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HIGH FLUX ISOTOPE REACTOR POWER UPGRADE STATUS

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ABSTRACT

A return to 100-MW operation is being planned for the High Flux Isotope Reactor (HFIR). Recent improvements in fuel element manufacturing procedures and inspection equipment will be exploited to reduce "hot spot" and "hot streak" factors sufficiently to permit the power upgrade without an increase in primary coolant pressure. Fresh fuel elements already fabricated for future use are being evaluated individually for power upgrade potential based on their measured coolant channel dimensions.

I. INTRODUCTION

A. Background

The HFIR is a high power-density research reactor located at the Oak Ridge National Laboratory and managed by Lockheed Martin Energy Research Corporation for the United States Department of Energy. It operated at its original design power of 100 MW from startup in 1966 through 1986, when the reactor was temporarily shut down for investigation of pressure vessel embrittlement issues. Operation was resumed in 1989 with the primary coolant pressure reduced from 5.3 MPa to 3.3 MPa and with a program of periodic hydrostatic tests to verify pressure vessel integrity. The reduction in primary coolant pressure forced a corresponding power reduction to 85 MW, in order to maintain the desired core thermal margins.

B. Incentives for Power Increase

Two developments since the 1989 restart have made a return to the original 100-MW rating, while retaining the current reduced primary pressure, especially desirable:

1. The reactor vessel service life has been reevaluated using probabilistic fracture mechanics methods developed for NRC use.[1] It was concluded that it has a total lifetime of about 50 full- power years (instead of the 26 full-power years conservatively established as a basis for restarting the reactor in 1989), provided the present operating pressure is maintained and the periodic hydrostatic testing is continued.

2. The recent cancellation of the Advanced Neutron Source (ANS) project, which was to have resulted in the construction of a replacement for the HFIR with enhanced experimental capabilities, makes continued operation of the HFIR at its maximum power level important to meet future research needs for neutron beams, isotope production, and experimental irradiations.

Since the HFIR has many years of useful life remaining and no replacement facility is currently planned, a power upgrade will enhance the value of the HFIR experimental facilities for many years to come, and will increase the future return on any investments made in upgrading these facilities. Currently, upgrades are in the planning stage in the following areas:[5] (1) installation of a cold neutron source in horizontal beam tube 4, and construction of a cold neutron guide hall; (2) enlargement of horizontal beam tube 2, installation of neutron guides, and construction of a thermal neutron guide hall; (3) enlargement of the in-reactor portion of the neutron activation analysis facility; and (4) increased capacity for isotope production in the reflector. In addition, the production of transplutonium elements (e.g., Cf, Es) for scientific and industrial uses, for which HFIR has unique capabilities, will benefit from the power upgrade.

C. Power Upgrade Plan

A review of the numerous hot channel effects related to HFIR fuel fabrication which are accounted for in the thermal analysis and of available as-built fuel data has shown that a great majority of fuel plates and elements exceed their minimum specifications to a significant degree, and could operate safely at 100 MW at the current pressure. With recently upgraded inspection equipment at the fuel supplier's plant, it is expected that the fabrication related hot channel factors in all new fuel can be reduced enough to permit 100-MW operation, without significant impact on manufacturing yield or cost. However, capturing the increased power capability in the fuel fabrication stream requires changes to the fuel specifications and a revised set of thermal analyses based on the new fabrication tolerances. While this effort at revising the fuel specifications and related thermal analyses is under way, HFIR fuel continues to be produced to the current specifications which, at minimum, guarantee only 85 MW capability, and there remains about a 4-year supply of fresh fuel in storage, built to the present specifications. In order to permit a transition to 100 MW as soon as possible, a method is needed to evaluate the current fuel inventory to determine which elements are capable of 100 MW. The subsequent sections of this paper describe (1) the thermal analysis methods and thermal limit criteria being used in the power upgrade analyses, (2) plans for modifying the fuel specifications to ensure 100-MW capability with minimum impact on manufacturing yield and cost, and (3) the approach developed for evaluating the existing fresh fuel inventory for 100-MW capability.

II. THERMAL ANALYSIS SUPPORTING POWER UPGRADE

A. Bases for Safety Limits and Limiting Safety System Settings

HFIR safety limits (SL) and limiting safety system settings (LSSS) are based on steady state thermal analyses at worst-case conditions of power, coolant flow, pressure, and inlet temperature, and include numerous "hot channel" effects, which account for fuel manufacturing tolerances, all combined in a direct fashion. This analysis is performed using the HFIR steady state core heat transfer code (the "SSHTC"), a computer model of the HFIR core that was developed during initial HFIR design[2] and modified subsequently to incorporate improved models of key thermal hydraulic processes. An important feature of this code is the detailed internal treatment of "hot channel" effects, which create appropriate hot streak/ hot spot models for evaluation of thermal limits based on user-supplied data in engineering format (e.g., coolant channel dimensions in "mils"). In addition to the use of this code to establish limits from steady state analyses, the extent of possible core and plant damage during accidents is calculated with a transient analysis tool and the overall risk of fission product release due to accidents is evaluated based on the frequencies and expected consequences of the accidents. It has been found that the steady-state power/flow ratio margin of 1.3 (at minimum pressure, maximum temperature conditions) adopted for the original HFIR safety analyses yields satisfactory consequences for all protected accidents, hence this value remains a general guideline for 100-MW core analyses.

B. Impact of Manufacturing Hot Channel Factors

Because the HFIR fuel plates are made by a powder metallurgy process involving U_3O_8-aluminum powder blending, pressing and rolling operations, the finished fuel plates are subject to local variations in fuel density and in finished fuel "core" dimensions. In addition, fuel plate distortions introduced in welding them into the sidewalls and minor differences in the involute shaping of fuel plates cause variations in coolant channel dimensions in a finished fuel element. Each of these effects impacts the core thermal behavior, and is accounted for on a worst-case basis in the thermal analysis.

In the HFIR, thermal limiting conditions occur first at the core outlet (bottom) where the fluid subcooling is least and the nearby axial reflector region induces a local power peak. The design thermal analysis procedure employed in the safety limit calculations previously discussed combines the worst-case fuel density distribution and minimum channel thickness at this point, assuming that a "hot streak" (higher density) of fuel exists for the entire heated length of the narrowest channel, and that the heat flux at the core exit is also increased by a "hot spot" of high- density fuel located at the tip. In addition, the worst allowable axial misalignment of adjacent fuel plates is assumed such that a hot plate with a long fueled core protrudes beyond its (shorter) neighbors into the thermal neutron flux peak in the lower axial reflector. The combined effects of these three factors—fuel homogeneity within a plate, fuel core length and axial alignment, and coolant channel dimensions—together account for a large overpower factor, which can be reduced through improvements in fuel plate homogeneity inspection, fuel element assembly methods, and if needed, coolant channel dimensional tolerances. This approach is being taken for upgrading the new fuel supply, with the objective of combining improvements in these areas so as to obtain the desired power increase while minimizing the impact on yield and cost. This is described in Section III below.

For the current inventory of fresh fuel and any additional fuel elements manufactured to the present specifications, neither the fuel plate homogeneity nor the fuel core alignment can be re-inspected or reviewed to establish any excess power margin, since these characteristics are inspected on individual plates before assembly into a fuel element, and quantitative results are not preserved on inspection records. The results of the coolant channel dimensional inspection are recorded however, in a summary form, and can be used to establish additional power capability for those elements in which every channel exceeds the minimum specifications. This is the basis for "upgrading" selected elements from the existing inventory of fuel for use at 100 MW, as described in Section IV.

III. IMPROVING THE POWER CAPABILITY OF NEW FUEL

HFIR U_3O_8 - aluminum dispersion fuel plates, like those for many other research reactors, are produced by pressing and rolling processes which result in natural variations in fuel density within the plate as well as variations in the outline of the fueled "core" of the finished plate. The thermal analysis models employed to establish power capability account for worst-case tolerances on both the internal homogeneity of the fuel and on its outline dimensions (particularly the extension below the nominal bottom of the fueled core). These effects, and means of reducing their impact on power capability, are discussed individually below.

A. Fuel Homogeneity Effects

The fuel density distribution over the entire surface of each finished HFIR fuel plate is inspected by a scanning X-ray transmission device (the "scanner") before the plates are formed into involute shape and assembled into an element. The X-ray beam is collimated into a 2-mm spot. and the transmission through the plate is monitored by a sodium iodide crystal and photomultiplier as the fuel plate is scanned axially along each of approximately 50 tracks by an automatic drive system, covering the entire plate. This device was developed in the 1960's,[3] and although the equipment was upgraded from time to time, until recently it retained the original analog-based methods of processing and interpreting the X-ray transmission signal. These basically were limited to creating two signals based on the photomultiplier current: (1) a "spot" (unfiltered) signal which corresponds to the instantaneous X-ray transmission (i.e., the local fuel density under the X-ray collimator) and (2) a filtered signal. created from the "spot" signal by passing it through a first-order lag with a relaxation time corresponding to about 13-mm (0.5-inch) travel of the scanner table, called the "average" signal. Each of these signals is continuously compared with limits derived from standards. These standards are machined aluminum blocks which provide the attenuation equivalent to nominal, maximum average, and maximum local fuel densities permitted by the fuel specifications. The standards are fastened to the (unfueled) ends of the fuel plate being inspected, and are scanned prior to inspecting each fuel track.

Consistent with this inspection procedure, the HFIR worst-case thermal analysis model assumes that any fuel plate could have (1) a local hot spot at any position, caused by a local concentration of fuel at the "spot" fuel density limit and (2) an averaged density over part or all of any axial track at the "average" limit. (The *total* fuel loading of each plate is controlled in the powder blending process to a ±1% tolerance.) The homogeneity limits are currently 127% and 112% of nominal for local and averaged fuel density, so these assumptions have a significant impact on thermal margin. Quantitative inspection results from the original homogeneity scanners are not retained, so there are no records that show how "good" each accepted fuel plate may be.

In 1992, one of the two homogeneity scanners used by the fuel supplier was modified to incorporate digital conversion and processing of the homogeneity data,[4] as well as computer control of the scanner table motion. This upgraded device provides two important new capabilities: (1) it has much greater flexibility in processing homogeneity data to determine acceptability and (2) quantitative homogeneity data can be digitally stored and evaluated as an aid in understanding and monitoring the processes involved. A review of as-built digital homogeneity data on hundreds of fuel plates indicates that two key modifications can be made to the homogeneity specifications which will increase the fuel power capability with little or no impact on manufacturing yield or cost (i.e., no increase in rejects is expected). These changes are: (1) vary the maximum acceptable local fuel density with location on the plate, so that heat flux peaking due to local fuel concentrations is suppressed in critical regions (e.g., near the core outlet) while relaxing requirements in other regions and (2) establish varying limits on track-averaged fuel concentration as a function of averaging length and plate location, so that the very rare plates that have excessive track averages over the entire heated length (above, e.g., 106%) are rejected, while higher averages are accepted for shorter lengths.

These modifications will reduce both the total heat input along a hypothetical "hot streak" and the peak heat flux assumed at any point along the streak, and are also likely to reduce the frequency of rejects caused by the short averaging length used in the current fuel specification.

B. Fuel Core Axial Alignment

HFIR fuel plates are now aligned so that the fueled region (the "core") is centered axially within the fuel plate. Consequently, with a ± 12.7-mm core length tolerance, an overlength core can extend up to 12.7 mm beyond neighboring short cores in a worst-case configuration. This alignment is important due to steep thermal flux gradients in the axial reflector region which would cause local heat flux peaking in a protruding fueled core. Two specific changes are planned to reduce this effect:

1. Reduce non-squareness of fuel core ends, by reversing direction on the first pass through the rolling mill. This change has been introduced already into the rolling procedures, with a resulting improvement in squareness of fuel core ends.

2. Align fuel cores at their bottom ends (rather than centering them within the plate). This will reduce the maximum axial misalignment to no greater than the non-squareness at the bottom end, while increasing the allowable misalignment at the top of the core where the thermal margin is greater. The combination of these changes is expected to cut the heat flux peaking effect due to axial misalignment by 30 to 40%.

C. Net Impact on New HFIR Fuel

The relatively minor changes described above involving homogeneity specifications and fuel alignment procedures are expected to reduce the hot channel factors sufficiently to allow an increase in nominal power to 100 MW. Additional power capability can be gained, if needed, through changes in the minimum coolant channel dimension specifications.

IV. SELECTION OF EXISTING HFIR FUEL ELEMENTS FOR 100 MW

The coolant channel dimensional reports prepared by the fuel coolant channel inspection gage contain the only quantitative as-built data available for the current inventory of assembled HFIR fuel with the potential to establish a significant excess power capability for selected fuel elements that exceed the minimum specifications. To determine the potential for a power increase based on channel dimensions alone, a series of survey calculations was made using the HFIR SSHTC with varying input values of minimum local channel spacing, which is assumed in the analysis model to exist along a narrow track for the entire core length. Results of this brief study showed that about half of the "tracks" (i.e., about half of the channel span) of both the inner and outer fuel elements would be undercooled at 100 MW operation with the current minimum channel dimension requirement of 1.0 mm, while the flow through the remainder of the channel was sufficient at 100 MW. The increased cooling capacity available in selected cores with favorable as-built channel dimensions is illustrated in Figure 1, which shows the calculated maximum allowable local heat flux at the channel outlet (the "burnout heat flux") as a function of channel thickness at several points (tracks) along the channel span for inner and outer elements. This plot shows that increases in uniform as-built channel thickness up to about 1.17 mm will be needed for the most limiting tracks, to obtain the desired power increase of about 18%.

The coolant channel thickness of assembled HFIR fuel elements is measured with a gage containing five pairs of capacitance sensors distributed across the approximately 76 mm channel span. The sensing head is passed through the full length of each coolant channel while the gage readings are digitized and stored. Following each pass through a new channel, the minimum, maximum and axial average thicknesses read by each of the five sensors are calculated and at completion of the entire element, a report is printed which includes the min, max and avg values for each gage sensor for each channel, as well as overall min, max and average data for the entire element. For the inventory of fuel on hand these data are available only on printed copies of the report, making automated data processing difficult.

A review of channel inspection data for several HFIR elements shows that the dimensions recorded along each gage track may vary considerably, but the axial average thickness for any channel, which is most closely related to the pressure drop (or hot streak flow), is typically near the overall element average of about 1.27 mm, and is very rarely less than 1.1 mm. Local measurements within the channel however may approach the minimum (1.0 mm) and maximum (1.5 mm) specification limits. No evidence was found of narrow regions of a channel which extend the entire length of the core, although they are conservatively assumed in the thermal analysis model.

Since the typical axially-averaged coolant channel thickness allows much more flow than the uniform narrow streak assumed in the thermal analysis model, most fuel elements have higher power capability than predicted by the standard thermal analysis method. The information added by the axial average and max measurements can be used to adjust the calculated cooling capacity of a channel, provided the channel thickness profile is either known from the measurement or can be arbitrarily assigned in some conservative fashion (i.e., so as to maximize the pressure drop). Since the measured profile is not available, a limiting channel thickness profile is created by assigning to each node in the channel either the min or max measured dimension, selected in the correct proportion to yield the measured average thickness. The flow computed for this limiting channel profile can then be used in lieu of the flow that would result if the thickness of the entire channel were uniformly equal to the minimum local value. This approach is used in evaluating the as-built channel thickness measurements, aided by a spreadsheet and graphics which show the minimum required average thickness for power upgrade as a function of the minimum and maximum measured values.

V. CONCLUSION

Improvements in HFIR fuel fabrication and inspection methods and equipment have provided the means to reduce the fuel manufacturing uncertainty factors sufficiently to return to 100-MW operation without an increase in primary coolant pressure, and with no significant impact anticipated on fuel manufacturing yield or cost. During the time required to prepare revised fuel specifications and complete and review the thermal analysis supporting a power upgrade, the existing inventory of fresh fuel is being sorted according to its power capability, using results of the coolant channel measurements performed on all HFIR fuel elements by the fuel supplier, and fuel elements that do not meet requirements for 100 MW will be scheduled for use prior to a power increase. Based on results of this process to date, it is expected that a large majority of the existing fuel elements will be acceptable for use at 100 MW.

The ability to reduce the hot channel factors of HFIR fuel by exploiting detailed results of the fuel coolant channel inspection and the capabilities of the digital homogeneity scanner illustrate the value of continued modernization of fuel fabrication and inspection equipment and the importance of close coordination between fuel fabrication and reactor analysis personnel.

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Figure 1

Heat Flux Limit vs. Channel Thickness