Assumptions and Criteria for Performing a Feasibility Study of the Conversion of the High Flux Isotope Reactor Core to Use Low-Enriched Uranium Fuel

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Abstract

This paper provides a preliminary estimate of the operating power for the High Flux Isotope Reactor when fuelled with low enriched uranium (LEU). Uncertainties in the fuel fabrication and inspection processes are reviewed for the current fuel cycle [highly enriched uranium (HEU)] and the impact of these uncertainties on the proposed LEU fuel cycle operating power is discussed. These studies indicate that for the power distribution presented in a companion paper in these proceedings, the operating power for an LEU cycle would be close to the current operating power.

KEYWORDS: HFIR, LEU, uranium-molybdenum, thermal hydraulics, operating power

1. Introduction

A companion paper [1] in these proceedings discusses the configuration of the High Flux Isotope Reactor (HFIR) and the request from the National Nuclear Security Administration, through the Reduced Enrichment for Research and Test Reactors (RERTR) program, to conduct an engineering design study of the use of low enriched uranium (<20% enriched) as a fuel for HFIR. The fuel form selected by the RERTR for evaluation is 10 wt.% molybdenum-in-uranium metal (U-10Mo). The spatially dependent power distributions determined from the calculations described in the companion paper were input to a thermal hydraulics computer program [2] to determine the maximum allowable operating power for the reactor. This thermal hydraulics program also requires, as input, the manufacturing tolerances for the HFIR fuel plates. This paper will review the values of the manufacturing tolerances that are input to the thermal hydraulic code. The calculated reactor operating power – determined by coupling the reactor physics output documented in the companion paper with manufacturing tolerances and irradiation phenomena - will be reviewed for both the current, highly enriched uranium (HEU) cycle and the proposed LEU cycle.

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2. Input to thermal hydraulic analyses

The computer program documented in [2] is a two-dimensional (across the width and down the length) model of a single channel in the inner element and a single channel in the outer element. Power densities from the reactor physics calculation as a function of time-during-fuel – cycle are assigned to the grid points of the mesh. Other input to the program include plant operating conditions (inlet temperature, pressure, coolant flow rate) and fraction of fission heat deposited in the core versus the reflector. The program includes correlations to calculate the aluminum oxide buildup on the fuel plates as a function of time and position, pressure loss as coolant flows along the channel, fuel plate deflections induced by differential pressures and temperature (narrowing of coolant channels), allowance for lack of heat conduction due to lack of bonding of fuel to clad, determination of value of heat transfer coefficients for clad and oxide, and allowance for radiation induced swelling of clad (narrowing of coolant channels). Uncertainties in both fuel plate as-fabricated dimensions and previously-mentioned correlations are accounted by the use of uncertainty factors.

The basic approach used in the analysis is to calculate the thermal hydraulic history of the fuel channels at a specified power level for all time increments prior to the time at which the reactor power is specified by the user to be raised to the value that yields incipient boiling or burnout. This accounts for the burnup of the fuel and for the buildup of the oxide on the fuel plates. At the time specified by the user, the code iteratively searches for the power level corresponding to either the incipient boiling or burnup criteria. For the current fuel cycle, the most restrictive condition is at beginning-of-life.

2.1 HFIR fuel plate geometry

The HFIR design evolved from previous, Materials Test Reactor (MTR) designs. It is a plate-type reactor; composed of 1.27 mm thick fuel plates. The plates are 61 cm in length; coolant flow path is down the plate from top to bottom. The coolant channel thickness is also 1.27 mm. The plates are approximately 9 cm wide and are curved along their width in the shape of an involute of a circle (constant water gap thickness everywhere along the plate). The plate is a "sandwich" design; aluminum 6061 clad containing a mixture of U_3O_8 and Al powder. The clad thickness is 0.254 mm. The central 0.762 mm section of the plate (frequently termed the "meat") is divided into a fuel region and a filler region. The fuel meat is of variable thickness along the width of the plate but, at any given width (or radius), does not vary axially. The distribution of fuel mixture and filler as a function of distance along the plate (width) is shown in Fig. 1.

The HFIR fuel manufacturer is required to fabricate the profile shown in Fig. 1 to within +/-12% on fuel thickness. Furthermore, the edges of the fuel region (left and right) must be positioned to within +/-0.635 mm of the nominal endpoint.

An axial view of the end region (top) of an inner element fuel plate is shown in Fig. 2. The manufacturing tolerances (in inches) are noted in Fig. 2. The HFIR core is formed by loading fuel plates into aluminum sideplates; 171 fuel plates are loaded in the inner element, 269 plates are loaded into the outer element. The lower and upper boundaries of the fuelled region inside a plate have manufacturing tolerances of 1.27 cm.

Figure 1: Fuel thickness profile inside HFIR inner and outer element fuel plates.

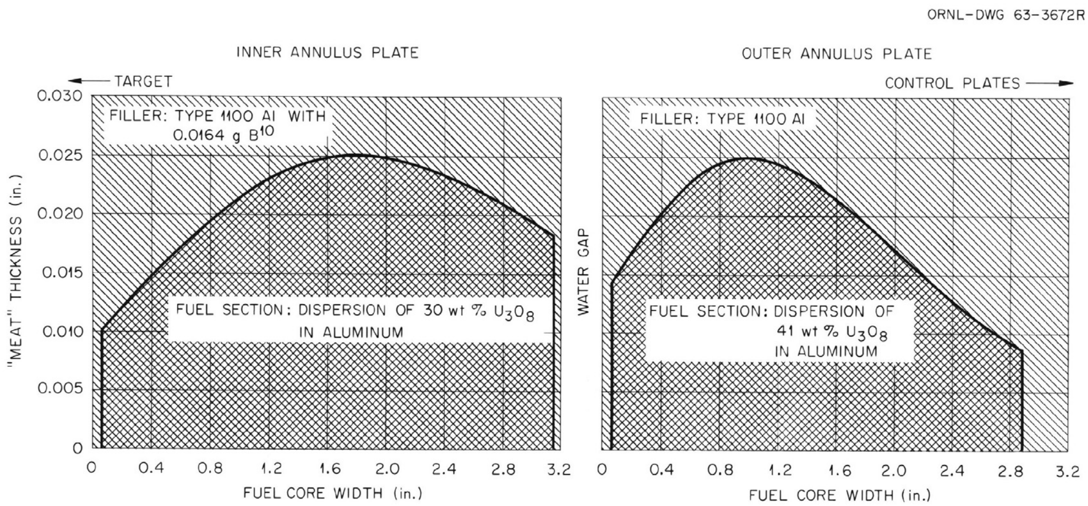
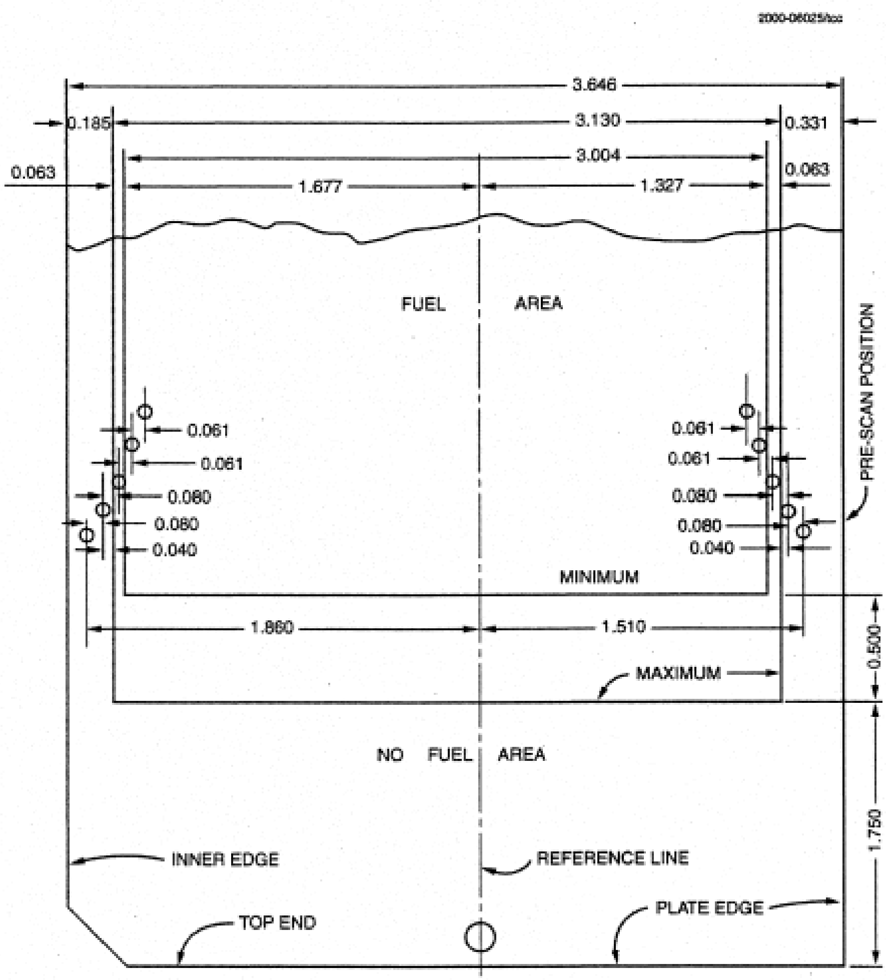


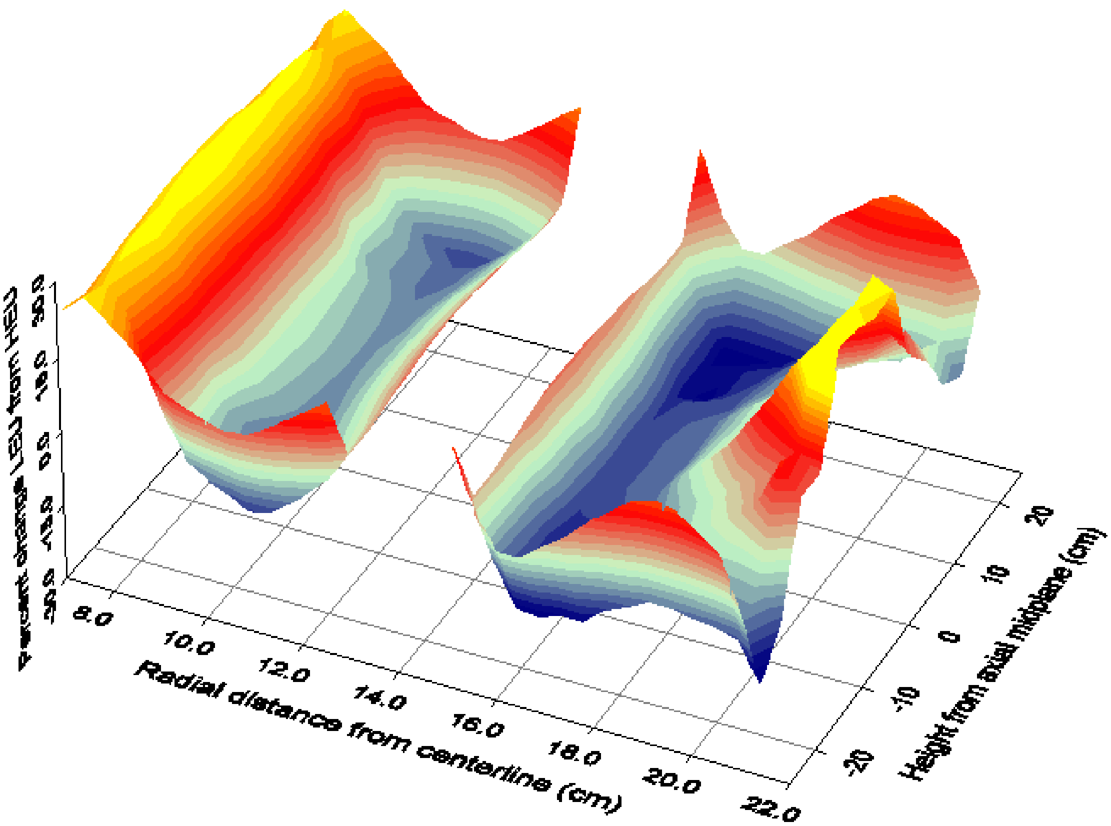
Figure 2: Schematic of axial end of inner element fuel plate



2.2 Core power distributions for HEU and LEU

The companion paper [1] describes the reactor physics methodology and the results of the neutronics analyses. A "summary" of that work can be viewed in Figure 3. The diagram shows the percentage increase or decrease in local power density for the beginning-of-cycle LEU core (inner and outer elements) relative to the current HEU core. The blue and green regions indicate volumes in the fuel elements where the LEU core relative local power densities (relative to the core average) are lower than or equal to those of the corresponding positions in the HEU core. The red and yellow regions indicate volumes where relative local power densities are greater in the LEU core than in the HEU core.

Figure 3: Percent changes in local, relative power densities when HFIR is fueled with LEU in place of the current HEU



2.3 Manufacturing tolerances for HEU (and LEU) plates and derived limiting plate description

A list of fabrication parameters that impact the assessment of the incipient boiling limit is provided in Table 1 along with their values. These manufacturing tolerances are applied to the plate configuration input and result in the uncertainty factors that are listed in Table 2 and which are input to the thermal hydraulic analyses. All of these data are for the current fuel cycle – compacted and rolled, highly enriched U_3O_8 in aluminum. The fabrication procedure for U-

10Mo is currently under development and corresponding manufacturing tolerances for that fuel are not available. For the studies reported here, the U-10Mo fuel is assumed to have the same tolerances/uncertainties as the current fuel. An assessment of the extent and cost of an experimental program to gather these data for U-10Mo fuel is planned for 2007.

2.4 Uncertainties in correlations describing plate performance under irradiation

The HFIR thermal analysis program includes allowances for fuel plate deformation due to thermal stresses and radiation induced behavior. These correlations were developed from out-of-reactor experiments performed prior to the startup of HFIR and also from examining fuels discharged from other aluminum-clad uranium oxide fueled reactors. The uncertainties in these correlations are input to the computer program and their values for the current fuel are provided in Table 3. The aforementioned experiment planning process will also include assessment of resources needed to gather data comparable to Table 3 for U-10Mo fuels.

Table 1: Manufacturing tolerances for HFIR fuel

Maximum fuel plate thickness	1.2954 mm
Nominal coolant channel thickness	1.27 mm
Maximum coolant channel thickness averaged across width of plate at any given elevation	1.4224 mm
Minimum coolant channel thickness averaged across width of plate at any given elevation	1.1176 mm
Maximum local coolant channel thickness	1.524 mm
Minimum local coolant channel thickness	1.016 mm
Nominal distance of fuel bearing portion from upper and lower edges of the fuel plate	50.8 mm
Maximum distance of fuel bearing portion from upper and lower edges of the fuel plate	57.15 mm
Minimum distance of fuel bearing portion from upper and lower edges of the fuel plate	44.45 mm
Minimum radial distance of the fuel bearing portion of the fuel plate from the side plate	1.143 mm
Nominal heat transfer area	39.83 m^2
Minimum heat transfer area	39.12 m^2
Maximum diameter of non-bond between fuel and clad	1.5875 mm
Tolerance on total fuel loading within an individual fuel plate	±1.0%
Tolerance on fuel loading within a 5/64-in. diameter spot	+27%, –100%
Average tolerance on fuel loading within a rectangular area 5/64 in. × 1/2 in.	±12%

2.5 Instrumentation uncertainties and SCRAM settings

HFIR limiting control settings determine the point at which the reactor automatically SCRAMs. Current settings of relevance to the thermal hydraulic analyses are maximum overpower of 30% before trip (flux-to-flow ratio of 1.3), inlet coolant temperature maximum of 57.2°C (135°F), core inlet pressure minimum of 2413 kPa (350 psia), and coolant flow rate minimum of 94.6 liters/s (1500 gpm). These limiting control settings, rather than nominal reactor operating conditions, are input to the thermal hydraulic code to determine the maximum reactor power that can be sustained without initiating boiling anywhere in the reactor core (termed incipient boiling limit).

Table 2: Derived uncertainties in input to HFIR heat transfer analyses based on Table 1.

Uncertainty in the reactor power level	1.02
Uncertainty in the total heat transfer area	1.045
Uncertainty in the power density distribution	1.155
Uncertainty in the "average" fuel concentration in the hot plate	0.90 for upper half /1.12 for lower half
Uncertainty in the "average" fuel concentration in the cold plate	1.10 for upper half /0.88 for lower half
Uncertainty in the inlet coolant temperature	1.015
Uncertainty in the friction factor	1.05
Uncertainty in the local heat transfer correlation	0.90
Uncertainty in the oxide film correlation	1.25
Uncertainty in the relationship for deflection as a result of the differential pressure across the plate	1.10
Uncertainty in the relationship for deflection of plate being considered in reference to an average plate as a result of temperature differences	1.10
Uncertainty in the increase in the fuel plate thickness as a result of thermal expansion	2.00
Fuel segregation flux peaking on the hot side of the fuel plate	1.27
Fuel segregation flux peaking on the cold side of the fuel plate	1.27
Uncertainty in the incipient boiling correlation	1.00
Hot streak factor	1.12
Range of peaking factors for fuel extending beyond base of inner plate	1.00 – 1.44 depending on position
Range of peaking factors for fuel extending beyond base of outer plate	1.00 – 1.35 depending on position

Table 3: Uncertainties in experimental correlations encoded in HFIR heat transfer program

Uncertainty in the power density distribution	1.155
Uncertainty in the friction factor	1.05
Uncertainty in the local heat transfer correlation	0.90
Uncertainty in the oxide film correlation	1.25
Uncertainty in the relationship for deflection as a result of the differential pressure across the plate	1.10
Uncertainty in the relationship for deflection of plate being considered in reference to an average plate as a result of temperature differences	1.10
Uncertainty in the increase in the fuel plate thickness as a result of thermal expansion	2.00
Uncertainty in the incipient boiling correlation	1.00

3. Results of thermal hydraulic analyses

The operating power for HFIR is determined by establishing the reactor power that corresponds to the incipient boiling limit. It is noteworthy that due to the small thickness of the HFIR coolant channels, the incipient boiling heat flux is only slightly lower than the burnout heat flux. This operating power is established by assuming that all fuel fabrication parameters (dimensions, fuel thickness variation, etc.) and reactor instrumentation (pressure sensors, flow rate, inlet temperatures, etc.) are at the limit of their allowable ranges (tolerance limits) and at the values that would be most favorable to the onset of boiling.

3.1 Current fuel cycle - HEU

3.1.1 The perfect core

The current operating power for the HFIR is 85 MW. The impact of all of the tolerances and uncertainties in the fuel manufacturing and inspection processes and the uncertainties in the experimental correlations of fuel performance under irradiation can be assessed by setting all of the uncertainties to zero, i.e., uncertainty factors in Tables 2 and 3 set to 1.0 and all plate dimensions (Table 1 values) are nominal. Executing the HFIR thermal hydraulics program with this input yields an operating power of 180 MW.

3.1.2 Safety analysis report assumptions

The thermal analysis documented in the HFIR Safety Analysis Report [3] is based on a reactor power distribution derived from experiment-corrected diffusion theory. The calculations date to 1971 [4]; the computer codes and nuclear data libraries used at that time are no longer available. Nevertheless, power distribution measurements made at critical conditions and documented in [4] remain, even today, the best reference for safety analyses. When the beginning-of-cycle power distribution from [3, 4] is input to the HFIR thermal hydraulics code with the uncertainty factors set to the values contained in Tables 2 and 3, the derived incipient boiling limit is calculated to be 88 MW, thus the origin of the value of the current maximum operating power level of 85 MW.

3.1.3 Current diffusion theory calculation

The HEU power distribution that is the basis of Fig. 3 and the reference for the companion paper on LEU fuel in HFIR [1] was input to the HFIR thermal hydraulics program. Uncertainty factors were set to the values noted in Tables 2 and 3. The derived operating power was 72 MW. Note that unlike the power distribution discussed in section 3.1.2, no experiment-derived corrections were applied to this diffusion-theory based power distribution. A comparison of the power distribution from [1] with the critical experiment data and "corrected" power distribution in [4] reveals that the current work appears to be overestimating the amount of power generated at the edges of the fuel elements and underestimating the power densities along the axial centerline of the core.

3.1.4 MCNP calculation

Though the critical experiments documented in [4] and 40 years of operation have shown 85 MW to be a safe operating power for HFIR, extrapolating this experience to a new fuel type <u>and</u> insuring the safety of HFIR operation requires resolution of the discrepancy between the methods documented in sections 3.1.2 and 3.1.3. Tallies were added to fuel zones in an existing MCNP model [5] of the HFIR and two dimensional power distributions, albeit a much coarser grid than the diffusion theory calculations (119 zones versus 438), were generated and input to the HFIR thermal hydraulics code. The calculated operating power was 91 MW. Visual inspection of the power profile showed that local power densities along the lower edges of the fuel elements were less than corresponding values from the diffusion theory calculation (section 3.1.3).

3.2 LEU

3.2.1 Perfect fabrication – zero tolerances

As in section 3.1.1, the impact of all of the tolerances and uncertainties in the fuel manufacturing and inspection processes and the uncertainties in the experimental correlations of fuel performance under irradiation can be assessed by setting all of the uncertainties to zero (uncertainty factors to 1.0). Executing the HFIR thermal hydraulics program with this input yields an operating power of 166 MW.

3.2.2 Current diffusion theory calculation

The LEU power distribution that is the basis of Fig. 3 and the results of which are documented in the companion paper on LEU fuel in HFIR [1] was input to the HFIR thermal hydraulics program (uncertainty factors having the values in Tables 2 and 3). The derived operating power was 56 MW. A previous publication [6] had reported a higher value but was incorrect due to inconsistencies between mesh structures for the neutronics and thermal hydraulics calculations.

3.2.3 MCNP calculation

Having achieved good agreement between experiment-corrected diffusion theory and Monte Carlo theory for the HEU case, atom densities for the LEU case were extracted from the diffusion theory model and incorporated into the MCNP model mentioned in section 3.1.4. The power density profile was calculated and input to the HFIR thermal hydraulics code. An operating power of 84 MW was determined based on LEU MCNP power distributions.

4. Conclusions

The HFIR fuel cycle is essentially unchanged since the reactor first achieved full power in 1966. While calculations guided the reactor design, experimental measurements were the basis for establishing operating power and certifying that the reactor could be operated safely and with sufficient margin to boiling. Current Monte Carlo methods appear to be able to replicate the experiments performed in the 1960s but many additional studies of the critical experiment data and operating reactor data remain to be performed. It is possible that Monte Carlo results can be used to refine the cross section processing procedure for data input to diffusion theory codes and thereby improve the accuracy of their predictions.

However, agreement between calculation and experiment for HEU is not a guarantee that comparable agreement can be obtained for LEU, especially since the burnup/depletion characteristics of LEU will be considerably different than HEU. While the level of accuracy attainable in reactor physics calculations is uncertain and significant, these studies show that even greater uncertainty in the estimated operating power for HFIR with LEU is due to unknown fabrication tolerances and uncertainties in the applicability of irradiation performance correlations developed for uranium oxide fuel.

Acknowledgements

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