Probability of Detecting Leaks in RPV Upper Head Nozzles by Visual Inspections

Revision 1
June 17, 2002

Prepared for:
MRP PWR Alloy 600 Assessment Committee

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Background

Visual inspections of the reactor coolant system pressure boundary have proven an effective method for identifying leakage from PWSCC cracks in Alloy 600 base metal and Alloy 82/182 weld metal. Specifically, visual inspections have detected leaks in RPV head CRDM nozzles, RPV head thermocouple nozzles, pressurizer heater sleeves, pressurizer instrument nozzles, hot leg instrument nozzles, steam generator drain lines, a RPV hot leg nozzle weld, a pressurizer PORV safe end, and a pressurizer manway diaphragm plate.

Visual inspections are an important element of Alloy 600 inspection programs since they have been proven effective, are cost effective, and, depending upon conditions, are capable of detecting very small leaks.

The purpose of this document is to demonstrate that a bare-metal visual inspections of reactor vessel top head surfaces will result in a high probability of leak detection (POD) provided that there is visual access to the locations where the nozzles penetrate the vessel top head surface, and the access is not hindered by pre-existing boric acid deposits.

Probability of Detecting Leaks by Bare-Metal Visual Inspection

An estimate of the probability of leak detection (POD) by visual means can be developed based on recent field experience, the calculated annulus gap under operating conditions, tribology considerations, and experience with leaks for nozzles that are roll-expanded into the pressure vessel shell. The estimated POD will continue to be refined as the results of visual inspections are correlated with increasing numbers of non-destructive examinations.

1. <u>Field Experience</u>
   Through May 2002, thirty-two CRDM nozzles at eight plants (ANO-1, Crystal River 3, North Anna 2, Oconee 1-3, Surry 1 and TMI-1) have been found to have leaks based on visual inspections.

Non-visual NDE inspections have been performed on 578 CRDM and CEDM nozzles at sixteen plants. The sixteen plants consist of the eight plants with visually detected leaks plus eight other plants (ANO-2, Cook 2, Davis-Besse, Ginna, Millstone 2, North Anna 1, Palo Verde 2, and SONGS 2). The non-visual NDE inspections were performed for the following reasons:

- 62 nozzles (11%) were inspected to confirm the visually identified leak path or to assess locations where visual inspections were masked

- 80 nozzles (14%) were inspected to assess the extent of condition in plants where leaking nozzles were discovered

- 367 nozzles (63%) were inspected at plants where bare metal visual inspections are not possible

- 69 nozzles (12%) were inspected based on a regulatory commitment even though a visual inspection would have been possible

The 578 non-visual inspections identified three leaking nozzles in addition to the 32 discovered by visual means. However, these three additional leaking nozzles were at Davis-Besse where it is considered that they would have been discovered by the type of bare metal visual inspections performed subsequent to discovery of leaks at Oconee 1 in 1999.

In summary, all 35 leaking nozzles to date in domestic PWR plants have been, or would have been, discovered by top head bare metal visual inspections using industry guidance developed subsequent to discovering the first leak at Oconee 1. No leaking nozzles have been discovered by non-visual examinations, except for the three nozzles at Davis-Besse that would have been detected visually.

A case can be made that visual inspections may have missed some leaking nozzles. Two situations warrant discussion:

- It is likely that some of the leaking nozzles had been leaking for several years and that the leakage was missed during prior visual inspections. However, industry guidance developed over the past year in terms of the size leaks to be anticipated, evidence of leakage, need for clean heads, etc. is considered to have improved the visual inspections to the level that these leaks would be detected at the first evidence of leakage.

- It is reported that the Bugey 3 nozzle leaked during hydrostatic testing with no evidence of boric acid deposits on the vessel top head surface. However, inquiries by the MRP have failed to establish the level of visual inspections that had been performed, or the condition of the vessel top head surface, prior to the leak being identified during the hydrostatic testing. The case of Bugey 3 also illustrates that there must be some crack extension above the J-groove weld for there to be visually detectable leakage. At Bugey 3 the through-wall portion of the crack only extended 2 mm (0.08 inch) above the top of the J-groove weld.

2. Annulus Gap Opening

The eight plants with visually identified leaks (not including Davis-Besse) had maximum specified interference fits ranging from 0.0012" to 0.0015". The actual interference fit was measured during fabrication for several of the plants with identified leaks. Leaks have been visually identified in three nozzles with 0.0014" interference at Oconee 2.

Leaks at Davis-Besse nozzles 2 and 3 were originally identified by non-destructive examinations from under the vessel head but it is considered that both of these leaks would clearly have been identified by a bare metal visual inspection of a previously cleaned head. Davis-Besse nozzles 3 and 2 are reported to have had 0.0015" and 0.002" interference respectively.

Many plants have specified interference fits greater than the 0.002" for which leakage has been visually confirmed. Forty plants have specified maximum interference fits of 0.003", two plants have specified maximum fits of 0.0035", and three plants have specified maximum fits of 0.004".

Finite element gap displacement calculations have been performed for several plants with specified interference fits ranging from 0.0015 – 0.003". These analyses have demonstrated a leak path through the annulus region. In some cases the analyses have included the fact that a leak into the annulus region results in application of pressure on the outside of the nozzle and the inside of the hole in the vessel head. This change in boundary conditions from the as-designed configuration increases the pressure dilation of the vessel head (pressure applied to a larger diameter than the inside of the nozzle) and eliminates the pressure deflection of the nozzle. The net effect of the leak is therefore to increase the gap opening.

Figure 1 shows the specified interference fits relative to the vessel head radius to thickness ratio (R/T) , and the status of cases analyzed and confirmed leakage. These results show that calculations have demonstrated a leak path for nozzles with up to 0.003" specified maximum interference fit with the smallest R/T ratios. Designs with small R/T ratios will have smaller gap opening displacement than heads with large R/T ratios since they will have lower membrane stresses in the head and less pressure dilation of the vessel shell.

With the exception of Cook 2 which has already performed non-visual NDE of all nozzles, the plants with 0.0035" and 0.004" specified maximum interference fit all have relatively low predicted PWSCC susceptibility based on time and temperature.

Finally, it should be noted that the actual interference fits for most nozzles will be less than the maximum specified for two reasons. First, there is likely to be a statistical distribution of fits within the specified range. Second, from a manufacturing assembly standpoint it is desirable to avoid large interference fits since large interference fits increase the potential that a nozzle will become stuck in the head at the wrong elevation during installation. It has been confirmed for plants where the nozzle and hole dimensions have been recorded that the actual interference for most nozzles is significantly less than the maximum.

3. <u>Flow Passages for Cases With Predicted Interference Fit</u>
Even for cases where there is a nominal interference fit between the CRDM nozzle and hole in the vessel head under operating conditions, the actual area of metal-to-metal contact is quite small. Rabinowicz, *Friction and Wear of Materials*, gives the actual contact area between two adjacent metal surfaces as the applied load divided by three times the material yield strength. For a typical CRDM nozzle with 0.003" of interference and a yield strength of 50 ksi, the actual metal-to-metal contact area is about 5% of the interface surface area. The remaining approximately 95% of the surface area has small flow passages with an RMS height equal to the sum of the RMS surface roughness of the mating parts, or about $60\text{-}90 \times 10^{-6}$ inches (0.00006-0.00009").

Other manufacturing considerations such as straightness and out-of-roundness tolerances, etc. will result in actual flow passage sizes being greater than the minimum sizes based on surface roughness considerations.

4. <u>Roll Expansion Experience</u>
Finally, there have been several cases where leaks have occurred from Alloy 600 penetrations despite the penetrations having been roll expanded into the hole in the pressure vessel. Two cases documented in EPRI TR-103696, *PWSCC of Alloy 600 Materials in PWR Primary System Penetrations*, are steam generator drain pipes at Shearon Harris in 1988 and pressurizer instrument nozzles at Nogent 1 and Cattenom 2 in 1989.

Based on the above, the probability of visual detection for bare-metal visual inspections which are not compromised by pre-existing boric acid on the vessel head is expected to be high.

For probabilistic analyses, has been assumed that leaks will not be detected from any nozzle with greater than a 0.002" interference for which leakage has been confirmed at an operating plant. Based on a normal distribution of fits with the maximum and minimum specified values representing two sigma upper and lower bounds, 75% of the nozzles with a specified interference range of 0.000" to 0.003" will have an interference less than 0.002". The probability of detection assumed for probabilistic fracture mechanics analyses is 0.6.

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Figure 1
Reactor Vessel Head Designs for Which Leak Path Has Been Confirmed