ABSTRACT

Since 2001 the reactor pressure vessel head (RPVH) penetration nozzles have been volumetrically inspected to detect cracking, closure head wastage and leak paths. The inspection process has evolved over the years in response to a series of NRC bulletins, orders and rulemaking to address the failure mechanisms. The latest evolution has been the additional NRC requirements imposed on ASME Code Case N-729-1, which specifies the inspection requirements. The NRC rulemaking in September, 2008 specifies that leak path assessment for the annulus between the RPVH and nozzle be performed either by a surface examination of the j groove weld or a demonstrated ultrasonic inspection technique.

Ultrasonic inspection techniques for leak path detection have been used since 2002, however, the technical basis had been adequately documented or independently reviewed to satisfy the NRC expectations. In order to comply with the new NRC criteria, additional information was generated using field data, mockup testing and comparison of destructive testing to the ultrasonic test data.

Through destructive testing of removed nozzles from retired reactor vessel heads, multiple leak path scenarios were discovered and the inspection results for each condition were evaluated. Using a combination of ultrasonic inspection and bare metal visual inspection, a comprehensive process for detection of leakage has been documented. This paper will review the evolution of this process using the available field inspection, laboratory mockup results and destructive testing that was used to provide assurance of the defense in depth approach for RPVH nozzle inspections.

INTRODUCTION

The requirements for reactor vessel head penetration inspections that had been required under NRC Order 03-09 were superseded by ASME Section XI Code Case N-729-1 was incorporated via a rule making issued in 10cfr50.55a) on September 10, 2008. One of the requirements of this rule making was to have a demonstrated volumetric leak path inspection technique (or perform 100% surface examinations of the j welds).

The earlier work, described above, used a leak path model based on a loss of interference fit due to corrosion or steam cut leak path in the annulus between the alloy 600 penetration nozzle and the reactor vessel head. Accordingly, the mockups used had a simulated corrosion path and an interference fit. These results demonstrated that if an interference fit existed, then a local corrosion path is detectable using a zero degree ultrasonic technique.

After the North Anna 2 reactor vessel head nozzle was retired, the NRC sponsored a program at Battelle-PNNL to perform nondestructive and destructive testing on some of the nozzles. In particular, nozzle #31 was destructively tested at PNNL. The results of this study indicated that there were multiple scenarios possible if a coolant leak occurred into the annulus region.

The four possible conditions after a leak into the annulus are:
-1) a corrosion path exists eliminating the interference fit in a local path to the top of the head
-2) boric acid accumulates in the annulus and eventually a leak path washes away a region of the boron up to the top of the head
-3) by inference, boric acid accumulates in the annulus prior to a washed out path exists and does not reach the top of the head
-4) the annulus opens during operation and there is free escape of the borated coolant with no accumulation in the annulus, but boric acid on the top of the head.

These four scenarios and leak path detection schemes are discussed below.
ULTRASONIC THEORY

Case 1) Interference Fit and Local Corrosion of the Carbon Steel

In case 1) with a corrosion path with a metal to metal interference, the back wall ultrasonic reflection will increase in this local region. Prior work performed at Batelle-PNNL (Reference 1) on the effect of crack face compressive loading reported that a 12 ksi compressive force would reduce the reflection amplitude by 10 dB. Using the nominal values for alloy 600 and carbon steel, this would equate to a 3 mil radial interference fit. A study was done on as built dimension for several reactor vessel heads and found that the nominal diametrical interference fit was 1.5 mils (0.75 mils radial). Assuming the nominal radial interference fit of 0.75 mils, this corresponds to an expected drop in back wall amplitude of 2 dB, which is consistent with mockup results.

Cases 2 and 3: Accumulation of Boric Acid in the Annulus

In cases 2) and 3), the predominant effect is the presence of the boric acid in the annulus. Compacted boric acid acts as an ultrasonic couplant allowing the through transmission of the sound wave through the interface and into the carbon steel. The destructive testing at Battelle-PNNL on North Anna 2 nozzle 31 first reported this phenomenon (Reference 2). Subsequently, using mockups with compacted boric acid, EPRI has reproduced this effect (Reference 3). This nozzle was inspected during the initial outage in Fall 2002, and later re-inspected at PNNL three years later. There was essentially no change in the ultrasonic response indicating that the presence of boric acid rather than the possibility of entrapped water was the cause of the ultrasonic response. Unlike the initial corrosion model, now the ultrasonic back wall response reduces in amplitude.

Case 4) Open Annulus

In the destructive testing at PNNL, nozzle #31 actually was determined to have two leak paths, one at 135 degrees and one at 45 degrees, as shown in Figure 6. At the 45 degree location, it appears that the annulus opened sufficiently during operation to allow the free escape of coolant with no compacted boric acid remaining in the annulus. It is also clear that during shutdown condition, there is an interference fit. The machining marks from the carbon steel head are imprinted onto the alloy 600 nozzle, which could only happen with an interference fit condition. Although this condition is not detectable by the ultrasonic test leak path approach, it is obvious that such a condition would have to lead to a clear leak deposit on the top of the head, which would be detected by the bare metal visual examination.
Figure 1, from Reference 2, shows the ultrasonic response associated with the presence of compacted boric acid (blue areas) and a washed out “riverbed” pattern (orange/yellow) along with a picture of the actual annulus. It is obvious from the image that the ultrasonic response is mapping the presence of the boric acid. It is also important to note that there is no corrosion of the carbon steel at this level of leakage, so the overall reactor pressure boundary is not subject to failure, just minor leakage. The PNNL shows progressive water marks where the leak occurred, but no loss of carbon steel.

In addition to the UT, eddy current inspection of the J weld indicated cracking. The location of the leak path (washed away riverbed) at the triple point of the weld aligned with the location of the through weld crack. (The crack on the J weld is at 155 degrees and the exit point at the triple point is at 130 degrees. The crack grows normal to the weld rather than vertically, following the nozzle, so this projects to the triple point exit location.)

Since it is necessary for the boric acid accumulation to occur first, there is a possible scenario in which the boric acid is present due to a leak, but either the boric acid has not reached the top of the head or a sufficient leak flow is not present to wash away the boron. Field data was reviewed to determine if such an instance was found and a number of such conditions were identified.

REFERENCES

1) Integration of NDE Reliability and Fracture Mechanics, NUREG/CR 1696-V1, March 1981 (PNNL report)
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3) EPRI presentation at NRC/NEI/MRP/PWROG public meeting, March 17, 2009