ENHANCED HFIR OVERPOWER MARGIN THROUGH IMPROVEMENTS IN FUEL PLATE HOMOGENEITY INSPECTION

R. B. Rothrock
Oak Ridge National Laboratory
P. O. Box 2008
Oak Ridge, Tennessee 37831
(615) 574-0568

R. E. Hale
Oak Ridge National Laboratory
P. O. Box 2008
Oak Ridge, Tennessee 37831
(615) 574-8537

R. W. Knight
Oak Ridge National Laboratory
P. O. Box 2008
Oak Ridge, Tennessee 37831
(615) 574-5713

R. D. Cheverton
2703 West Gallaher View Road
Knoxville, Tennessee 37932

ABSTRACT

Fuel homogeneity inspection techniques used on the HFIR fuel plates have recently been improved through conversion of the X-ray inspection device to acquire, store, and process data digitally. This paper reports some early results from using the improved equipment and describes future plans for obtaining enhanced fuel thermal performance by exploiting this improved inspection capability.

I. INTRODUCTION AND BACKGROUND

The High Flux Isotope Reactor (HFIR) is a high-power-density research reactor located at the Oak Ridge National Laboratory (ORNL) and managed by Lockheed Martin Energy Systems, Inc., for the U.S. Department of Energy. It operated at the design power rating of 100 MW from its startup in 1966 and at a primary coolant pressure of 5.3 MPa (750 psig) until it was temporarily shut down in 1986 while pressure vessel embrittlement issues were investigated. Operation was resumed in 1989, with the coolant pressure reduced to 3.3 MPa (468 psig) to extend the pressure vessel service life. Because of the reduced operating pressure and corresponding lower core outlet subcooling, the operating power was reduced to 85 MW when operation resumed in 1989 to preserve an overpower margin consistent with its original design basis.

This paper describes recent improvements in the collection and use of as-built fuel plate homogeneity inspection data, which have the potential to reduce the hot channel factors related to fuel fabrication and to recover a significant part of the HFIR power capability that was lost as a result of the reduction in operating pressure. In a broader context, this paper illustrates how improved fuel inspection technology may be exploited to improve fuel performance by matching the inspection criteria more closely to the assumptions of the thermal analyses.

II. HFIR FUEL DESIGN AND HOMOGENEITY INSPECTION

The HFIR was designed to maximize neutron leakage into the internal flux-trap region for production of transplutonium isotopes, leading to a highly symmetric annular core design with a high average power density. The core is surrounded by a beryllium reflector, which also contains facilities for experimental irradiations and for extraction of neutron beams. Annular control elements are raised and lowered in the clearance space between the core and reflector to preserve azimuthal symmetry and minimize power peaking. The core itself (shown in Figure 1) is fabricated in two concentric pieces using involute curved fuel plates that contain UO₂-aluminum dispersion fuel compacts in aluminum cladding fabricated by pressing and rolling operations. The reactor is cooled and axially reflected by light water, resulting in pronounced fission rate peaks at the top and bottom of the core because of the thermal neutron current entering from the axial reflector regions. Because of the small and tightly coupled core that is completely replaced each cycle, a standard fission rate distribution is used in the thermal margin analysis with a small uncertainty allowance for perturbations caused by experiments or other factors. The local fission rate peaks at the ends of the core, in combination with a minimum subcooling at the bottom (outlet) end of the coolant.
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channels, result in the minimum thermal margin occurring at the bottom tips of the fuel plates.

The HFIR fuel manufacturing process, which is common to many research reactors, results in small random variations in local fuel density throughout each fuel plate. This in turn causes local deviations from the nominal core thermal hydraulic conditions such as subchannel coolant temperature and local heat flux, which are typically accounted for in thermal design analyses and safety studies through the use of hot channel factors. After the plates are rolled and before forming into their final involute curvature, the fuel homogeneity in each HFIR fuel plate is inspected by a scanning X-ray transmission device to ensure that only fuel plates with acceptable fuel homogeneity are used in HFIR fuel elements. This machine scans the entire surface of the plate along a continuous raster pattern, measuring the transmission of a 55-KeV X-ray beam collimated into a 2-mm-diameter spot along approximately 50 adjacent axial "tracks" extending the length of the plate. The transmitted beam intensity is continuously measured by a sodium iodide scintillator crystal and photomultiplier.

This inspection system was developed in the early 1960s and although the components have been upgraded from time to time, until recently the equipment still employed the original analog-based methods of processing and interpreting the X-ray transmission signal. This approach involved the use of two signals that were termed (1) the "spot" signal, which is obtained from the instantaneous photomultiplier current with no additional filtering, and (2) the "average" signal, which is obtained from the spot signal by filtering with a first-order lag circuit having a time constant equivalent to 17 mm (0.667 in.) scanner travel. To evaluate the plate homogeneity, the spot signal is continuously compared with an upper limit, and plates with excessive local fuel overloads are rejected. Similarly, the averaged (filtered) signal is compared with upper and lower limits to reject plates with fuel loadings outside the tolerance band when axially averaged over lengths of 17 mm or greater.

The acceptance limits for track-average and local fuel density are obtained by the scanner from X-ray attenuation standards, made from carefully machined aluminum blocks that are positioned on the fuel plate at either end and scanned by the machine before inspection of each fueled track. The signal voltages corresponding to transmission through these standards are held as inputs to comparator circuits throughout the scan of each fueled track, and a comparator output is produced if the spot or average fuel density exceeds the acceptance band. When a region of a fuel plate is found that exceeds these acceptance values, it is marked by colored ink on a companion X-Y plot synchronized to follow the motion of the X-ray scanner table so that the location of any homogeneity defects can be determined. Plates that pass this inspection are ensured of having no "hot spots" with local fuel densities exceeding the spot attenuation standard and no "hot tracks" of length 17 mm or greater, which exceed the average standard.

In the design fuel thermal analyses, various hot-spot and hot-channel effects are combined to calculate the thermal performance of a worst-case fuel element at its most limiting point. In this analysis, local fuel overloads and track-averaged fuel overloads affect the fuel performance in the following ways:

1. Local coolant channel thickness. The local coolant channel thickness is reduced because of differential fuel plate bowing caused by ununiform fuel distribution between the top and bottom halves of the plate.

2. Subchannel coolant temperature. The coolant temperature rise along any subchannel is increased as a result of the assumed presence of axial track-averaged fuel overloads (hot tracks) equal to the "average" acceptance limit.

3. Local heat flux. The heat flux at any point on a fuel plate is subject to local peaking caused by an assumed segregation ("spot") defect equal to the local segregation acceptance limit.

The first two effects mentioned are controlled through the track average fuel density tolerance, whereas the third effect is controlled through the maximum allowed "spot" fuel density. With the present specification limits of maximum-average fuel density deviation of ±12% and maximum local fuel density deviation of +27% of nominal, these three effects together account for about 30 MW of core overpower margin.

III. IMPROVED HOMOGENEITY DATA COLLECTION AND UTILIZATION
Recently, one of two X-ray scanner systems used for HFIR fuel homogeneity inspection was converted by replacing the analog signal processing components with an analog-to-digital converter and a digital computer-based processing and storage system and installing a digital-motion control system for the table drive. The digital processing system was initially programmed to emulate the characteristics of the old analog components for the purpose of verifying the operation of the digital scanner by comparison with the remaining unmodified system and to conform with the existing fuel homogeneity specifications, which were based on the characteristics of the original analog scanner design. However, because of the greater flexibility of the digital equipment, the converted equipment has the potential to provide significant reductions in the hot channel factors associated with fuel homogeneity. Besides producing a permanent record of the as-built spatial fuel distribution within each plate inspected, the digital scanner has capabilities that exceed the original analog design in five areas: 1) the digital equipment can compute multiple axial averages using a variety of averaging lengths and algorithms, whereas the analog equipment was limited to a single exponentially weighted average; 2) the digital equipment can use spatially dependent acceptance bands to evaluate the fuel density at various locations on a plate, whereas the analog equipment was limited to a single set of acceptance criteria for each axial track, established by scanning the attenuation standard at the beginning of the track; 3) the digital equipment can, if desired, evaluate an entire two-dimensional fuel plate as a whole, whereas the analog equipment was limited to analyzing one track at a time; 4) the digital scanner can use any desired algorithms to evaluate the fuel density record, and it is not limited to a simple comparison of local or exponentially averaged X-ray transmission data against an acceptance standard; and 5) the digital scanner produces an accurate quantitative record of the fuel density distribution, whereas quantitative data from the analog scanner are difficult to obtain and subject to considerable noise.

The first two advantages stated can be exploited to create an inspection algorithm that more closely matches the HFIR fuel plate thermal performance requirements. Specifically, two changes are planned that emphasize the critical nature of the bottom end of the HFIR fuel plates and that were beyond the capability of the original design analog inspection equipment. First, the track average over the entire 0.5-m (20-in.) fuel length will be computed rather than the 17-mm average used at present, and the tolerance band will be reduced. Because averages taken over the larger interval are closer to nominal than with the shorter averaging length currently used, it is expected that the hot channel factor for coolant outlet temperature uncertainty can be reduced to around 1.04 (from 1.12) with no increase in fuel rejects. Secondly, the local fuel "spot" density limit will be varied with axial position so as to reduce the allowance for local fuel overloads at the critical lower end of the fuel plate, while accepting somewhat larger deviations in less important regions.

Preliminary core thermal analyses indicate that the reduction in the track-average factor applied at the core outlet, combined with a reduction from 27% to around 20% in local fuel overload factor at the same location, can increase the thermal margin to hot-spot burnout by about 10 to 14 MW without a significant impact on manufacturing yield.

IV. PRELIMINARY RESULTS FROM USE OF DIGITAL SCANNER

After conversion of one X-ray scanner to acquire and process data digitally, a number of HFIR fuel plates were inspected with both the upgraded scanner and the remaining analog scanner to compare results. For this comparison, the digital scanner was programmed to reject fuel plates with the same homogeneity tolerances as used in the analog equipment, However, the track average inspection was initially performed with a moving average algorithm, using an averaging length of about 12 mm (0.5 in.). It was found that with this algorithm, the digital scanner produced consistently more rejections for track-averaged fuel density than the analog scanner. The track-average fuel density calculation has subsequently been changed to implement the same exponentially weighted average as used in the analog equipment, and results from the two scanners are now in good agreement. Although this temporary change in digital scanner programming was a convenient method for verifying its operation by comparison with the remaining unmodified scanner, it is planned in the future to investigate other averaging algorithms that may have characteristics closer to those assumed in the relevant thermal analyses, including averages over multiple averaging lengths.
After the adjustment of inspection algorithms, over 100 additional HFIR plates that had been rejected for homogeneity defects were inspected on both the digital and analog machines to compare results. This comparison showed that in a great majority of cases, both machines agreed on identifying a plate as either acceptable or unacceptable. Where a homogeneity defect was found by one machine and not by the other, the quantitative digital scanner record was examined. In general, the local peak or average fuel density was found to be very close to the rejection threshold so that typical variations in scanner calibration and performance might cause either acceptance or rejection of the plate. After a statistical evaluation of these results, it was concluded that the digital scanner as now programmed produces results consistent with the analog machine and with the fuel specifications and has some indications of a slightly greater sensitivity than the analog scanner. On this basis, the digital scanner was accepted for routine use in the inspection of production HFIR fuel plates according to the current fuel homogeneity specifications (which were originally formulated to match the analog scanner capabilities). Current plans include upgrading the second homogeneity scanner to digital operation.

During initial testing of the digital homogeneity scanner, results of fuel homogeneity inspections on 450 fuel plates were stored on high-capacity media and sent to ORNL for evaluation. This provides the first large data set of quantitative as-built fuel homogeneity information to become available for detailed examination. Preliminary thermal studies have shown the type of changes in homogeneity specifications that can be exploited to improve the core thermal performance (such as those mentioned in Section III), and the data base of as-built information is being used to adjust how best to adjust the specifications to obtain improved performance without a significant impact on the yield of acceptable fuel plates.

V. CONCLUSION

One of two HFIR fuel X-ray scanners was modified to allow digital acquisition, processing, and storage of fuel homogeneity data, and it has already provided a valuable data base of quantitative as-built fuel homogeneity information. In addition, the increased capabilities of the digital homogeneity inspection system can be exploited to obtain improved core thermal performance by tailoring the homogeneity inspection criteria more appropriately to the thermal characteristics of the core. This process generally involves using multiple and longer averaging lengths for "track average" effects and spatially varying acceptance bands for local fuel overloads that emphasize the critical regions of the fuel plate. Work on developing improved fuel homogeneity specifications and corresponding inspection algorithms is under way at ORNL, with the objective of attaining increased fuel power capability without a significant impact on fuel manufacturing yield.

REFERENCES

Figure 1. HFIR Core.