inner and an outer fuel element; 230,000 fuel plates), there have been no fuel plate or fuel element failures during reactor operation. There have been no vibration, corrosion, or erosion problems. About 10-15% of the fuel plates were typically out-of-specification when manufactured but were deemed to be acceptable for use following deviation control analyses by the HFIR staff. From 3–5% of manufactured fuel plates are rejected at the manufacturer each year as being unacceptable for use in the reactor. When an acceptable LEU fuel element design is developed, the economic assessment of LEU conversion will require input from materials scientists and fuel fabricators as to whether comparable reliability and performance in the manufacturing processes can be attained for the LEU fuel.

6. Beyond-reactor-site fuel cycle issues

Currently, charges for the processing of highly enriched uranium to the form of U_3O_8 are funded from the HFIR budget but there is no charge from the Department of Energy for the highly enriched uranium. If LEU is produced by down-blending from HEU, an additional fuel production step would be added to HFIR operations along with the associated cost. If instead, uranium is to be enriched from natural to 20 wt. %, that production step would be added to HFIR operations. An assessment should be made of the quantity of 20% enriched uranium that the Department of Energy might already have available for use in HFIR operations.

Development of a uranium-molybdenum fuel will require the development of certified production processes. The procurement of equipment, development of new procedures, and the training of qualified operators will require financial investments and continuing resources to support them.

The shipment of irradiated fuel containing uranium-molybdenum alloy to off-site spent fuel storage will necessitate a re-certification of the shipping cask used for HFIR fuel. The acceptability of this spent fuel form to a DOE storage site and, possibly, to a permanent repository, must be assessed.

7. Criteria for conversion study derived from design bases

A tentative set of assumptions that will guide engineering studies to be conducted during FY06 include:

- There shall be no change in the physical dimensions of the core.
- There shall be no change in the fuel geometry; that is, the fuel shall be involute plates of the same physical dimensions as the current HEU core and shall have an equivalent graded fuel loading across the span of the plate as needed to achieve a radially flat power distribution across the core annulus.
- The minimum clad thickness on each side of the fuel meat in the LEU fuel plate shall be maintained, nominally, at 10 mils (254 microns, minimum clad thickness of 8 mils).
- There shall be no reduction in core power level (85 Mega-Watts-thermal) or core lifetime (nominally 26 days at full power) from the values achievable in the current HEU core.
- The margins of safety in the bases of the currently-approved Technical Safety Requirements shall be maintained.
- There shall be no change to core coolant flow requirements or to the allocation of flow to research locations.
- The LEU core should require no changes to the control and protection systems; however, if such changes are needed, such changes shall not require a major redesign of systems. A major redesign is one that requires more than a few percent of the HFIR annual budget to implement and verify. Major redesigns could be considered as changes requiring an outage time more than twice as long as current practice and/or an Operational Readiness Review for restart.
- Each fresh LEU fuel element (inner or outer) separately shall have an adequate margin of subcriticality under any credible configuration. The two assembled fresh LEU fuel elements should remain subcritical when fully reflected by light water or concrete. If subcriticality is not achievable for the two assembled fresh LEU fuel elements when fully reflected by light water or concrete, simple but diverse and redundant single-failure-proof measures for assuring subcriticality shall be available, such as a fixed neutron poison in a shipping cask or storage array.
- There shall be no change to the methods now approved for handling and storing irradiated fuel elements.
- The reliability of the manufacturing process should be the same or similar to existing fabrication methods.

8. Potential indicators for judging performance with LEU

8.1 Neutron scattering

The principal mission for HFIR for the future is to be a source of neutrons for neutron scattering measurements. Within the area of neutron scattering, the “cold” energy range of neutrons – energy corresponding to a temperature of 20^{o}K or around 0.002 eV – is the area for which the most research proposals are currently being submitted to the Department of Energy and for which the HFIR would be the best facility for performing the measurements. The HFIR cold source is currently under construction and is scheduled to begin operation around October 1, 2006. The calculated flux of cold neutrons at the exit of the cold source moderator vessel is 10^{15} n/(cm^{2}s). To a first approximation, fluxes from a cold source scale as the reactor power. Competing reactor cold sources to the HFIR are the High Flux Reactor at ILL in France and the University of Munich reactor in Germany. These have power levels of 58 MW and 20 MW, respectively, but experience less than a linear decrease in flux versus power due to the presence of heavy water reflectors as opposed to the beryllium reflector at HFIR. For neutron scattering applications that employ thermal neutrons, the thermal ($\leq$ 0.625 eV) neutron flux at the origin of the beam tubes – meaning the tip of the tube at the point closest to the reactor core – is $8(10^{14})$ n/(cm^{2}s). The flux values for these two regions will serve as metrics for LEU performance.

Both the availability factor – defined as the fraction of time that the reactor is operating during a calendar year – and the length of time of an operating cycle will be important metrics for comparing LEU to HEU performance. The "down time" between operating cycles will likely be independent of the use of HEU or LEU fuel. The length of the fuel cycle may be strongly dependent on the type of fuel. The current fuel cycle length is 19 – 26 days depending on the loading of experiments to the central target and beryllium reflector positions.

8.2 Isotope production and materials irradiation

Secondary missions of HFIR, in terms of fractional financial support to the operating expenses of the facility, are the production of trans-plutonium isotopes, principally californium, medical radioisotopes, and un-instrumented, small sample material irradiations. The perturbed thermal flux in the central target region – the location for these missions - is $2.6(10^{15})$ n/(cm^2*s) and the total flux is $5(10^{15})$ n/(cm^{2}s). The Advanced Test Reactor (ATR) is the only domestic U.S. reactor that achieves neutron fluxes close to these values but would require facility modifications, additional transportation costs for sample transit to Oak Ridge, and most importantly, would likely experience the same modifications in performance due to conversion from HEU to LEU as would HFIR. While international purchase and shipment of irradiated specimens is conceivable, procurement time for short-lived isotopes would make some of the current missions unachievable. The metrics for evaluating the impact of LEU on these secondary missions would likely be the production rate for isotopes, the time-to-achieve-fluence-goal for materials irradiations, and minimizing any perturbation to the neutron spectra. Currently, about 25% of the central target locations in HFIR are unused – aluminum rods are substituted for isotope production rods.

A tertiary mission of the HFIR, in terms of financial support to the operation of the reactor, is the use of the reactor as a neutron source for activation analyses. This mission, while small (financially), is growing. Fluxes of 10^{14}n/(cm^{2}s) are not currently achievable in U. S.-based LEU reactors. A similar facility with this flux level does not exist at other, currently HEU-fueled, U.S. reactors. Due to the short half-lives of the activated nuclides, performance of this mission at reactors outside the U. S. is not possible. The metric of evaluating the impact of LEU on this mission will be a review of irradiations conducted over the lifetime of the activation analysis facility to determine if the perturbation in flux level due to LEU would have precluded or hindered any of these measurements.

While not a current mission of HFIR, a fourth category would be consideration of the impact of LEU on the potential to perform larger-sample-size (relative to the central target region) and/or instrumented irradiations in various locations in the beryllium reflector. Since these facilities are currently unused and since the ATR was specifically constructed as a materials irradiation facility, the impact of LEU on this potential mission capability would not seem to be a metric for evaluation of performance.

9. Conclusions

A preliminary review of the design bases for the HFIR reactor and its fuel cycle have been conducted in order to develop both goals and constraints for subsequent engineering evaluations of possible conversion of the HFIR from HEU to LEU fuel. The requirements not to reduce the margin of safety from that present in the current design, maintain reactor performance, and minimize the potential cost of conversion have led to the conclusion that the only region of the reactor that will be considered for study is the uranium- and aluminum-bearing fuel meat region of the fuel plates located inside the fuel clad.

10. References

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