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Pacific Northwest National Laboratory
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A Review of Proposed Upgrades to the High Flux Isotope Reactor and Potential Impacts to Reactor Vessel Integrity

F. A. Simonen

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Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RL01830

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Summary

The High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory (ORNL) was scheduled in October 2000 to implement design upgrades that include the enlargement of the HB-2 and HB-4 beam tubes. Higher dose rates and higher radiation embrittlement rates were predicted for the two beam-tube nozzles and surrounding vessel areas. ORNL had performed calculations for the upgraded design to show that vessel integrity would be maintained at acceptable levels. Pacific Northwest National Laboratory (PNNL) was requested by the U.S. Department of Energy Headquarters (DOE/HQ) to perform an independent peer review of the ORNL evaluations. PNNL concluded that the calculated probabilities of failure for the HFIR vessel during hydrostatic tests and for operational conditions as estimated by ORNL are an acceptable basis for selecting pressures and test intervals for hydrostatic tests and for justifying continued operation of the vessel. While there were some uncertainties in the embrittlement predictions, the ongoing efforts at ORNL to measure fluence levels at critical locations of the vessel wall and to test materials from surveillance capsules should be effective in dealing with embrittlement uncertainties. It was recommended that ORNL continue to update their fracture mechanics calculations to reflect methods and data from ongoing research for commercial nuclear power plants. Such programs should provide improved data for vessel fracture mechanics calculations.

Contents

Introduction

The High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory (ORNL) was scheduled in October 2000 to implement design upgrades that include the enlargement of the HB-2 and HB-4 beam tubes. Enlargement of the beam tubes gives higher dose rates and thus higher radiation embrittlement rates for the two beam-tube nozzles and surrounding vessel areas. ORNL has performed probabilistic fracture mechanics calculations for the upgraded design to show that vessel integrity is maintained at acceptable levels. Justification for continued operation is based in large measure on periodic hydrostatic pressure tests of the vessel. The technical bases for the hydrostatic test program are described in ORNL/TM-1999/181/R1 (Cheverton and Bryson 2000). Pacific Northwest National Laboratory (PNNL) was requested by the U.S. Department of Energy Headquarters (DOE/HQ) to perform an independent peer review of this ORNL document, and of other ORNL documents that support the conclusions of the ORNL evaluation. The PNNL review was to complement a DOE/HQ evaluation described in USQD-D-HFIR-1999-007. The present report describes the scope, conclusions, and recommendations of the PNNL review.

The proposed HFIR upgrades involve the replacement of existing beam tubes with beam tubes of larger diameter. Installation of the new tubes requires no structural changes to the reactor pressure vessel, because the new tubes are designed to bolt onto the existing vessel flanges. However, the larger diameter tubes result in significantly greater radiation doses to the vessel wall and, in particular, to the highly stressed corner region of the nozzle penetrations to the vessel. Irradiation-induced embrittlement at the critical locations will increase more rapidly than for the existing smaller diameter beam tubes. ORNL staff have performed extensive evaluations of the structural integrity of the HFIR vessel to ensure the continued safe operation of the vessel and to establish if the modified HFIR vessel can achieve its life extension goal to 50 effective full power years (EFPY) of operation. The PNNL review addresses the methods and conclusions of the ORNL evaluations.

Scope of Review

Three senior staff from PNNL performed the peer review, each from the standpoints of their specialized technical knowledge and experience. Dr. F. A. Simonen led the review and addressed issues related to fracture mechanics calculations and failure probability predictions. Drs. F. A. Garner and L. R. Greenwood assisted by reviewing issues related to radiation damage to materials and flux calculations/dosimetry, respectively.

Components of concern to the HFIR upgrades were the reactor pressure vessel and the beam tubes. From the initial review of DCM HFIR-197M-4 it was concluded that the review should be most heavily focused on the pressure vessel and the effects of the enlarged beam tube on radiation-induced embrittlement of the vessel (the nozzle corner regions in particular). This focus was driven in part by the potentially significant consequences of a vessel failure and also by the life limiting implications to HFIR of the vessel. The vessel (unlike the beam tube) is not considered a replaceable component.

The primary source of information for the technical bases for the HFIR upgrades was the document ORNL/TM-13698 (Cheverton and Dickson 1998). This ORNL report was supplemented with documentation on the proposed hydrostatic test and on pressure temperature limits provided by ORNL/TM-1999/181/R1 (Cheverton and Bryson 2000) and with documentation for the neutron and gamma fluxes as provided by ORNL/TM-13693 (Blakeman 2000). Other ORNL documents were made available to PNNL as listed in the reference section of the present report. In addition to the written documents, PNNL staff prepared questions for ORNL staff. These questions were to gain clarification and more details regarding the ORNL studies. The written questions formed the basis for teleconferences that included PNNL and ORNL staff along with staff from DOE/HQ.

Probabilistic Fracture Mechanics Methodology

The ORNL methodology used to calculate failure probabilities for the HFIR vessel follows the approach that was developed and approved during the mid 1980s by the U.S. Nuclear Regulatory Commission (NRC) to perform probabilistic fracture mechanics calculations for pressurized water reactor (PWR) vessels for conditions of pressurized thermal shock (PTS) transients. Since that time the NRC has been funding continuing research (including studies at ORNL) to advance the 1980s technology. NRC is currently in the process of using the advances in knowledge to update their regulatory guidance for evaluations of PTS risks. Many changes to the computational methodology and to inputs to the calculations are expected. These changes will result in less conservative and more realistic predictions of vessel failure probabilities. The current HFIR calculations by ORNL are based on the currently approved NRC methods, and as such do not exploit potentially less conservative approaches that are supported by the results of ongoing research programs.

Part of the PNNL review was to identify areas where the ORNL calculations are conservative or possibly unconservative, and to estimate the extent to which the calculations may overstate failure probabilities for the HFIR vessel. The main focus of PNNL evaluations as described in the next section was on issues related to the number and sizes of flaws in vessel welds and plate material because (1) flaw-related inputs were identified by ORNL as the greatest source of uncertainty in their calculations, and (2) PNNL research for NRC has resulted in new data that greatly reduces the level of uncertainty in flaw related inputs.

Key assumptions and inputs to the ORNL fracture mechanics calculations are addressed briefly below.

Simulation of a Sequence of Hydrostatic Tests and Potential Over Pressure Events – PNNL identified concerns with the method used to generate Figures 5 and 6 in ORNL/TM-13698. The ORNL computer runs for these calculations simulated only one hydrostatic test at selected times over the time period of 22 to 55 EFPY. Failure probabilities for a sequence of hydrostatic tests were then evaluated by manipulating the results of these computer runs rather than by actually applying the fracture mechanics code to numerically simulate the sequence of pressure loadings. This ORNL approach greatly simplified the calculations, was intuitively reasonable, but was not supported by rigorous derivations. Therefore, PNNL performed test calculations with the VISA-II code to compare results from the ORNL methodology with results from more detailed simulations of a time sequence of pressure loadings for conditions of decreasing fracture toughness as a function of time. Numerical results from the two alternative methodologies were found to give identical results within the numerical truncation error of the Monte Carlo method.

Flaw Aspect Ratio – The ORNL calculations assumed that all flaws had an aspect ration of 6:1 (the ratio of flaw length to flaw through-wall depth dimension). Some flaws found by PNNL in the PVRUF and Shoreham vessels exceeded this 6:1 ratio, but most flaws (particularly the larger flaws) were less than the 6:1 ratio. On this basis, the results of the ORNL calculations should be conservative with respect to inputs for flaw aspect ratios.

Estimation of Fracture Toughness – The ORNL work used an approach common to the ASME Section XI Code and current NRC guidance for a reference toughness curve and the concept of the RTNDT temperature. Current developments (the master curve approach) are expected to lead eventually to ASME and NRC adoption of an improved description of the temperature dependence of the fracture toughness of ferritic steels. This approach also addresses toughness changes from radiation damage that causes a shift in RTNDT. Recent research shows that the current ORNL approach is conservative, which means that adoption of the master curve approach should result in lower values of calculated failure probabilities.

Residual Stresses – The ORNL calculations accounted for the relatively modest levels of residual stresses that are expected to remain at weld locations even after stress relief heat treatments are performed. The assigned levels of these residual stresses at welds are consistent with available data. In contrast, ORNL made no allowance for residual stresses that may exist in base metal regions. Although PNNL would expect residual stresses for base metal to be less than for welds, the ORNL reports do not justify the assumption of zero residual stresses. An acceptable justification could be a citation of relevant data that shows inner surface stresses to be very small or compressive in nature. Alternatively, ORNL could cite NRC guidance for PTS evaluations.

Stress and Fracture Mechanics Solutions – PNNL reviewed the stress levels reported in Tables 1 through 5 of ORNL/TM-13698. These stresses are mainly due to internal pressures with some contribution from residual stresses and clad thermal expansion stresses. Independent stress and fracture mechanics calculations to validate the ORNL results were beyond the scope of the PNNL review. However, the numbers cited in the ORNL report are consistent with PNNL hand calculations. In particular, the stress concentration of about 3.0 for nozzle corner regions is consistent with expected values.

Flaws at Nozzle Corner Locations – The ORNL calculations assumed that corners of the nozzle forgings are just as likely to have flaws as the plate material of the vessel shell. Lacking detailed knowledge of the nozzle, this assumption is a reasonable basis for fracture mechanics calculations. However, much could be gained by detailed consideration of the forging process used to manufacture the nozzles and the inspection methods used to examine the forgings both before and after machining the nozzles to final shape. It is expected that the fabrication processes have been optimized to ensure that any flaws, if present, are not at the critical locations or at orientations to interact with the elevated stress levels that are known to be present at nozzle corners. Subject to future discussions with experts on vessel fabrication, it is therefore reasonable to bound occurrence rates for nozzle corner flaws with data on through-thickness flaws in rolled plate material used to fabricate vessel shells.

Initial Toughness of Vessel Materials – The initial toughness levels of the plates, forgings, and welds were based on tests of samples taken from the actual materials used in the construction of HFIR. The main concern was with the values of RTNDT that directly affect the amount of radiation damage that can be tolerated. For the critical nozzle forgings that have the highest fluence exposures, PNNL noted very favorable properties, with RTNDT values listed by ORNL as low as -110°F. The use of these values is well justified because ORNL has actual properties of the forging materials used for the HFIR vessel.

Predictions of Radiation Degraded Toughness – The predictions of current and future levels of embrittlement are based on data from exposure within the HFIR reactor of archival materials from construction of the HFIR vessel. The exposed materials have been installed in surveillance capsules and then subjected to actual HFIR environments. The data are considered to provide an excellent basis to estimate embrittlement levels. ORNL has also shown that the HFIR data are consistent with other published data on embrittlement at relatively low temperatures. Furthermore, trends from HFIR data have been extensively discussed within the technical community of experts on radiation damage, and have as such been subjected to a high level of peer review.

Spatial Variations in Stress and Fluence – The ORNL fracture mechanics calculations have accounted for the large variations in applied stress and fluence (neutron and gamma) levels. The calculations have taken a conservative approach of basing inputs for each computational subregion on the peak stress and fluence for any location within the subregion. The locations of these peak levels of fluence and stress are conservatively assumed to coincide.

Effect of Cladding – The ORNL fracture mechanics calculations have included the adverse effects of differential thermal expansion of stainless steel cladding material relative to the underlying ferritic steel of the vessel wall. The methods used to account for these clad-related stresses are consistent with the approaches recommended in NRC guidance for fracture mechanics analyses of LWR vessels.

External Loads to Vessel Flanges – PNNL addressed the possible stresses in the HFIR vessel associated with attachment of the beam tubes to the vessel flanges. Such loadings and stresses were not discussed in any of the documents submitted to PNNL for review. This concern was discussed with ORNL staff by teleconference. Possible sources of stress were bolt-up loads from attachment of the beam tubes to the flanges, thermal expansion loads, and vibrational loads due to flow-induced vibrations. PNNL was informed that such loads have been considered in past evaluations of HFIR and found to be insignificant compared to the pressure loadings to the vessel. The beam tubes are relatively light and compliant compared to the vessel wall, and thus are not capable of imposing substantial loadings at the attachment points to the vessel. Flow velocities within the outer part of the vessel occupied by the beam tubes are relatively low. Thus, flow-induced vibrations are not of concern. The reactor operates at relatively low temperatures with only about a 40°F range of temperature between cold and hot conditions. This results in low levels of thermal expansion stresses.

Flaw Densities and Size Distributions

ORNL has properly identified that the greatest uncertainty in their methodology for predicting failure probabilities is related to the inputs for the numbers and sizes of flaws in various regions of the vessel. The ORNL calculations have allowed for these uncertainties by introducing two significant conservatisms into the calculations:

(1) All flaws are assumed to be located at the vessel inner surface, although most (if not all) actual flaws will be buried within the vessel wall, and are thus far removed from the critical inner surface locations.

(2) Based on prior uncertainty analyses, ORNL has increased the number of flaws by a factor of 45 to correlate their best estimate calculations to correspond to mean values of failure probabilities from the uncertainty analyses.

The PNNL evaluation presented below shows that recent data on vessel flaws could be applied to demonstrate that these two measures are more than adequate to allow for the uncertainties of concern.

Figure 1 compares the ORNL estimates (based on the current NRC-approved methodology) for the number and sizes of flaws in the HFIR vessel with the number and sizes of observed flaws that have been found by PNNL by examinations of vessel welds and plate material. The studies by PNNL were part of NRC-funded research (Doctor et al. 1999) that made use of both nondestructive and destructive examination methods.

Data from the PVRUF and Shoreham vessels show that flaw densities in weld metal are much greater than the 1.0 flaw per cubic meter (best estimate) value of the current NRC methodology. Even with the factor of 45 to account for the uncertainty in the flaw density, the values used for the HFIR evaluation are still unconservative. On the other hand, the PNNL vessel examinations show that weld flaws are distributed uniformly through the thickness of the vessel wall, rather than at the inner surface of the vessel (worst-case location). The effect of flaw location is shown here to more than offset the underestimation of flaw density.

The observed flaw density for base metal is about 1.0 flaw per cubic meter compared to the 0.1 flaws per cubic meter value of the current NRC methodology. The factor of 45 used by ORNL for HFIR calculations is more than adequate to bound the data from the PNNL studies. The PNNL studies for base metal have focused exclusively on flaws with radial (through-wall) extent rather than benign flaws that

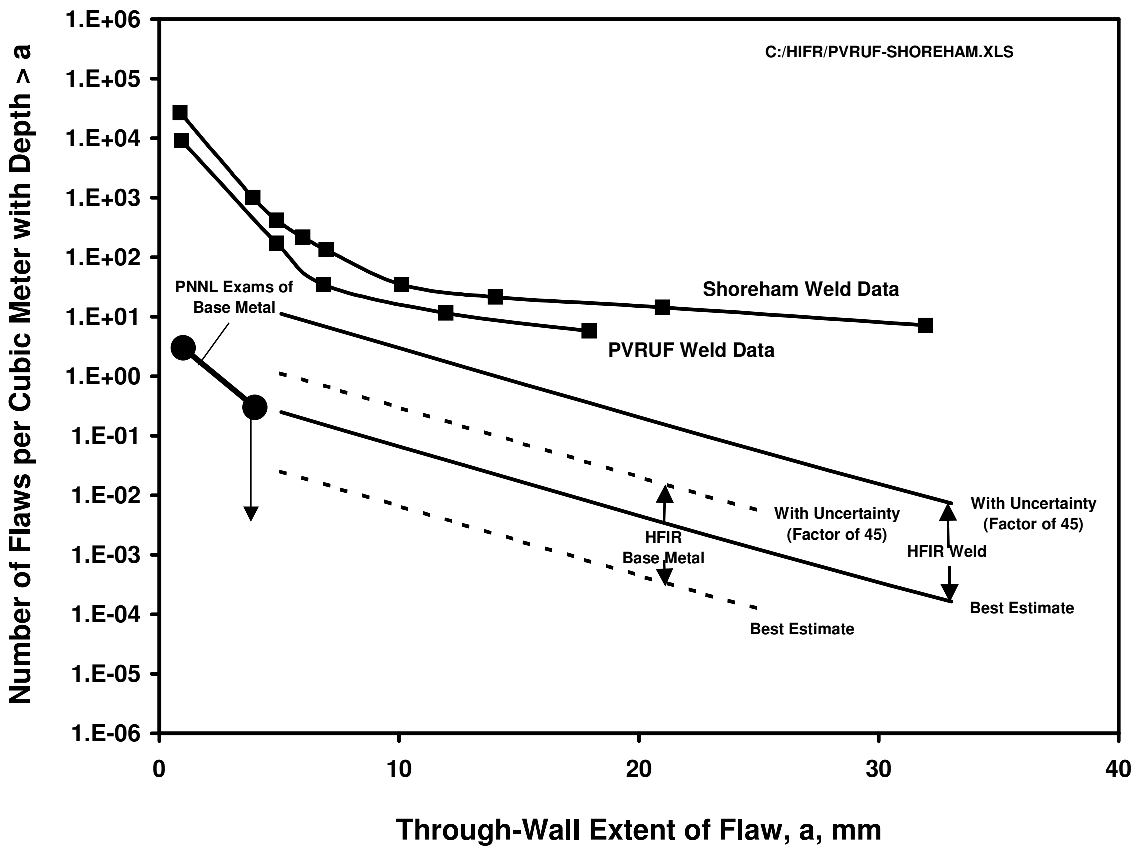

Figure 1. Flaw Frequencies as Estimated for HFIR Vessel Compared to Data From Recent NRC Research Studies at PNNL.

are parallel to the vessel surface. In the examinations to date, about one cubic meter of plate material has been examined. Only one flaw (about 1-2 mm in size) has been detected (shown as a data point on Figure 1). The other data point conservatively assumes that examinations of a greater volume of material would detect about 0.3 flaws per cubic meter with a depth of 4 mm. Flaws of 4 mm depth can be detected by PNNL's ultrasonic method with a high level of reliability.

As part of the current review, sensitivity calculations were performed with the VISA-II probabilistic fracture mechanics code (Simonen et al. 1986). Results for axial welds and for the vessel shell (base metal) are shown in Figures 2 and 3, respectively. The two contrasting cases of interest are

(1) HFIR flaw distribution with a factor of 45 applied to flaw density and with all flaws located at the inner vessel surface

(2) the PVRUF flaw distribution with no factor applied to flaw density and with the flaws distributed uniformly through the thickness of the vessel wall.

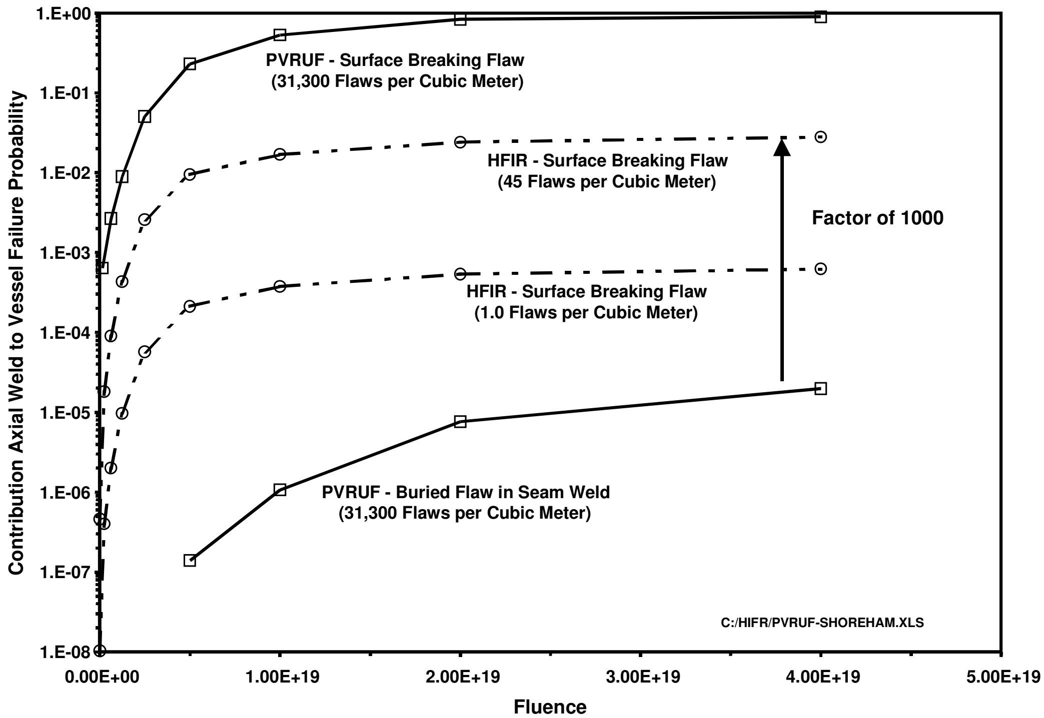

Figure 2. Calculated Failure Probabilities for Axial Weld of HFIR Vessel Showing Effect of Conservative Assumptions for Flaw Related Inputs.

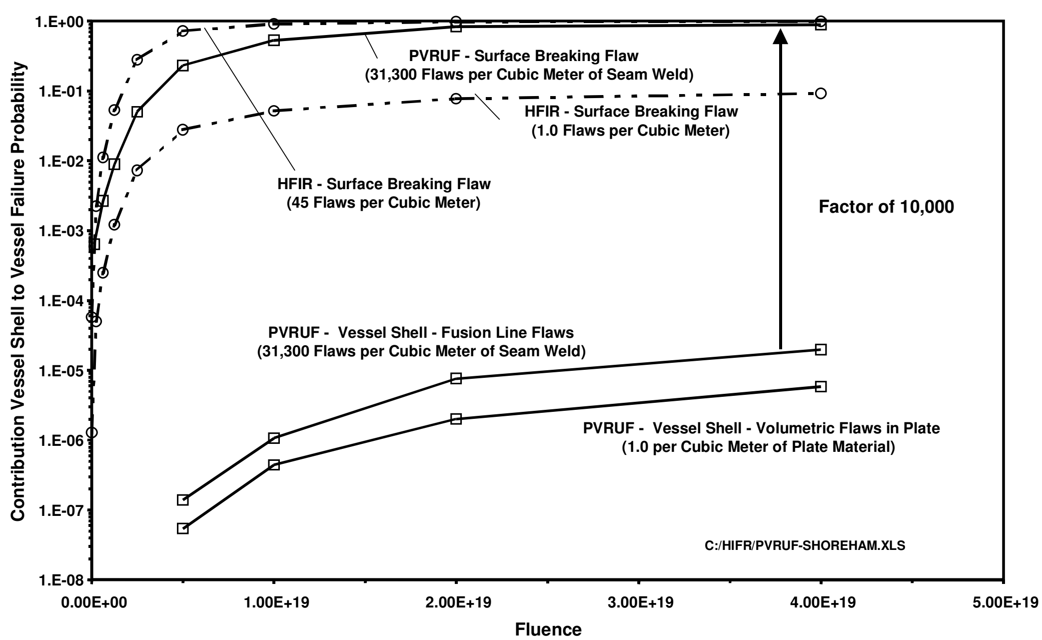

Figure 3. Calculated Failure Probabilities for Vessel Shell of HFIR Vessel Showing Effect of Conservative Assumptions for Flaw Related Inputs.

The calculations show that placing the flaws at the inner surface is a very conservative assumption, which by itself more than offsets the uncertainties associated with the ORNL inputs for flaw densities.

The sensitivity calculations by PNNL indicate the following:

(1) Figure 2 shows that the HFIR evaluations may overestimate the failure probabilities for welds by a factor of 1,000 compared to PNNL predictions made on the basis of the more realistic data for flaw densities and size distributions.

(2) Figure 3 indicates that the HFIR evaluations may overestimate the failure probabilities for the vessel shell by a factor of 10,000 compared to PNNL predictions made on the basis of the more realistic data for flaw densities and size distributions.

In conclusion, the ORNL probabilistic fracture mechanics model is very conservative with respect to the assumptions and inputs for flaws in both the welds and base metal of the HFIR vessel.

Integrity of Beam Tube

In addition to issues related to vessel integrity, the document USQD-D-HFIR-1999-007 addresses the structural integrity and the consequences of failure of the HB-2 and HB-4 beam tubes. No other documents were made available for review by PNNL. The cited document presented only a summary of issues related to the beam tubes and concluded that the design and construction of the larger diameter beam tubes followed the same approach as used for the existing beam tubes. The wall thickness was increased in accordance with the larger diameter to maintain the stresses at the same levels as for the smaller diameter tubes. For this reason, no new degradation mechanisms or failure modes were identified by ORNL for the modified beam tubes. It was also noted that the tubes are hydrostatically tested at 1.5 times their design pressure of 1,000 psig before they are installed, which provides assurance of their integrity and ability to sustain the expected service loads. Given no new identified issues with the beam tubes, the focus of PNNL's review was directed to concerns with the reactor vessel and the effect of increased radiation levels on structural failure probabilities.

Probabilistic Criteria for Hydrostatic Tests

The ORNL conclusions regarding the ability to safely operate HFIR to 55 EFPY and also the bases for the recommend hydrostatic tests are founded on probabilistic fracture mechanic calculations along with criteria for acceptable levels of failure probabilities. While the detailed equations for the probabilistic criteria will not be cited here, the following discussion summarizes the ORNL approach.

Hydrostatic tests are performed on a periodic basis with the pressures being sufficiently high to ensure that any incipient failures will occur during the hydrostatic tests rather than during the subsequent periods of operation. It is assumed that fuel will be removed from the reactor during hydrostatic tests to minimize the consequences of a failure during the test. The hydrostatic tests are performed at pressures and at test intervals determined by calculations of relative probabilities for vessel failure during the test versus failure probabilities for operational and accident conditions. With the use of relative probabilities, this aspect of the probabilistic criteria is relatively insensitive to uncertainties in the fracture mechanics model and inputs to the model.

A second aspect of the probabilistic criteria is expressed in terms of absolute rather than relative probabilities, and is sensitive to uncertainties in assumptions and inputs to the probabilistic model. The ORNL criteria states that the probability of vessel failure during any given hydrostatic test should be less than 1×10^{-5} failures per test. The adoption of this failure probability as being acceptable is a judgment call that must be agreed upon by the various stakeholders in the HFIR reactor. The 1×10^{-5} criterion was outside the scope of PNNL review. PNNL would only note that the 1×10^{-5} number is about the same as the failure frequency (failures per year) that is stated in the NRC guidance for PWR/PTS evaluations. These evaluations address vessel failures caused by events that occur during full power operation, whereas the hydrostatic tests of HFIR are performed with all fuel removed from the reactor. This means that the consequences of vessel failure will be much less for HFIR than for the PWR/PTS condition. Accordingly, this review concludes that the 1×10^{-5} criteria for HFIR is more conservative than NRC guidance for LWR power reactors.

The present review has identified conservatisms in both the methods and inputs to the calculations of vessel failure probabilities. Calculations by PNNL have specifically addressed the conservatisms associated with inputs for flaws in the HFIR vessel. As noted above, it is estimated that the ORNL calculations predict failure probabilities that are a factor of 1000 greater than would be predicted using results of recent research on flaw occurrence rates. On this basis, PNNL estimates that the probability of vessel failure during a hydrostatic test is more like 1×10^{-8} rather than 1×10^{-5} as estimated by ORNL.

Probabilistic Criteria for Pressure Temperature Limits

ORNL/TM-1999/181/R1 presents the results of calculations and the supporting technical bases for the pressure temperature limits that will govern the future operation of HFIR. Two P/T curves are developed. The more conservative curve (limiting conditions for operation or LCO) is based on the assumption that a hydrostatic test is performed at a frequency of only once per six EFPY. The other curve (pressure safety limit curve or PSL) is based on the expected frequency of hydrostatic tests (nominally once per 3 EFPY). The ORNL documents did not explain how these two limits would be applied to govern the operation of HFIR. One possibility is that the operating procedures at HFIR may be based on the more conservative LCO curve for P/T limits, whereas the PSL curve may be used to define set points for alarms and pressure control devices or to impose enforcement of actions if safety violations occur.

PNNL reviewed the basis of the P/T curves of ORNL/TM-1999/181/R1 and concluded that the recommendations provide an acceptable basis for operation of HFIR. The development of these curves is based on a number of stated and unstated conservatisms as follows:

(1) The ORNL probabilistic fracture mechanics model has conservative assumptions regarding the flaws in the various regions of the vessel; the conservative assumptions are estimated to increase the calculated failure probabilities by a factor of 1000 or more.

(2) The pressure temperature limits are based on the embrittlement levels that are predicted to exist for the end-of-life conditions at 50 EFPY; this imposes conservative limits on HFIR operation for the present embrittled condition of the vessel.

(3) The use of the LCO limits allows for additional uncertainties in the fracture mechanics calculations by imposing a P/T curve based on a six EFPY interval for hydrostatic tests rather than a more realistic interval of three EFPY.

It is concluded that, for the next few years, the proposed P/T limits will provide a very conservative basis for operating HFIR. For later operating periods, there will be additional dosimetry data, material property measurements from ongoing surveillance programs, and enhancements to the fracture mechanics calculations. It will then be possible to make improved evaluations of P/T limits and to modify HFIR operating practices as needed.

Radiation Damage to the HFIR Vessel

An important part of the PNNL review focused on radiation damage aspects of the HFIR reports. Dr. F. A. Garner, an internationally recognized expert in this field of research, performed this review.

The general assessment of the ORNL reports was very positive. One of the most significant concerns was that the ORNL reports address directly and adequately the issue that caused HFIR to suspend operation some years ago. This was the unanticipated “acceleration” of embrittlement of the pressure vessel. As finally resolved, it was found that the apparent acceleration occurred not because the damage correlation was inadequate or incorrect, but that the damage levels used as input to the correlation were low by a factor of 5 to 6. This underestimate arose because it was not originally recognized that the unique features of HFIR construction led to a damage dose rate from gamma rays that was much greater than that from neutrons. In most reactors this predominance of gamma dose does not occur and is usually negligible. This was especially true for the test volumes used to generate the correlation. The only lingering question was the possibility that there might be a dependence of embrittlement on dpa rate, either between the correlation database and the pressure vessel, or between the current beam environment and the modified environment. The success in resolving the original apparent acceleration appeared to put this issue to rest.

The modification of the beam tubes not only increases the total dpa, but also allows the possibility of significant shifts in the gamma/neutron dose ratio. Therefore, it is important to address the issue head-on. It appears that ORNL has risen to the challenge and adequately analyzed the modified environment and its consequences on vessel performance. In addition, the radiation transport results also appear to be reasonable. However, short of an extended effort to address details of the transport code and its input, this review will need to assume that the calculations were done correctly.

It is important to note that two assumptions on radiation response to the calculated dpa levels drive the analysis.

(1) The choice of the Remec correlation over that of Cheverton, Dickson, and Nanstad is significant. It appears that the former was chosen because it was considered “excessively conservative” and “the linear extrapolation is not satisfactory” for predicted embrittlement levels to 50 EFPY for the enhanced radiation levels associated with the enlarged beam tubes. No adequate defense of this statement is given and, assuming the other correlation as being correct, might significantly change the conclusion. It is recommended that the choice of the Remec correlation should be better defended.

(2) It is assumed that dose rate effects can be ignored in the analysis. Since the new environment moves closer to the conditions embodied in the Remec correlation, this is judged to be an adequate and safe assumption.

In conclusion, PNNL believes that radiation damage levels have been appropriately estimated. The uncertainties as identified above are concerns that do not have the potential to impact the near-term safety of operability of HFIR. The existing dosimetry and surveillance programs at HFIR can be relied upon to address longer-term concerns.

Fluence and Dosimetry

The reports prepared by ORNL present a thorough and comprehensive summary of the neutron flux, gamma flux, and radiation damage calculations. These calculations are required to determine the impact of the proposed HFIR upgrades on the pressure vessel and other structural components. Although a detailed review of the accuracy of the calculated fluxes and damage rates was not practical, the ORNL calculations appear to be well documented and to include sufficient internal consistency checks to give us some confidence in their validity. The proposed, ongoing surveillance program will validate the calculations in short order once operations are resumed. Hence, it is important to point out that there is no real concern about the longer-term safety of the upgraded HFIR operations because periodic surveillance specimens will directly determine the neutron and gamma doses as well as provide a direct measure of the nil ductility at key locations. The proposed neutron, gamma, and materials surveillance program for future operations appears to be quite thorough. These future measurements will ultimately determine the safe operating lifetime of the upgraded HFIR facility, rather than the present calculations.

Nevertheless, it is important that the present evaluations be done correctly in order to avoid a premature shutdown of HFIR due to a significant miscalculation or underestimation of the radiation damage effects.

The prior dosimetry measurements conducted for HFIR by Remec et al. (1994) provide a solid basis for validating and normalizing the neutron and gamma flux calculations. This renormalization appears to be appropriate at locations where previous measurements have been performed when the locations are well removed from the proposed beam tube modifications. However, in reviewing the renormalization process, there are two areas of concern that should be addressed:

(1) The normalization factors vary significantly from location to location. Table E.1 in ORNL/TM-13698 shows that the neutron factor varies from 0.56 to 1.0 while the gamma factor varies from 1.09 to 0.54. Hence, it is not always clear what normalization factors were used (or should be used) for the new beam tube locations. This point needs some additional discussion in the ORNL reports to clarify exactly how the normalizations are being estimated and applied for new geometries.

(2) Because of the significant variation in the normalization factors, it is not clear that we can confidently predict the proper normalization of the neutron and gamma fluxes at the critical new beam tube locations, since the reasons for the differences between the measurements and calculations may not be sufficiently understood. Some additional discussion is needed on this point. It is critically important that we assume a sufficiently conservative estimate of these factors to ensure that we are not significantly underestimating the radiation damage at the critical new locations.

Again, it should be noted that the ongoing surveillance program will provide data to correct and update the calculations once HFIR operations are resumed.

Conclusions

It is concluded that the calculated probabilities of failure for the HFIR vessel during hydrostatic tests and for operational conditions as estimated by ORNL are an acceptable basis for selecting pressures and test intervals for hydrostatic tests and for justifying continued operation of the vessel. It is expected that future calculations based on improved fracture mechanics models and inputs to these models will give significantly lower probabilities of failure compared to those now calculated by ORNL.

The PNNL review concludes that ORNL has a well-founded technical basis for predicting future levels of embrittlement of the materials in the HFIR vessel. While there are some uncertainties in the embrittlement predictions, the ongoing efforts at ORNL to measure fluence levels at critical locations of the vessel wall and to test materials from surveillance capsules should be effective in dealing with embrittlement uncertainties. Unfavorable trends in vessel embrittlement would become known on a timely basis such that corrective actions could be taken to minimize risks of vessel failure.

In contrast, uncertainties in the fracture mechanics calculations are not addressed by the dosimetry and surveillance programs for HFIR materials. Of greatest concern are the inputs to the probabilistic fracture mechanics model related to flaw densities and flaw size distributions. There are at present no ongoing programs to obtain better information on the flaws that may exist at the nozzles and other critical locations of the HFIR vessel. It is recommended that ORNL continue to update their fracture mechanics calculations to reflect methods and data from ongoing research for commercial nuclear power plants. Such programs should provide improved data for vessel fracture mechanics calculations. The specific concerns with nozzle corner flaws will need to be addressed specifically for HFIR, because nozzle corner flaws are not a critical issue or the focus of research for LWR vessels.

A number of recommendations are given in the following section regarding activities that will further minimize the probability of failure for the HFIR vessel. These activities will also provide an enhanced level of confidence that the probabilities of failure are indeed as small as predicted and that the program of hydrostatic tests continues to guard against unexpected failures under operating conditions.

Recommendations for Future Activities

Recommendations are made as follows to ensure continued safe operation of the HFIR pressure vessel:

(1) Dosimetry at critical vessel locations, including the nozzle corners, should be performed on a continuing basis to maintain a validated basis for estimating accumulated fluence levels for use in estimating embrittlement levels.

(2) Exposures of archival materials in the surveillance capsules should be continued along with material testing to maintain an updated basis for levels of embrittlement.

(3) The probabilistic fracture mechanics calculations should be revisited on a regular basis to reevaluate the risks of vessel failure; the methodology should be updated in accordance with NRC guidance that is expected to be revised in the near future.

(4) Hydrostatic test requirements should be reviewed and revised on a periodic basis in accordance with improved estimates of embrittlement rates and refinements in the probabilistic fracture mechanics calculations.

(5) Procedures for reactor operation should be modified as practical to minimize the challenges to vessel integrity by maximizing vessel temperatures, minimizing pressures, and implementing procedural and hardware changes that will prevent the occurrence of over-pressure events.

(6) Inservice inspections of the vessel should focus on the nozzle corner regions to obtain additional assurance by nondestructive testing (e.g., ultrasonics) that the nozzle corners are free of structurally significant flaws.

(7) The inputs for flaw probabilities at the nozzle corners should be reviewed and updated based on systematic considerations of the forging and cladding processes relevant to fabrication of the HFIR vessel.

(8) Design and construction records for the HFIR vessel should be assembled and reviewed to verify that estimates of flaw distributions based on LWR vessel data for welds and plates are relevant to the HFIR vessel; the data of interest should address details of welding and cladding processes.

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