15-1

Draft
Version 6
9/8/2000

Technical Evaluation Report (August 21, 2000)

Restart of Indian Point 2 Following Steam Generator Tube Failure on February 15, 2000 and Catagory C-3 Steam Generator Inspection Results

1.0 Introduction

Consolidated Edison Company of New York, Inc. (ConEd), the licensee for Indian Point Unit 2 (IP2), experienced a steam generator (SG) tube failure on February 15, 2000. After achieving safe shutdown of the plant, ConEd proceeded to inspect the SG tubes to determine the cause of the failure. Because the forced shutdown occurred close to its planned refueling outage date, the licensee elected to perform a complete SG tube eddy current inspection in accordance with its technical specifications (TS). The results of the first and second sample inspections fell into TS category C-3, thus requiring NRC approval prior to startup. This report documents the NRC staff's review of the February 15, 2000 tube failure, the events that led up to that failure, the licensee's actions taken to prevent recurrence, and the justification for continued operation. NRC had not reached conclusions regarding the acceptability of plant restart or for how long operation could be authorized at the time ConEd decided not to seek restart with the existing SGs but, instead, to install replacement SGs. The purpose of issuing this report is to provide ConEd feedback on activities related to the post-tube failure inspection and maintenance of the existing SGs and to identify and discuss technical issues that arose as part of the NRC staff's review of the licensee's operational assessment intended to support continued operation of the SGs. It is expected that this information will be useful not only to ConEd but to the rest of the industry in managing SG tube integrity and to all interested stakeholders.

2.0 Background

2.1 IP2 Steam Generator History

IP2 has four Westinghouse Model 44 SGs with mill annealed alloy 600 tubing, carbon steel drilled hole tube support plates (TSPs), and partial depth rolled joints in the tubesheet. IP2 received its operating license in September 1973 and began commercial operation in August 1974. Early in its operating life, IP2 experienced extensive tube denting which in turn resulted in significant flow slot hourglassing at the lower TSPs. Steam generator tube denting occurs under certain secondary side conditions. The general corrosion of the carbon steel TSPs and tubesheet results in a buildup of iron oxide corrosion product in the annulus between the tube and the TSP or between the tube and the tubesheet. This buildup "squeezes" the tubes enough to cause permanent, plastic deformation of the tube. As tube denting increases throughout the SG, the TSPs begin to deform in response. Eventually continued denting can cause "hourglassing" which refers to deformation of the TSP such that the shape of the flow slots deform from their original rectangular shape to an hourglass shape. Flow slot hourglassing pulls the legs of the tubes in towards one another, thus increasing the stress placed on the tube, particularly in the apex region of the low row, small radius tubes. Operating experience relative to denting and hourglassing and subsequent tube degradation include the Surry Unit 2 tube rupture which occurred in September 1976. The root cause of the Surry rupture was determined to be related to tube denting and hourglassing of the TSP flow slots. In response to the tube rupture, the staff closely monitored the conditions at IP2 and other plants with highly dented TSPs similar to Surry Unit 2. Through several IP2 inspection efforts and subsequent

J/195

staff interactions that occurred in the late 1970s and early 1980s, special requirements were added to the IP2 TS related to denting and TSP hourglassing to ensure that the NRC staff would be alerted to any significant change in the status of denting or hourglassing of the uppermost TSPs.

- The IP2 TS require ConEd to provide an evaluation to address the long term integrity of small radius U-bends beyond row 1 within 60 days of any finding of significant hourglassing of the upper support plate flow slots.

- The IP2 TS require ConEd report to the NRC a significant increase in the rate of denting.

- The IP2 TS require ConEd to plug tubes that do not permit passage of a 0.610 inch diameter probe.

- The IP2 TS require ConEd to obtain NRC approval for startup if the SG tube inspection results fall into the C-3 condition.

2.2 1997 Steam Generator Tube Eddy Current Inspection

Prior to the February tube failure, ConEd last performed a steam generator tube eddy current inspection in May 1997. The licensee submitted the inspection results in a letter to the staff dated July 29, 1997. Active tube degradation mechanisms reported included wear at the antivibration bars (AVBs), outside diameter initiated stress corrosion cracking (ODSCC) and pitting in the sludge pile region (this is the area above the top of the tubesheet and below the 1st TSP), ODSCC and intergranular attack (IGA) in the tubesheet crevice, and primary water stress corrosion cracking (PWSCC) at the tubesheet roll transitions and low row U-bends. ConEd identified PWSCC in the low row U-bends for the first time in the 1997 inspection. **Figure 1** illustrates these degradation mechanisms and the various locations in the SG tube bundle which are most susceptible to these forms of degradation. To detect and disposition flawlike indications, ConEd used primarily a 0.700-inch diameter combination Cecco/bobbin eddy current probe, although progressively smaller diameter probes were used up to and including a 0.610-inch diameter bobbin probe. The licensee plugged any tube that did not permit passage of the 0.610 inch diameter probe. ConEd used a midrange frequency +Point probe to inspect the bends of the low row U-bends and also used this probe for further characterization of certain Cecco/bobbin indications. ConEd generally imposed a "plug on detection" repair criteria except for AVB wear, pitting, and PWSCC at the roll transitions. For those forms of degradation, the licensee relied upon sizing techniques to disposition AVB wear and pitting; they applied the F* criterion to disposition PWSCC at the roll transitions.

Based on the 1997 inspection results, ConEd identified and tested four tubes with degradation in the tubesheet crevice area that exceeded the EPRI and/or Westinghouse in situ hydrostatic test criteria. ConEd tested two other tubes that did not exceed the criteria because one was typical of tube roll transition cracking and the other because it was located at the top of the tubesheet (in the sludge pile freespan location). No leakage from any of the 6 tubes was detected up to pressure differentials equivalent to three times normal operating pressure (3ΔP). The staff notes that ConEd identified for the first time in 1997 PWSCC in a low row U-bend tube, in steam generator #24, row 2 column 67 (#24-R2C67), but ConEd did not in situ test this tube. In later interactions with the staff, ConEd stated that sizing estimates placed the PWSCC flaw in R2C67 below the in situ screening threshold and thus they did not test the tube [Reference 1: Letter dated May 12, 1999 from James S. Baumstark to Document Control Desk, "Response to Request for Additional Information - Proposed Amendment to Technical Specifications Regarding Steam Generator Tube Inservice Inspection Frequency"].

ConEd also performed secondary side inspections of the SGs in 1997. They inspected the lower TSP flow slots using a video camera through the handholes above the tubesheet in all four SGs. ConEd stated in the July 29, 1997 letter that they observed no change in the amount of hourglassing present at the lower TSPs. They also stated that one flow slot at the 2nd TSP showed closure which they evaluated and determined to be acceptable. The licensee also conducted video examinations of the #22 and #23 SGs through the hillside inspection port located just above the top TSP. They stated that they observed no significant hourglassing of the flow slots in the uppermost TSPs.

2.3 Tube Failure Circumstances and Identification of Leaking Tube

The licensee first identified primary to secondary leakage by condenser off-gas sampling in September 1998 with a quantified leak rate of 0.5 gallons per day (gpd). The leak rate slowly increased during the next 12 months and reached 2 gpd when a plant trip resulted in the unit being shutdown to hot standby for 2 months starting in August 1999. During the shutdown, the licensee performed tritium surveys that indicated that the #24 SG was the primary source of the leakage. Following startup in October, 1999, the leak rate varied from 2 to 4 gpd but returned to the pre-shutdown levels of 1.5 to 2.0 gpd through December 1999. Beginning in January 2000 the leak rate slowly increased to about 3 to 4 gpd just prior to the tube failure on February 15, 2000, when leak rates reached about 146 gpm [Reference 2: Letter dated April 28, 2000 from Hubert J. Miller (NRC) to A. Alan Blind (ConEd), "NRC Augmented Inspection Team - Steam Generator Tube Failure - Report No. 05000247/2000-002."]. Upon shutdown following the February 15, 2000 tube failure, the licensee determined the location of the leaking tube to be in tube R2C5. The licensee visually inspected this tube and verified the location to be near the apex of the tube. Through subsequent eddy current inspection, ConEd determined the crack was primarily axially-oriented and initiated on the inner diameter of the tube. Subsequent eddy current examinations of the defect indicated a length of approximately 2.2 - 2.5 inches. Based on this length estimate, Westinghouse calculated that the average depth of the defect was approximately 90% through wall immediately prior to the failure. [Reference 3: Letter from John F. Groth (ConEd) to William Travers (NRC), dated June 2, 2000, "2000 Refueling Outage Steam Generator Inspection Condition Monitoring and Operational Assessment Reports"].

3.0 Staff Evaluation

3.1 2000 Steam Generator Tube Eddy Current Inspection

ConEd initially planned to follow an eddy current inspection scope and use eddy current test techniques for the 2000 inspection that were essentially identical to the 1997 inspection described earlier. However, ConEd implemented significant changes in the inspection scope and in the eddy current inspection techniques applied during the course of the inspection.

These changes resulted from NRC staff interactions with the licensee regarding issues with the inspection results and their implications. These issues and subsequent eddy current inspection changes are the focus of this safety evaluation report, particularly with respect to the inspection of the low row U-bends and the inspection of the sludge pile region. Each of these areas is discussed in turn below.

3.1.1 U-bend Inspection

ConEd applied a midrange frequency +Point probe to rows 2 - 4 tubes from the 6th hot leg TSP (6H) to the 6th cold leg TSP (6C). From this inspection, they identified three PWSCC indications in the Row 2 U-bends in addition to the failed tube, #24-R2C5. These tubes are identified as #21-R2C87, #24-R2C69 and #24-R2C72. All four indications appear centered on the apex of the tubes. ConEd reviewed the 1997 data for these four tubes and could identify PWSCC indications in the 1997 inspection data. ConEd did not identify these indications in 1997.

The staff noted at the end of its site visit on March 9 and 10, 2000 that the eddy current inspection data obtained from the low row U-bend inspection using the midrange frequency data quality had noise levels that could inhibit effective inspection of the tubes. The staff discussed with ConEd concerns that the inspection of the low row U-bend tubes did not employ a technique sensitive enough to detect small, precursor flaws such as those missed in 1997, including one which led to a tube rupture. The NRC staff noted that ConEd had not identified any similarly small flaws this outage using their current technique (i.e., the midrange frequency +Point probe). The NRC staff made several recommendations to the licensee on methods to enhance the inspection sensitivity to PWSCC flaws in order to minimize the size of the flaw that may be missed. The most significant of these recommendations, in terms of the effect on the data quality, included the use of a high frequency +Point probe.

After some discussion, ConEd responded to the staff's concerns and reinspected all the row 2 and row 3 U-bends with a high frequency +Point probe. They also used this probe to reinspect any row 4 U-bend tube with poor data quality. From this inspection, ConEd identified 4 additional PWSCC indications in tubes #24-R2C4, #24-R2C71, #24-R2C74, and #23-R2C85. Except for R2C4 and R2C74, precursor indications could be identified for these tubes in the 1997 inspection data. ConEd agreed that the high frequency +Point probe enhanced the analysts' ability to detect PWSCC flaws.

ConEd plugged all tubes with identified U-bend defects and also preventively plugged all other row 2 tubes in all four SGs.

The staff concluded that ConEd used the most PWSCC-sensitive probe readily available to inspect the low row U-bends (i.e., the high frequency +point). The staff also concluded that the scope of the program (i.e., row 2 and row 3, from 6H to 6C, and row 4 tubes with poor data quality) was sufficient in that the most susceptible area (the U-bend area) was completely inspected. Based on the inspection results, the high frequency +Point probe enhanced the eddy current analysts' ability to detect PWSCC flaws because of the large reduction in noise signals. The staff agrees that the licensee's decision to plug all defective tubes and preventively plug the remaining row 2 tubes was appropriate.

With the row 2 tubes plugged, the operability of the row 3 tubes, which have the smallest radius U-bends of the unplugged tubes, needs to be assessed. The operational assessment for these tubes is very sensitive to an input parameter called "probability of detection (POD)." Although the high frequency +Point probe improved the ability of analysts to detect PWSCC, the quantification of this improvement is difficult to evaluate. This subject is discussed in more detail later in this safety evaluation, specifically in Section 3.6.1. It should be noted that the use of the high frequency +Point probe does not enhance sensitivity to ODSCC. The noise levels observed in the low row U-bends at IP2 may still obscure ODSCC flaws and cannot be overcome with a simple application of the midrange or the high frequency +Point probe. The staff estimates that ODSCC flaws may have to penetrate to 70% of the initial wall thickness before becoming detectable. At this point in time, IP2 has not observed ODSCC in its low row U-bends, nor is it a prevalent degradation mode for the industry as a whole.

3.1.2 Sludge Pile Inspection

The staff also devoted significant attention to ConEd's inspection of the sludge pile region of the SGs. The staff focused on this area because it appeared to be the most likely area to challenge tube integrity at IP2, next to the low row U-bends. This is because of the high noise levels in the area which make eddy current inspection challenging to analysts, the active degradation mechanisms (e.g., ODSCC and pitting), and the absence of any constraining effects against tube burst provided by the tubesheet or TSPs.

For the 2000 inspection, ConEd originally applied a combination Cecco/bobbin probe to inspect the sludge pile region and used a midrange +Point probe to characterize the Cecco/bobbin indications, similar to their 1997 inspection practice. They reported a limited number of axially-oriented ODSCC indications in the sludge pile region, consistent with their past inspection results. At the end of a site meeting March 15 and 16, 2000, the staff identified to ConEd concerns related to the inspection of the sludge pile region. During on site observations of the steam generator inspections, the staff identified very noisy areas in the uppermost portion of the span of tubing between the top of the tubesheet (TTS) and the 1st TSP. The staff's assessment was that the noise levels seen in the Cecco/bobbin probe were sufficiently high that ODSCC indications would be very difficult to detect. In addition to this finding, another issue arose after in situ pressure testing of #22-R34/C51. ConEd performed a post in situ eddy current inspection of the defect and found that an indication located in the crevice region of the tubesheet in the same tube had been missed by the Cecco/bobbin analysts. When the licensee began to reevaluate other crevice data, they found more missed crevice indications in other tubes. As a result of these issues, ConEd decided to enhance its inspection efforts in this region of the SGs by employing a midrange frequency +Point probe (which is the appropriate frequency range because the primary form of degradation is outside diameter initiated) over the entire sludge pile region. This is an enhancement over the Cecco/bobbin combination probe primarily because of the improved data quality obtainable with the +Point probe. Use of this inspection technique is also consistent with general industry practice in this region of the steam generators.

Using the +Point probe, ConEd performed a 20% inspection on the hot leg side in all four SGs from the tube end to just below the 1st hot leg TSP, concentrating this sample in the sludge pile "kidney region" where degradation would be expected to most likely occur. ConEd analyzed the results of this inspection to determine the maximum elevation above the TTS at which axial

ODSCC indications occurred to define the upper boundary for +Point inspection of the remaining hot leg tubes. The highest axial indication reported in the four SGs was 12.9" above the TTS. To add conservatism to the inspection scope, ConEd inspected to 24" above the TTS in the remaining hot leg tubes (i.e., ConEd inspected 100% of the hot leg tubes from the TTS to at least 24" above the TTS).

ConEd performed the same initial sample program on the cold leg side of one SG (#23) and did not identify any cracklike indications although they found pitlike indications as high as 7.6" above the TTS. ConEd then inspected a 20% sample to a height of 24" in the remaining SGs on the cold leg side. They expanded the inspection scope to 40% of the tubes on the cold leg side in the #21 and #22 SGs because ConEd identified pitlike indications that exceeded the plugging limit of 28% through wall. (The plugging limit for pitlike indications comes from an Appendix H sizing qualification study.) The expansion sample resulted in ConEd identifying additional defective tubes in the sludge pile region of the SGs. However, because no cracklike indications or pitlike indications exceeded 28% through wall in this expanded sample, ConEd did not further expand the inspection scope.

The staff concludes that ConEd's reinspection of the sludge pile region was acceptable in that they used a probe that improved the data quality (the midrange +Point probe as opposed to the Cecco/bobbin combination probe) thus enhancing the eddy current analysts' ability to detect flaws. Use of the +Point probe is also consistent with industry practice for inspection of this region of the steam generators. We conclude also that the scope of the +Point inspection adequately covered the most ODSCC-susceptible areas in that they inspected 100% of the hot leg side of the SGs up to 24" above the TTS and a large sample of tubes on the cold leg side (more than 20 % of the population).

3.2 Secondary Side Inspections

Secondary side visual examinations were performed for purposes of monitoring the condition of the SG internals, including the condition of the tube support plates (TSPs). In addition, inspections for loose parts and foreign objects were performed as part of the licensee's Foreign Object Search and Retrieval (FOSAR) program.

IP-2 experienced denting early in its operating life in the mid-1970's. This denting led to extensive in-plane deformation of the TSPs and cracking of support plate ligaments. One manifestation of TSP deformation is deformation of the six initially rectangular flow slots located along the open lane separating the hot and cold leg of the tube bundle. Flow slot deformation is generally referred to as "hourglassing." Much of the hourglass deformation at IP-2 which is readily visible today occurred prior to 1984. Based on visual inspection of three flow slots at the uppermost TSP in SGs 22 and 23 dating back to that time, the licensee has consistently reported through the years that the uppermost TSP had not experienced significant hourglass deformation.

Hourglass deformation of the uppermost TSP flow slots was known to have potential tube integrity significance. Such deformation causes the legs of the small radius u-bends to displace inward, substantially increasing the stress level at the apex of the u-bend and thus the potential for stress corrosion cracking at that location. This phenomenon led to a rupture of an inner row u-bend at Surry Unit 2 in 1976. The amount of hourglass deformation of the adjacent flow slot was 1.3 inches. Accordingly, the licensee for IP-2 has routinely inspected three flow slots in the uppermost TSP in SG 22 and SG 23, respectively. Based on these inspections, the licensee has consistently reported through the years that the uppermost TSPs were free of significant hourglass deformation. SGs 21 and 24 did not have access ports permitting visual inspection of the uppermost TSP flow slots.

Following the failure of R2C5 in SG24, the licensee installed access ("hillside") ports in SGs 21 and 24 to permit visual inspection of three flow slots in each of these SGs, including the flow slot adjacent to R2C5 in SG 24. The licensee reported that the visual inspections, performed with a video camera, did not provide a clear indication of hourglass deformation of the upper TSP flow slots due to limitations presented by camera angle and lighting. At the staff's suggestion, the licensee mounted a measuring device to the camera assembly and determined that hourglass deformation was in fact present in the flow slot adjacent to R2C5 in SG 24. The amount of hourglass deformation was 0.47 inches, compared to the nominal flow slot width of 2.75 inches. As discussed in Section 3.4.1, this amount of hourglass deformation is sufficient to create an abnormal level of stress at the apex of the u-bend, thereby enhancing the susceptibility of this location to stress corrosion cracking.

The licensee did not perform direct flow slot measurements for other flow slots in any of the four SGs during the 2000 inspection. Given that u-bend cracks have also been found in row 2 tubes adjacent to other flow slots, including flow slots in SGs 21 and 23, and that a number of tubes adjacent to the flow slots have restricted probes with diameters as low as 0.610 inches, it appears likely that hourglass deformation of the uppermost TSP flow slots is general throughout all four SGs.

In the absence of direct measurements, past inspections in SGs 22 and 23 are inconclusive regarding how long the upper flow slots have experienced significant hourglass deformation. Hourglass deformation of lower TSP flow slots is much more substantial than at the upper TSP such that it is readily observable by visual inspection, but has not progressed significantly since about 1984. Thus, significant hourglass deformation of the upper TSP flow slots may possibly date back to that time. This would be consistent with the low growth rates (3.8%/EFPY in terms of average crack depth) estimated by the licensee for the row 2 u-bend indications. The staff concludes that the licensee's inspections of the upper TSP flow slots dating back to that time (as described in Reference 3) were inadequate for purposes of detecting "significant" hourglass deformation, i.e., hourglass deformation which may lead to abnormal stress levels at the apex of the u-bends enhancing the potential for stress corrosion cracking.

Apart from flow slot hourglass deformation, visual inspections were also conducted to assess the general condition of the TSPs and SG wrapper. Where accessible to the video camera, in-plane deformation (growth) of the TSPs due to denting was observed to have caused the support plates to be in contact with the wrapper, except in the near vicinity of the wedge supports. Although not stated specifically by the licensee, the staff infers from Reference 3 that this condition is not new since support plate deformations largely occurred prior to 1984. All wedges and welded connections were observed to be in good condition. The licensee reported that there was no visible deterioration of the wrapper. Further, the licensee determined that the wrapper is in its proper position and has not dropped.

TSP cracks at IP-2 have been monitored visually since 1976. These include cracks at the flow slots, cracks at the inner ligaments between the tube holes and flow holes in the vicinity of the flow slots, and cracks at the outer peripheries of the support plates. The 2000 inspection indicated some continued progression of TSP crack activity. However, the licensee concludes that these cracks do not impair the tube support function of the tube support plates. As noted previously, the TSPs are in contact with the wrapper at locations around its periphery. The licensee states that the reactions loads at the periphery of the TSPs maintain the plate in a high state of compression. As in the past, the licensee has performed a detailed structural analysis of the degraded support plates to demonstrate that they are capable of providing adequate lateral support to all unplugged tubes under operating and postulated accident conditions. The staff has not reviewed the licensee's support plate integrity analysis in detail since (1) the condition of the support plates does not appear to have significantly changed in recent years, (2) the TSP cracks are not directly related to the failure mechanism for R2C5 as discussed in Section 3.4.1 nor to programmatic shortcomings contributing to the failure as discussed in Section 3.4.2, and (3) the cracks are not directly relevant to the technical specification Category C-3 tube inspection results necessitating staff review and approval for plant restart. Similarly, the staff has not reviewed the licensee's FOSAR program implemented during the 2000 inspection outage.

3.3 Condition Monitoring Assessment

The licensee's condition monitoring assessment is documented in its Condition Monitoring and Operational Assessment (CMOA) report submitted by letter dated June 2, 2000 (Reference 3). Condition monitoring involves monitoring and assessing the as found condition of the tubing relative to success criteria termed SG tube integrity performance criteria. The as found condition of the tubing refers to the condition of the tubes during an SG inspection outage, prior to any plugging or repair of the tubes. The condition monitoring assessment is "backward looking" in that its purpose is to confirm that tube integrity has been maintained since the previous SG inspection. In general, the failure of one or more tubes to satisfy the performance criteria may be indicative of changing conditions in the steam generators or of deficiencies in the licensee's program for monitoring and maintaining SG tube integrity.

The performance criteria applied to the IP-2 condition monitoring assessment were taken from NEI 97-06, Revision 1b, "Steam Generator Program Guidelines," dated January 2000 (Reference 4). The NEI guidelines were submitted to the NRC by letter dated February 4, 2000 (Reference 5). These criteria include performance criteria for structural integrity, accident leakage integrity, and operational leakage integrity. The structural performance criteria include maintaining a margin of three against burst under normal operating pressure ("3ΔP" criterion) and a margin of 1.4 during postulated accidents. These criteria are consistent with the ASME Code, Section III stress limits. The accident leakage criterion is that the potential for leakage during the most limiting design basis accident, other than a steam generator tube rupture, shall not exceed the leak rate assumed in the accident analysis (for off-site dose) in terms of total leak rate for all SGs and leak rate for each individual SG. The licensee states that the applicable criterion for IP-2 is 1 gpm/SG during a design main steam line break (MSLB) accident. The operational leakage criteria is that operational leakage should not exceed 150 gpd/SG.

The staff has not yet formally reviewed NEI 97-6, Revision 1b. However, this document and the included performance criteria were the subject of considerable interaction among NEI, industry representatives, and the NRC staff. These performance criteria are similar to those proposed in draft Regulatory Guide DG-1074, "Steam Generator Tube Integrity," (Reference 6) which was issued for public comment in December 1998. In addition, the staff concludes that meeting the criteria ensures that tube integrity is being maintained consistent with the plant licensing basis, including applicable regulations and thus use of these criteria for IP-2 is acceptable.

3.3.1 Small Radius U-Bends

The staff's evaluation of the licensee's condition monitoring assessment for the small radius u-bend indications is discussed in detail in Appendix A of this safety evaluation. The staff's conclusions stemming from this evaluation are summarized as follows:

1. The failed tube, R2C5, was in a condition such that none of the applicable performance criteria were satisfied.

2. All other small radius u-bends with detected indications, with the possible exception of R2C71, were demonstrated to have met the applicable performance criteria. In-situ pressure testing was inconclusive as to whether the 3ΔP criterion was satisfied for R2C71. The staff believes it questionable that R2C71 was capable of sustaining 3ΔP without burst.

3. The in-situ pressure tests provide limited insight regarding the sizing accuracy of either the 400 KHz or 800 KHz measurements viz-a-viz the performance which is assumed in the operational assessment (Section 3.6.1.2). Only 4 of the tests provided any sort of benchmark. One of the four tests, R2C72, does not allow one to conclude whether the flaw size measurements were conservative or non-conservative, but only to conclude that the sizing measurements were not gross underestimates. A second test, R2C74, indicated that the flaw dimensions had been underestimated beyond what would be expected on the basis of the assumed error distributions in the operational assessment. The other two tests (R2C69 and R2C71) indicate that best estimate burst pressures based on sizing estimates using 400 KHz data may overestimate the actual burst pressures by as much as 25%. This comparison, however, is confounded by uncertainties in the assumed prediction models, material properties, and in how to interpret the test results. Sizing measurements based on the 800 KHz data appear to be more consistent with the results than those based the 400 KHz data, but still have significant uncertainties as discussed in Section B.2 of Appendix B.

3.3.2 Condition Monitoring Results for the Sludge Pile Region

ConEd elected to in situ pressure test all ODSCC indications in the sludge pile region (15 tubes with 25 indications). Only one of the tubes tested, #22-R34C51, had indications that met the EPRI screening criteria. This tube had three sizeable indications:

- crack 1 with an NDE estimated length of 1.26 inches, a maximum depth of 91% through wall and an average depth of 64% through wall.
- crack 2 with an NDE estimated length of 1.33 inches, a maximum depth of 90% through wall and an average depth of 66% through wall.
- crack 3 with an NDE estimated length of 0.590 inches, a maximum depth of 93% through wall and an average depth of 75% through wall.

All tubes except for R34C51 were tested to a pressure of 5173 psi without any observable leakage. This value of 5173 psi slightly exceeds the 3ΔP criterion of approximately 5042 psi (corrected for temperature). Tube R34C51 began to leak at a rate of 0.0027 gpm at a pressure of about 4678 psi. ConEd continued to pressurize the tube up to 4985 psi with a leakage of 0.0089 gpm when they lost pressurization capability. Post in situ eddy current inspection verified that crack 2 contributed to the leakage observed during the test. Cracks 1 and 3 did not open. ConEd concluded that by reaching 4985 psi they essentially demonstrated that the tube met the 3ΔP criterion. The staff concludes that the tube failed the 3ΔP performance criterion of 5042 psi, although the failure was marginal.

As discussed above for the U-bends, in situ testing provides an opportunity to benchmark sizing capabilities by comparing test results with computed results. It must be remembered that there may be errors in the computed results. That is why the staff encourages pulling tubes to test them in the laboratory and perform destructive examinations to verify results. Nevertheless, in situ pressure testing allows some insight into sizing performance. Crack 2 was sized (based on +Point data) as being 1.33 inches long, with a maximum depth of 90% and an average depth of 66%. ConEd's nominal predicted burst pressure for this crack was 4405 psi, thus indicating that the sizing was relatively accurate.

ConEd in situ pressure tested tubes that contained ODSCC indications located in the tubesheet crevice region, axially-oriented PWSCC in the roll expansion region, pitlike indications in the sludge pile region, and volumetric indications in the sludge pile region. The indications tested represented the most severe flaws of these types identified during the 2000 inspection. ConEd tested all tubesheet crevice indications to 2844 psi which is representative of SLB pressure differentials and observed no leakage. ConEd tested all sludge pile region indications to the full 3ΔP pressure differential of 5042 psi and observed no leakage. Because of the one marginal failure in #22-R34C51, the staff concludes that the in situ pressure test results indicate that ODSCC in the sludge pile region bound the other degradation mechanisms, excepting PWSCC in the low row U-bends.

3.4 Contributing Factors Relating to Failure of R2C5

By letter dated April 14, 2000, the licensee submitted a report entitled "Root Cause Evaluation For Steam Generator Tube Rupture Event of February 15, 2000" (Reference 7). The licensee supplemented this information by letters dated June 13, 15, and June 16, 2000 (References 8 through 10). For purposes of this safety evaluation, the staff considers the contributing factors to fall into two categories. The first category is discussed in Section 3.4.1 and involves factors contributing to the development of the crack in R2C5 which ultimately lead to failure of the tube on February 15, 2000. The second category is discussed in Section 3.4.2 and involves programmatic issues (i.e., inspections, engineering, and management). The adequacy of the corrective actions taken by the licensee to support restart are discussed in Section 3.5.

3.4.1 Contributing Factors to the February 15, 2000 Tube Failure - Failure Mechanism

Visual inspection of R2C5 with a fiberscope revealed a through-wall crack about 2 to 2.4 inches long. This crack was located at the apex of the u-bend on the extrados. The crack appeared to be dominantly axial. However, the crack appeared to have a dog-leg shape with a significant oblique (diagonal) component. The crack appeared to be a coalescence of several crack segments that were initially separated by ligaments. Many of the individual crack segments also had an oblique orientation. The staff agrees with the licensee that it can be reasonably postulated that the failure of R2C5 occurred when one or more of the ligaments degraded to a critical minimum size causing a zipper like effect and rupture of the other remaining ligaments. The staff notes that it is not clear from the available evidence whether the array of cracks in R2C5 was the source of the operational leakage identified in SG 24 prior to the failure of R2C5.

Only limited eddy current examination of the R2C5 failure location could be performed since the wide crack opening interfered with passage of rotating coils. Bobbin coil examination confirmed the apex location of the crack and its length as being approximately 2.4 inches long. A modified plus-point adapted for this particular crack confirmed these findings and also the extrados location of the crack.

Both the visual and NDE data for R2C5 were ambiguous as to whether the crack had initiated from the inner diameter (ID) surface or from the outer diameter (OD) surface. However, a look back analysis of the 300 and 400 KHz data obtained with the mid-range plus-point probe during the previous inspection of this tube in 1997 indicated that the crack had been present at that time but not detected (Section 3.4.2). Analysis of this signal indicated that the crack initiated from the ID surface. Apart from R2C5, seven additional row 2 tubes were found to contain axially oriented indications, initiating from the ID, at the apex of the u-bends at the extrados.

The staff agrees that the visual and NDE evidence is consistent with the licensee's conclusion that primary water stress corrosion cracking (PWSCC) is the mechanism for crack initiation and growth for the cracks identified in the IP-2 row 2 u-bends. The staff notes that all factors necessary to cause stress corrosion cracking are present in the small radius u-bends; namely high stress, a susceptible material (i.e., Alloy 600), and an aggressive environment (i.e., high temperature primary water). These conditions exist in all u-bends fabricated from Alloy 600. The occurrence of PWSCC and outer diameter stress corrosion cracking (ODSCC) in small radius u-bends is not uncommon. Most of these cracks have occurred at or near the u-bend tangent point locations. However, PWSCC at the apex of the small radius u-bends is relatively uncommon and has caused three tube failures world-wide. The two u-bend failure occurrences preceding the IP-2 failure appear to have been associated with abnormal stress levels existing at each of these units. Section 3.4.1.1 discusses the industry wide experience with u-bend cracks including the two earlier failures and is presented for background purposes. Sections 3.4.1.2, 3.4.1.3, and 3.4.1.4 discuss the staff's evaluation of potential abnormal circumstances that may have existed at IP-2 in terms of stress, material susceptibility, and/or environment, respectively.

3.4.1.1 Operating Experience Pertaining to Cracks in Small Radius U-bends

Historically, the small radius u-bends (rows 1 through 3) have been subject to both PWSCC and ODSCC. PWSCC has typically fallen into one of two categories, PWSCC at "tangent point" locations and PWSCC at apex locations. The tangent point location refers to the transition location of the u-bend to the straight length port of tubing. Tangent point locations for row 1 and 2 u-bends sometimes contain a geometric discontinuity (and resulting residual stress) as a result of use of a ball mandrel during the tube bending process. Tangent point cracking has occurred at many Westinghouse SGs, but has not been observed at Indian Point 2. Tangent point cracks have exhibited very high growth rates as evidenced by the fact that they have led to small leaks necessitating plant shutdown as early as the first operating cycle. Tangent point cracks have historically been a significant contributor to the frequency of forced SG shutdowns. However, these cracks have exhibited good leak before break characteristics and have not caused a tube failure event. Many plants preventively plugged all row 1 and sometimes row 2 tubes. Other plants stress relieved the row 1 and 2 u-bend to reduce the incidence of these kinds of cracks.

PWSCC at the apex of the u-bends is relatively uncommon. Axially oriented PWSCC at the Apex has led to three tube failure events to date, Surry Unit 2 in 1976, Doel Unit 2 (Belgium) in 1979, and Indian Point Unit 2 in 2000. The Surry failure involved a row 1 tube. Subsequent investigation revealed the failure to have been associated with abnormally high stress at the apex due to hourglass deformation of the upper support plate flow slots which in turn was caused by denting. Surry Unit 2 received its operating license in January1973; thus the rate of denting, hourglass deformation, time to crack initiation, and growth rate were relatively high. All row 1 and row 2 tubes at Surry Unit 2 were preventively plugged prior to restart. The staff estimates that roughly half of the row 3 tubes were also preventively plugged at that time. Most of the remaining row 3 tubes were plugged prior to steam generator replacement in 1980. In response to the Surry event, preventive plugging of small radius u-bends was conducted at other plants which had also experienced severe denting and flow slot hourglass deformation at the uppermost support plate. At IP-2, denting was considered by the staff to be severe at that time (Reference 11), although hourglass deformation was only being observed at support plates below the uppermost support plate. Special requirements were added to the IP-2 technical specifications to ensure that the NRC staff would be alerted to any significant change in the status of denting or hourglass deformation of the uppermost support plate (see Section 2.1). With the exception of IP-2, all plants with sufficient denting to have caused hourglass deformation at any of the support plate elevations had undergone SG replacement by the mid-1980s. Denting still continues to pose an operational problem for a number of plants since it continues to cause PWSCC at dented tube to tube support plate intersections; however, the staff is not aware of any plants other than IP-2 that have experienced detectable hourglass deformation in existing steam generators at any of the support plate elevations.

The Doel failure also involved a row 1 tube. Doel had not experienced significant denting or flow slot hour glassing. However, ball gage inspections revealed the row 1 tubes to be ovalized beyond the 10% allowed by the manufacturing specification. Unlike row 1 and 2 tubes at IP-2, the row 1 and row 2 u-bends at Doel were fabricated without use of a ball mandril. The purpose of the ball mandril is to minimize ovality induced by the tube bending process. Ovality at Doel was observed to decrease with increasing row number. The licensee reports that initial cracking did not occur in row 2 at Doel until 1994. The staff notes that the maximum and average ovalities reported for the Doel row 2 tubes was <8.2% and 9.2%, respectively, which were within the manufacturing specification.

Apart from IP-2, there has been one isolated instance of an apex PWSCC indication affecting row 2, Diablo Canyon Unit 2 in 1998, and one affecting row 3, McGuire Unit 1 in 1991 (prior to SG replacement). These steam generators were affected by denting; however, McGuire reportedly contained no evidence of flow slot hourglass deformation. The staff has no information concerning whether there is any hourglass deformation at Diablo Canyon Unit 2. Based on information provided by phone, visual inspection of the lower support plates at Diablo Canyon have revealed no discernable hourglass deformation. In addition, no dents have been identified in the uppermost support plate of the affected SG making it very unlikely that the subject apex indication is associated with hourglassing.

Scattered instances of ODSCC have been observed at both the tangent point and apex locations of row 1, 2, and 3 u-bends at a number of units. Both row 1 and row 2 u-bends at Surry Unit 2 were found to contain ODSCC cracks at the apex during destructive examinations of the tubing in the replaced steam generator following their retirement in 1980. No row 3 ODSCC was found.

3.4.1.2 Stress Considerations

The finding of hour-glass deformation of the flow slot adjacent to R2C5 (the failed tube) provides strong evidence that an abnormal stress condition existed at the apex of that tube. A detailed stress analysis described in Section B.8 of Appendix B indicates that the measured amount of hour-glass deformation, 0.47 inches, is sufficient to increase nominal stress levels (residual stress associated the tube bending process plus nominal pressure and temperature induced stress) in row 2 and some row 3 tubes to above the yield stress thus significantly enhancing the susceptibility of the small radius u-bend to PWSCC attack. (The relative susceptibility between row 2 and row 3 u-bends is discussed in Section B.8 of Appendix B.)

The hourglass deformation associated with the IP-2 failure (0.47 inches) is less than that associated with the Surry Unit 2 tube rupture (1.3 inches). This is consistent with the apparent longer time necessary to initiate and grow cracks at IP-2 as compared to Surry 2.. As discussed in Section 3.2, hourglass deformation at IP-2 was present in the late 1970s and has not changed significantly since the early 1980s based on visual observations of the lower TSPs. That hourglass deformation of the uppermost support plate may date to the late 1970's or early 1980s is consistent with the very low growth rates estimates for the u-bend indications found at IP-2. The hourglass deformation and tube rupture at Surry occurred just 3-1/2 years following issuance of its operating license. The relatively high rate of change of strain in the u-bends may have also contributed to the early failure at Surry.

The licensee's secondary side inspection was not sufficient to confirm that all other row 2 tubes with u-bend indications were adjacent to flow slots which had undergone significant hour-glass deformation (see Section 3.3). However, there are no other factors in evidence which could have contributed to the abnormal state of stress in small radius u-bends. For example, excessive, fabrication-induced ovality such as occurred at Doel does not appear to be a likely contributor to abnormal stress levels in the IP-2 u-bends. Row 1 and 2 u-bends at IP-2 were fabricated with the aide of a ball-mandril device for the explicit purpose of minimizing ovality effects such as were observed at Doel. The staff is not aware of any problems in the U.S. relating to excessive ovality of the small radius u-bends introduced during manufacturing. The staff concludes that all row 2 u-bend cracks were likely caused by the same mechanism which caused cracking in R2C5; namely, denting-induced hour-glass deformation of the adjacent upper support plate flow slots.

The licensee provided tube plugging maps and tube restriction maps for the uppermost support plates for only SG 22 and SG 24. The staff notes that roughly half of the row 2 tubes in SG 22 had been plugged as of 1997. This may explain why no row 2 u-bend cracks were found in SG 22.

The licensee provided very little discussion on the level of tube restriction activity that has existed through the years adjacent to the upper support plate flow slots and how this activity may have been symptomatic of the potential for hourglass deformation.

The licensee's July 29, 1997 letter (Reference 12) summarizing the results of the 1997 SG inspection reported 19 small radius u-bends as restricting passage of a 0.610 inch diameter bobbin probe. These included 15 tubes in row 2, 4 in row 3, and one in row 4. The licensee has reevaluated the 1997 data and concluded in Reference 10 that the probe was actually restricted at the sixth support plate. The licensee was more equivicable in an earlier document where the licensee concluded that its reevaluation revealed no evidence of u-bend restrictions, but that the reevaluation could not absolutely rule out the possibility that some of the u-bends could have been restricted. However, the staff notes that the earlier draft document gave a credible explanation as to why the operator could have recorded the restriction as being in the u-bend when in fact it was likely at the sixth support plate. The staff notes that the majority of the reported u-bend restrictions were in SG 22 which did not contain any of the row 2 tubes with detected u-bend indications. Further, none of the reported restrictions occurred in SG 24 where six of the eight tubes with u-bend indications, including the failed tube were located. In addition, the reported restrictions in SG 21 and SG 23 involve tubes adjacent to flow slots different from those adjacent to tubes containing u-bend indications. The staff concludes that the reported u-bend restrictions in 1997 are very likely a reporting artifact and are likely not related to excessive ovality, either from fabrication or from flow slot hour glassing. However, these restrictions are evidence of denting activity that has been contributing to flow slot deformation.

3.4.1.3 Material Susceptibility to PWSCC

The SG tubing at IP-2, as in virtually all first generation PWR steam generators, was fabricated from Alloy 600, mill annealed (MA). Operating experience has shown Alloy 600 MA tubing to be susceptible to stress corrosion cracking. The licensee reviewed the processing and heat treatment records for the IP-2 tubing and found that the IP-2 tubing had received a relatively high mill anneal temperature, 1850 degrees F, compared to that for tubing at other plants. The staff notes that operating experience and laboratory studies have shown that Alloy 600 MA tubing with a relatively high mill anneal temperature (such as that at IP-2) to be relatively less susceptible to ODSCC and PWSCC than tubing with a lower mill anneal temperature (e.g., 1700 degrees F). The staff concludes that an abnormal condition related to material susceptibility to cracking does not exist at IP-2 and thus was not a contributing factor to the failure of R2C5.

3.4.1.4 Environmental Considerations

High temperature primary water is known to provide an environment which is conducive to stress corrosion cracking. The licensee stated that its primary water chemistry program was developed in accordance with industry guidelines (EPRI PWR Primary Water Chemistry Guidelines). The licensee reviewed its water chemistry performance for the past operating cycle and concluded that boron/lithium concentrations and hydrogen concentrations were maintained within acceptable limits. The staff did not review the licensee's chemistry program or chemistry performance in detail; however, based on the above, abnormal chemistry was not a contributor to the failure of R2C5.

Time to PWSCC initiation is known to be very temperature sensitive. However, IP-2 operates with a T-hot of 590 degrees F which is well within operating temperatures at other plants which have ranged as high as 621 degrees F. The staff finds that operating temperature was well within the industry norm and not an abnormal contributor to the failure of R2C5.

3.4.1.5 Conclusions - Failure Mechanism

The staff concludes that the failure mechanism for R2C5 was PWSCC. The potential for PWSCC was increased as a result of abnormal stress levels induced by hourglass deformation of the uppermost TSP flow slots which was, in turn, caused by corrosion of the TSPs (i.e., denting).

3.4.2 Contributing Factors to the February 15, 2000 Tube Failure - Programmatic Issues

As discussed in a letter to ConEd dated August 31, 2000, [Reference 13: NRC special inspection report from Region 1], the NRC staff concluded that ConEd's technical direction and execution of the 1997 steam generator inspection were deficient in several respects. After identifying, for the first time, a new and significant degradation mechanism (i.e., PWSCC) in the apex region of a row 2 tube, ConEd did not identify the underlying root cause and take corrective action that could have avoided the February 15, 2000 tube failure event. In addition, ConEd did not initiate actions to reassess previous assumptions made about the condition of the low row, small radius tubes. Actions, such as in situ pressure testing and reanalysis of eddy current data from the U-bends, were not undertaken. Nor did they identify or address the amount of noise present in the 1997 eddy current data for the low row, small radius tubes could mask a large flaw. This noise level masked several PWSCC flaws, one of which resulted in the February 15, 2000 tube failure. The staff observed several other areas of weakness in ConEd's technical management of its steam generators such as analyst training and eddy current probe calibration. These other deficiencies in and of themselves did not directly cause the February 15, 2000 tube failure. Additional observations the staff made during the NRC special inspection are discussed in the NRC special inspection report (Reference 13).

3.5 Proposed Corrective Actions

3.5.1 Failure Mechanism

As previously discussed, the failure mechanism for R2C5 was PWSCC. The potential for PWSCC was increased as a result of abnormal stress levels induced by hourglass deformation of the uppermost support plate flow slots which was, in turn, caused by denting.

The licensee's proposed corrective action was to plug all row 2 tubes, irrespective of whether they were found to contain indications during the inspection. Abnormal stress levels due to hourglass deformation extend beyond row 2, but generally attenuate with increasing row number. The proposed corrective action was not intended to eliminate (correct) abnormal stress levels existing beyond row 2, but simply to remove from service those tubes most likely to contain significant, but undetected flaws (i.e., row 2 tubes) which could potentially impair tube integrity during the requested four month operating interval. The licensee's operational assessment, which includes an assessment of the relative susceptibility of row 2 and row 3 u-bends to PWSCC, was intended to constitute the technical justification for the proposed corrective action. The staff's evaluation of that assessment is presented in Section 3.6.1. The staff had not reached a final conclusion at the time ConEd decided to replace the SGs rather than to return the existing SGs to service.

3.5.2 Corrective Actions Taken in Response to Programmatic Issues

ConEd implemented several corrective actions during the course of this inspection. For the low row U-bends, these actions include:

- use of the high frequency +Point probe in rows 2 and 3 to detect smaller PWSCC flaws and reduce noise signals,
- use of the high frequency +Point probe in row 4 for tubes with poor data quality,
- more robust and documented training program to improve analyst sensitivity to PWSCC,
- use of tertiary review of the U-bend data to confirm inspection results,
- plugged all row 2 tubes, including tubes without detectable degradation,
- applied a noise criteria and plugged row 3 and row 4 tubes with poor data quality,
- shortened operating cycle,
- more stringent operational leakage requirements, and
- planned SG replacement

No conclusions had been reached concerning the adequacy of these corrective actions to support operation with the existing SGs at the time the licensee decided to commence SG replacement. The planned SG replacement obviates the need for many of these corrective actions.

3.5.3 Operational Restrictions

3.5.3.1 Operating Interval Restriction

By letter dated June 2, 2000 (Reference 3), the licensee concluded on the basis of its attached operational assessment report (initial operational assessment) that continued operation of the currently installed steam generators would require more frequent inspection such that mid-cycle outages will be needed. The licensee stated that its initial assessment, discussed in Section 3.6, supports an SG operating interval of 1.0 effective full power year (EFPY) consistent with maintaining adequate structural and leakage integrity of the tubing. The licensee further stated that the operating time to "mid-cycle" was 0.85 EFPY which is when the mid-cycle inspection would be "recommended." However, the licensee noted that as electric power production of the plant is currently limited by steam flow to the turbine with the throttle valves fully open, the number of tubes requiring plugging as a result of the 2000 inspection program will result in a 3 to 4% output reduction. Accordingly, the licensee concluded that the steam generators were nearing the end of economic life and that replacement of the steam generators would begin by the end of this year (2000), prior to the time a mid-cycle inspection would be needed.

Subsequent letters from the licensee, dated July 7 and July, 27, 2000 (References 14 and 15), supplemented the initial operational assessment to address the sensitivity of tube integrity and leakage margins to limiting the length of the SG operating interval to as little as 0.33 EFPY. As discussed in Section 3.6.1, the staff has reviewed the licensee's assessment but had not reached a conclusion regarding whether tube integrity can be assured upon plant restart or for how long after restart it could be maintained when the licensee decided not to restart with the existing steam generators.

3.5.3.2 Operational Leakage Restrictions

The technical specification LCO limit on operational primary-to-secondary leakage is 0.3 gallons per minute (gpm) which is equivalent to 432 gallons per day (gpd).

The licensee's leakage monitoring program was developed consistent with the EPRI PWR Primary-To-Secondary Leakage Guidelines. The licensee utilizes diverse methods for monitoring leakage including the use of N-16 monitors, air ejector radiation monitors, and analysis of chemistry samples. The N-16 monitor has a number of alarm set points beginning at 5 gpd and ranging to the administrative leakage limit. The licensee's program includes administrative limits on allowable leakage which are substantially more restrictive than the LCO limits in the technical specifications. These administrative limits have been revised downward, in response to the failure event on February 15, 2000, to one-half the values in the latest (February 2000) revision to the EPRI guidelines. These include a 30 gpd leak rate limit for a period of >1 hour where the rate of leakage increase is less than 15 gpd/hour. Under these circumstances the unit must be in Mode 3 within 24 hours. However, if the rate of leakage increase exceeds 15 gpd/hr at the time the leak rate exceeds 30 gpd, the plant must be at less than 50% within two hours and in Mode 3 in the next 2 hours.

The NRC AIT report (Reference 2) noted some shortcomings in the licensee's implementation of the monitoring program; for example, the N-16 strip chart recorder had been out of service for *several weeks* prior to the tube failure event. Overall, however, the license's program proved very effective in its ability to detect leakage at a very low level (<1 gpd) and in monitoring and trending this leakage over time. The tube failure event appears in no way related to shortcomings in the licensee's ability to monitor and trend the leakage.

Operating experience indicates that degraded SG tubes usually, but not always, exhibit leak before break behavior. There have been 188 unplanned or forced plant shutdowns in the U.S. since 1975 due to SG tube leakage. These unplanned shutdowns typically involve maximum leak rates ranging from 50 to 1000 gpd (0.035 to 0.7 gpm). Only eight of these shutdowns involved a tube rupture or failure event with leak rates exceeding 100 gpm. Effective leakage monitoring in conjunction with implementation of appropriate leakage limits has proven to be an effective approach for minimizing the incidence of tube failure and for providing added assurance of tube integrity. The current trend in the industry to adopt more and more restrictive administrative leakage limits will further their effectiveness in preventing tube ruptures. However, these programs can never provide complete assurance against tube rupture even if the leakage limits are reduced to zero. This is evidenced by the fact that three of eight tube failures in the U.S. occurred without precursor leakage until moments before the event.

Precursor leakage at IP-2 prior to the event was extremely low level and trending up very slowly, reaching a maximum value of only 3.4 gpd (per N-16) immediately prior to the event. It is not known to what extent leakage from R2C5 contributed to the operational precursor leakage. In-situ pressure testing indicated that R2C71 may have been contributing about 1.2 gpd. The secondary side hydro test indicated that some of the tube plugs were leaking. Therefore, it can only be concluded that R2C5 was leaking somewhere between zero to about 2.2 gpd prior to the event. This low level of precursor leakages suggests that cracked small radius u-bends may be expected in general to exhibit poorer leak-before-break behavior than is typically the case for degraded tubing. The staff notes that in-situ pressure tests discussed in Section 3.3.1 indicate that one tube, R2C69, only leaked after being pressurized close to the point of possible incipient burst. The staff believes that this tube may be another example of a tube (besides R2C5) exhibiting poor leak before break behavior. R2C71 and R2C74 exhibited initial ligament tearing and low level leakage well in advance of the likely burst pressures and may be examples of tubes which may exhibit a little better leak before break performance.

The staff concludes that the administrative leakage limits being implemented by the licensee are more restrictive than industry guidelines and what is typically being implemented by other licensees. Although these limits are expected to be of little benefit in terms of precluding failure of u-bends affected by apex cracking, they are expected to be effective for ensuring timely plant shutdown should other active degradation mechanisms at IP-2 lead to leakage during service. The integrity of the u-bends can only be ensured through adequate inspections and by limiting the length of the upcoming operating interval sufficiently to ensure that tube integrity is maintained.

3.6 Operational Assessment

The licensee's operational assessment is documented in its CMOA report submitted by letter dated June 2, 2000 (Reference 3) and supplemented by letters dated July 7and July 27, 2000 (References 14 and 15). The purpose of operational assessments in general is to demonstrate that adequate structural margins and leakage integrity will be maintained until the next scheduled SG inspection outage. For Indian Point 2, the initial operational assessment was intended to demonstrate that adequate structural margins and leakage integrity will be maintained for at least 0.85 EFPY. This 0.85 EFPY period extends beyond the end of calendar year 2000 at which time the licensee stated it planned to shutdown for SG replacement. References 14 and 15 described the sensitivity of the initial assessment to assumed values of key input parameters and to shorter operating intervals ranging to as little as 0.33 EFPY.

The success criteria for structural margins and leakage integrity used for the IP-2 operational assessment are termed performance criteria and are the same as those used in the condition monitoring assessment (Section 3 of this SE), consistent with NEI 97-06, Revision 1b (Reference 4). These criteria are discussed in Section 3.3 of this SE and are acceptable to the NRC for reasons discussed in that section.

Draft NRC guidelines for performing operational assessments are contained in DG-1074 (Reference 6) which is publically available. These draft regulatory guidelines do not constitute regulatory requirements. However, the staff observes that the licensee's operational assessment followed a strategy generally consistent with DG-1074 but with some important differences in detail as discussed below.

3.6.1 PWSCC in the Low Row U-Bends

The staff finds that it is reasonably established (see Section 3.4.1) that the tube failure event at IP-2 on February 15, 2000 was the result of primary water stress corrosion cracking (PWSCC) at the apex of a row 2 u-bend (i.e., R2C5) at the extrados. Subsequent NDE inspections with the mid-range and high frequency plus point probes revealed seven additional row 2 tubes with PWSCC indications at the apex of the u-bend at the extrados. No PWSCC indications were identified in the row 3 u-bends or beyond. The licensee elected to plug all row 2 tubes irrespective of whether they were found by inspection to contain PWSCC indications. This was done to minimize the likelihood of any new or undetected cracks in the small radius u-bends.

The licensee's operational assessment conservatively assumes that row 3 u-bends are equally susceptible to PWSCC as row 2 tubes which have not yet developed detectable cracks. The staff's evaluation of this operational assessment is discussed in detail in Appendix B of this safety evaluation. The licensee also assessed the relative susceptibility of row 3 to row 2 u-bends to demonstrate the operational assessment is conservative for row 3. The staff's evaluation of that assessment is discussed in detail in Section B.7 of Appendix B. The staff findings resulting from its evaluation of these assessments are summarized below.

The licensee analyzed the condition of the tubing vis-a-viz the applicable performance criteria as a function of time upon plant restart. The licensee concluded that the applicable performance criteria would be met for a period extending beyond the requested 0.85 EFPY operating interval. However, key input parameters for the analysis involve significant uncertainties. These include the assumed NDE probability of detection (POD) of PWSCC in the IP-2 small radius u-bends, the assumed NDE measurement error distributions, and the assumed growth rates for PWSCC in the IP-2 small radius u-bends. These uncertainties stem from a lack of validation of the assumed NDE flaw detection and sizing performance against destructive examination results of u-bend specimens containing ID cracks in a noise environment such as exists at IP-2. The licensee did not remove u-bend samples from the IP-2 SGs in order to validate the assumed NDE detection and sizing performance; but did initiate a program to fabricate laboratory specimens containing ID cracks to characterize NDE detection and sizing performance. Unfortunately, this program will not be completed until after the steam generators are replaced. In the meantime, the licensee assumed POD functions and flaw size measurement error distributions consistent with what was validated for PWSCC at dents. Based on a comparative noise study performed by the licensee, the staff finds that the noise levels during the high frequency plus point inspection of the small radius u-bends to be significantly higher than the relevant noise level for the dented tube data set. The mid-range probe, which was utilized to size the u-bend indications and to perform crack growth rate estimates, exhibited significant noise and signal distortion rendering sizing measurement error performance in the IP-2 u-bends particularly uncertain when compared to the dented tube data set.

The staff's review also indicates that the licensee's methodology for estimating the frequency and size distribution of undetected u-bend cracks is insensitive to the NDE measured flaw sizes for the flaws found during the inspection. This adds additional uncertainty to the analysis and appears to be an artifact of the "fractional flaw" approach in conjunction with use of a POD which varies as a function of crack size (see Section B.1 in Appendix B). Finally, the estimated crack growth rates appear to be highly uncertain, reflecting in large measure the high degree of uncertainty concerning the flaw sizing measurements with the mid-range probe. Although the licensee performed sensitivity analyses relating to the major modeling and input parameter uncertainties of the analysis, there is little basis to estimate a quantitative lower bound on these uncertainties relative to the 3 delta P limit, either at BOC or later into the operating interval.

The above discussion is based on the premise that undetected flaws are present in row 3 tubes, just below the threshold of detection. The licensee performed an analysis, described in Appendix B, Section B.7, to assess the relative time to cracking between row 2 and row 3 tubes based on their comparative stress levels. The licensee concluded that the time to crack initiation is 1.7 times as long for the most susceptible row 3 tube as for the most susceptible row 2 tube. The licensee did not address the significance of this result in terms of when row 3 tubes could be expected to initiate and grow to just below the threshold of crack detection. The staff finds that this result provides little insight on whether cracks may or may not have initiated in row 3 due to uncertainties in how long significant hourglass deformation (leading to an abnormally high state of stress at the apex of the u-bends) may have been present and uncertainty as to when cracks first initiated in row 2. The staff does acknowledge, however, that given the absence of detected row 3 tubes, the growth of an undetected row 3 indication to just below the detection threshold at the precise time that R2C5 failed and the inspection program was conducted would appear to be a relatively unlikely coincidence. The staff finds this to be a major element of conservatism.

The staff did not identify concerns about the operability of row 4 tubes. The most susceptible row 3 tubes can be expected to develop cracks before the most susceptible row 4 tubes just as the most susceptible row 2 tubes can be expected to crack before the most susceptible row 3 tubes. Given that no row 3 tubes contained detectible PWSCC indications during the 2000 inspection, there is reasonable assurance that any cracks in the row 4 u-bends would be inconsequential for the duration of the operating interval requested by the licensee.

3.6.2 ODSCC in the Sludge Pile Region and Other Degradation Mechanisms

For ODSCC in the sludge pile region, ConEd used an operational assessment methodology analogous to that used for PWSCC in the low row U-bends described in Appendix B. They concluded from their operational assessment that tube integrity would be satisfied for an operating period of 1 EFPY. For other degradation mechanisms such as tubesheet crevice indications and expansion zone cracks, ConEd used more qualitative arguments and concluded that tube integrity would be satisfied for an entire operating cycle. Based on the condition monitoring results discussed earlier in section 3.3.2, the staff concluded that the operational assessment for ODSCC in the sludge pile region is bounding for all other degradation mechanisms, excepting PWSCC in the low row, small radius U-bends. Therefore, the staff focused its review on the operational assessment for ODSCC in the sludge pile region, and the staff's conclusions for an acceptable operating cycle length for this degradation mechanism apply to all other degradation mechanisms as well, with the one exception of PWSCC in the low row, small radius U-bends.

ConEd used a methodology similar to that applied for the low row, small radius U-bends; therefore, many of the staff concerns discussed earlier in Appendix B concerning the PWSCC operational assessment apply also to the ODSCC operational assessment. Because these concerns could not be resolved in a timely way, the staff's approach to evaluating an appropriate operating cycle length for ODSCC in the sludge pile region relied upon a qualitative assessment. This approach, although not as sophisticated as the Monte Carlo analysis provided by ConEd, provides reasonable assurance that also justifies an operating period of 1 EFPY for ODSCC in the sludge pile region. This conclusion is based on the following observations:

- During the 1997 inspection, ConEd applied a combination Cecco/bobbin probe to inspect the sludge pile region of the steam generators. They plugged all tubes with cracklike indications and ran for approximately 1.48 EFPY until the February 15, 2000 tube failure. During the 2000 inspection, ConEd in situ pressure tested all tubes with cracklike indications in the sludge pile region. All tubes demonstrated adequate tube integrity with one exception. Tube #22-R34C51 began to leak at a rate of 0.0027 gpm at about 4678 psi. ConEd continued to pressurize the tube up to 4985 psi with a leakage of 0.0089 gpm when they lost pressurization capability. The 3ΔP criterion was 5042 psi. The staff concluded that although this tube did not fully demonstrate 3ΔP performance, the failure pressure was very close to the 3ΔP criterion and the tube would have satisfied the 3ΔP criterion for the majority of the previous operating cycle.

- During the 2000 inspection, ConEd applied a +Point probe to inspect the sludge pile region of the steam generators. The inspection scope was discussed in detail previously in section 3.1. The +Point probe inspection reduced noise levels in the eddy current data. This would enhance analysts' ability to detect flaws. It was also observed that additional indications were identified through the expanded +Point inspection program. Also, the scope of the inspection program was increased from the 1997 inspection to include a greater axial extent of tube inspected above the top of the tubesheet and a larger population of tubes on the cold leg side of the steam generators. Thus, overall we conclude that ConEd obtained a better inspection of the sludge pile region than was obtained in 1997.

To summarize, ConEd pressure tested all tubes with ODSCC indications and had one tube that marginally failed the 3ΔP criterion after being in operation 1.48 EFPY. ConEd obtained a better inspection during the 2000 outage. Based on the combination of a shorter cycle time and an improved, more sensitive inspection of the sludge pile region, the staff concluded that an operating cycle of 1 EFPY for ODSCC in the sludge pile region is justified.

References

1. Letter dated May 12, 1999 from James S. Baumstark (ConEd) to NRC Document Control Desk, "Response to Request for Additional Information - Proposed Amendment to Technical Specifications Regarding Steam Generator Tube Inservice Inspection Frequency"

2. Letter dated April 28, 2000 from Hubert J. Miller (NRC) to A. Alan Blind (ConEd), "NRC Augmented Inspection Team - Steam Generator Tube Failure - Report No. 05000247/2000-002."

3. Letter from John F. Groth (ConEd) to William Travers (NRC), dated June 2, 2000, "2000 Refueling Outage Steam Generator Inspection Condition Monitoring and Operational Assessment Reports"

4. NEI 97-06 (Rev 1B), "Steam Generator Program Guidelines," January 2000.

5. Letter, D. Modeen, NEI, to S. Collins, NRC, "Industry Steam Generator Program Generic License Change Package," dated February 4, 2000.

6. Draft Regulatory Guide DG-1074, "Steam Generator Tube Integrity," December 1998.

7. Letter dated April 14, 2000 from James S. Baumstark (ConEd) to NRC Document Control Desk, "Root Cause Evaluation For Steam Generator Tube Rupture Event of February 15, 2000."

8. Letter dated June 13, 2000 from James S. Baumstark (ConEd) to NRC Document Control Desk, "Response to the Staff's Questions Regarding the Root Cause Evaluation For Steam Generator Tube Rupture Event of February 15, 2000."

9. Letter dated June 15, 2000 from James S. Baumstark (ConEd) to NRC Document Control Desk, "Response to the Staff's Questions Regarding the Root Cause Evaluation For Steam Generator Tube Rupture Event of February 15, 2000."

10. Letter dated June 16, 2000 from James S. Baumstark (ConEd) to NRC Document Control Desk, "Response to the Staff's Requests for Additional Information (RAI) Regarding the Steam Generator Tube Examinations Conducted During the Spring of 2000 Outage, and the Root Cause Evaluation For Steam Generator Tube Rupture Event of February 15, 2000," dated June 16, 2000.

11. NUREG-0886 dated February 1982, "Steam Generator /tube Experience."

12. Letter dated July 29, 1997 from Stephen E. Quinn (ConEd) to NRC Document Control Desk, "Steam Generator Tube Inservice Examination 1997 Refueling Outage."

13. NRC Special Inspection Report - Steam Generator Tube Failure - Report No. 05000247/2000-010, dated August 31, 2000.

14. Letter (No. NL#00-085) dated July 7, 2000 from James S. Baumstark (ConEd) to NRC Document Control Desk, "Response to Staff Request for Additional Information (RAI) Regarding Steam Generator Operational Assessment Report."

15. Letter (No. NL-00-099) dated July 27, 2000 from James S. Baumstark (ConEd) to NRC Document Control Desk, "Responses to NRC's Request for Additional Information (RAI) Regarding Steam Generator Operational Assessment Report."

Appendix A

Condition Monitoring Assessment for the Small Radius U-Bends

The SG tube failure event on February 15 involving tube R2C5 in SG 24 indicates the IP-2 SGs failed to meet the applicable performance criteria during cycle 14 operation. The tube failure occurred under normal operating differential pressure (1539 psi) and temperature (T_{hot} = 590°F). The maximum primary-to-secondary leak rate during the event was 146 gpm, substantially exceeding the operational leakage performance criterion of 150 gpd. Westinghouse states on the basis of video camera inspection that there is no evidence that the failure was a tube "burst" involving crack extension at the tips of the crack or fishmouth. Based on the measured length of the flaw, however, the staff concludes that the actual burst strength of the tube was likely just slightly higher than 1539 psi. Thus, tube R2C5 did not satisfy the applicable performance criteria for burst margins during normal operation or postulated accidents and would have very likely burst had it been challenged by a MSLB in the months leading up to the failure event. In addition, R2C5 would have leaked in excess of the performance criterion for accident induced leakage given the occurrence of a MSLB in the months leading up to the failure event. Look back (hindsight) analysis of previous inspection data for R2C5 indicates that the flaw which led to the failure was present during the 1997 inspection outage. The licensee's calculations indicate that R2C5 failed to satisfy the performance criteria on burst margins even at that time, based on a best estimate flaw size measurement using the 1997 NDE data and an assumed flow stress of 79.4 ksi. Based on these calculations, the staff estimates the period of vulnerability during which R2C5 would have burst or leaked excessively given the occurrence of a design basis MSLB to be 0.86 effective full power years (EFPY) leading up to the failure event. (0.86 EFPY translates to approximately one year at a plant temperature above 200 degrees F.) The staff notes there is significant uncertainty associated with these estimates since the NDE flaw size measurements may be subject to significant error (see Section 3.6.1.2).

Causal factors leading to the failure of R2C5 are discussed in Section 3.4, "Contributing Factors to Condition Monitoring Failures" including failure mechanisms and programmatic deficiencies. The licensee's corrective actions are discussed in Section 3.5, "Proposed Corrective Actions."

Apart from R2C5 in SG24, the licensee found 7 additional row 2 U-bends tubes with PWSCC indications at the apex location. Each of the affected tubes was in-situ pressure tested to confirm adequate structural and leakage integrity consistent with the applicable performance criteria. The tests were whole tube tests with seals located near each tube end. The tubes were pressurized with water under room temperature conditions. The staff estimates from representative pressure versus time charts that the pressurization rate for these tests was relatively low; i.e., less than 1000 psi per minute. The test procedure involved pressurizing the tube to a pressure (temperature adjusted) equivalent to normal operating pressure differential and performing a leakage measurement. The pressure was then increased to a pressure equivalent to MSLB and another leakage measurement performed. The pressure was then increased to a maximum of 5500 psi, exceeding the pressure (4992 psi) equivalent to three times normal operating pressure.

Four of the seven tubes tested were tested to 5500 psi with no leakage, thus satisfying all applicable performance criteria. Based on the measured pre-test crack profiles determined with the mid-range probe at 400 KHz, three of these four tubes had expected (best estimate) burst pressures ranging from 8838 to 11314 psi using the burst prediction model discussed in Section 3.6.1.5. Expected ligament tearing pressures ranged from 8835 to 11664 psi using a ligament tearing model which is also discussed in Section 3.6.1.5. For these reasons, the in-situ data for these three tubes provide little insight into the accuracy of the NDE flaw sizing measurements. The fourth tube (R2C72) had expected burst pressures of 6219 psi and 5728 psi based on flaw profiles determined at 400 KHz with the mid-range probe and at 800 KHz with the high frequency probe, respectively. Expected ligament tearing pressures were 6022 psi and 5466 psi, respectively. Allowing for material strength and predictive model uncertainties (which are significant), the most that can be concluded for this tube is that the NDE measured profiles were likely not significantly underestimated. The staff notes that this tube had a fairly substantial voltage response, 3.17 volts at 400 KHz and 3.6 volts at 800 KHz.

A fifth tube, R2C74, exhibited no leakage at test pressures equivalent to normal operating conditions and MSLB. This satisfied condition monitoring criteria with respect to operational and accident induced leakage. Leakage was not observed until a test pressure of 4800 psi was reached. The measured (unadjusted, cold) leak rate at that pressure was 0.35 gpm. The leakage increased to 0.112 gpm as the tube was pressurized to the maximum test pressure of 5500 psi when the test was terminated. The post test profile of the indication at 800 KHz indicates a total crack length of 0.39 inches and an average crack depth over that length of 83%. The staff concurs that the as-measured post test profile suggests that the tube was not yet in a state of incipient burst. Thus, this tube can reasonably be judged to satisfy the 3ΔP criterion. Assuming the measured length to be correct, the average depth must be somewhat less than the measured value to explain why general ligament tearing did not occur over the entire length of the flaw before the test was terminated. However, localized tearing had already initiated as indicated by the leakage during the test. The post-test crack profile suggests that the tube may have been near the threshold of general ligament tearing. Given general ligament tearing over the 0.39 inch sometime prior to burst, the staff calculates a best estimate burst pressure of 6000 psi.

Pre-test NDE measurements significantly underestimated the size of the flaw in R2C74. The pre-test flaw profile for this tube as measured at 400 KHz exhibited a length of 0.11 inches with a maximum depth of 38% and an average depth of 19.4%. Based on these measurements, the burst and ligament tearing models (see Section 3.6.1.5) would predict a best estimate burst strength of 12,200 psi, and a ligament tearing pressure over the measured length of the crack of 11,100 psi leading to leakage less than that observed during the test. The 800 KHz measurements appear to be more accurate, but still significantly underestimate the size of the flaw. The 800 KHz data indicated a flaw length of 0.16 inches, a maximum depth of 53%, and an average depth of 39%. Based on these measurements, the licensee calculated a best estimate burst and ligament tearing pressure of 10202 psi.

A sixth tube, R2C69, had no leakage until a test pressure of 5172 psi was reached, thus satisfying the applicable performance criteria including the equivalent 3ΔP pressure of 4992 psi. A ligament tear at 5172 psi caused a leak in excess of the 2 gpm test system makeup capacity and the test was terminated. A subsequent leak test at 300 psi produced a leak rate of 2.5 gpm, indicating that significant ligament tearing and plastic crack opening had occurred. Post test examination of the flaw at 800 KHz with the high frequency probe could only be performed over a small portion of the crack profile since the probe became stuck.

While it can not be conclusively demonstrated, the evidence is generally consistent with a presumption that tube R2C69 was in a state of incipient burst at the time the test was terminated. The licensee estimated burst pressures of 6503 psi and 5235 psi based on the pre-test flaw profiles measured at 400 KHz and 800 KHz, respectively. The licensee estimated ligament tearing pressures of 5796 psi and 4580 psi for the pre-test flaw profiles measured at 400 KHz and 800 KHz, respectively. The burst and ligament tearing estimates based on the 800 KHz flaw measurements seem reasonably consistent with what has been observed from the test. These estimates suggest the possibility that the 400 KHz data has significantly underestimated the flaw dimensions. However, these comparisons are confounded by uncertainties in the assumed prediction models, material properties, and in how to interpret the test results.

The seventh tube, R2C71, exhibited low level leakage from the time pressurization was initiated. At an adjusted test pressure equivalent to normal operating pressure, the measured leak rate (adjusted to reflect operating temperature) was 0.12 gpd. This suggests that R2C71 was not a significant contributor to the measured leak rate of 3.4 gpd (per N-16) at IP-2 minutes prior to failure of R2C5.

The leak for R2C71 reached a temperature adjusted value of 0.024 gpm at a test pressure equivalent to MSLB pressure. R2C71 is the only tube which leaked during in-situ testing at a pressure equivalent to MSLB, including tubes affected by other degradation mechanisms (see Section 3.3.2). Thus, apart from R2C5 (the failed tube), the licensee concludes that total leakage from all other tubes during a postulated MSLB would be less than the applicable performance criterion of 1 gpm.

The leak rate escalated more rapidly as R2C71 was pressurized above MSLB pressure. The tube could not be pressurized beyond 4500 psi (unadjusted) when the leak rate reached the 2 gpm (unadjusted) test system capacity. This test pressure was less than the equivalent 3ΔP pressure of 5172 psi. A subsequent leak test of the tube at 1000 psi produced a 0.77 gpm leak. These tests plus a post-test NDE of the flaw indicated ligament tearing and plastic crack opening had taken place. This suggests that the test was terminated at or very near the threshold of ligament tearing over at least 0.35 inch length taking the post test NDE measurements at face value. Loss of the ligament would leave a through wall crack measuring about 0.7 inches long at the ID and about 0.35 inches long at the OD. The transition from the 0.7 inch length to 0.35 inches occurs abruptly at a depth of 70% of the tube wall thickness. The staff estimates a critical length of 0.6 inches at 4500 psi (cold) and 0.55 inches at 4800 psi (cold) where the cracks are of uniform length over their depth. Available ligament tearing and burst models for SG tubing do not allow one to assess this through wall geometry directly. It is the staff's judgement that the remaining ligament following loss of the 0.35 inch long ligament would not add significantly to the strength of the 0.7 inch long crack and, thus, burst would not be expected to occur at a significantly higher pressure than ligament tearing over the 0.35 inch length. Whether R2C71 was capable of meeting the 3ΔP criterion remains questionable.

Based on the pre-test 400 and 800 KHz profiles, the licensee estimated a ligament tearing pressure of 5215 psi and 4605 psi and a burst pressure of 5799 psi and 4828 psi (best estimate calculations). The burst and ligament tearing estimates based on the 800 KHz flaw measurements seem reasonably consistent with what has been observed from the test. These estimates suggest the possibility that the 400 KHz data has underestimated the flaw dimensions. These comparisons, however, are confounded by uncertainties in the assumed prediction models, material properties, and in how to interpret the test results.

Appendix B

Operational Assessment for PWSCC in Small Radius U-Bends

The staff finds that it is reasonably established (see Section 3.4.1) that the tube failure event at IP-2 on February 15, 2000 was the result of primary water stress corrosion cracking (PWSCC) at the apex of a row 2 u-bend (i.e., R2C5) at the extrados. Subsequent NDE inspections with the mid-range and high frequency plus point probes revealed seven additional row 2 tubes with PWSCC indications at the apex of the u-bend at the extrados. No PWSCC indications were identified in the row 3 u-bends or beyond.

The licensee elected to plug all row 2 tubes irrespective of whether they were found by inspection to contain PWSCC indications. This was done to minimize the likelihood of any new or undetected cracks in the small radius u-bends. However, the licensee's operational assessment conservatively assumed that only the row 2 tubes with detected indications were plugged. In effect, this assessment assumed that the row 3 tubes are equally likely to contain undetected PWSCC flaws or to develop new flaws as row 2 tubes without detected indications. The licensee's operational assessment is documented in Reference B1 with supplemental information in References B2 through B5.

The staff's evaluation of the licensee's operational assessment for u-bend PWSCC is discussed in Sections B.1 to B.8 below. Section B.1 discusses the flaws assumed to exist at the time of plant restart (i.e, beginning of cycle (BOC)). For each assumed BOC flaw, uncertainty distributions concerning NDE measurement error (Section B.2) and flaw growth (Section B.3) were randomly sampled to yield a corresponding flaw size at the next scheduled outage for SG inspection or replacement (i.e., termed "end of cycle" (EOC) for convenience). For each EOC flaw determined in this manner, uncertainty distributions for burst pressure (Section B.5) and accident induced leak rate (Section B.6) were sampled, resulting in a burst pressure and accident induced leak rate estimate. This statistical sampling approach is referred to as a Monte Carlo simulation. For a given BOC indication, thousands of such simulations were performed resulting in a distribution (i.e., probability density function) of EOC burst pressures for that indication (Section B.5). The distribution of burst pressures was evaluated at the lower 95% probability value of the distribution at 95% confidence (i.e., 95/95 lower bound) viz-a-viz the limiting 3 delta P structural performance criterion (4668 psi). For accident induced leakage, leakage estimates for each indication during each simulation were added together to yield a total SG u-bend leakage estimate for that simulation (Section B.6). Again, thousands of simulations were performed resulting in a distribution of total SG u-bend leak rate. This distribution was evaluated at the 95/95 upper bound. This 95/95 upper bound estimate for the u-bends was added to similar estimates for other IP-2 degradation mechanisms to yield a total accident leak rate estimate, which in turn was evaluated relative to the applicable performance criterion of 1 gpm (Section 3.3). This general approach, as outlined above, is consistent with the staff's draft guidelines in DG-1074 (Reference B6). Section B.7 discusses the relative susceptibility of row 3 tubes compared to row 2 tubes. Section B.8 discusses the staff's overall conclusions concerning the operational assessment for the small radius u-bends.

B.1 BOC Flaw Distribution in Small Radius U-Bends

The licensee has plugged all tubes found by inspection during the 2000 inspection to contain indications in the small radius u-bends (which were confined solely to row 2). Accordingly, any indications remaining in the small radius u-bends at BOC must be undetected indications.

The traditional approach for assessing the potential for undetected indications is to consider the probability of detection (POD) performance of the inspection technique as a function of flaw size or other surrogate parameter as determined from a performance demonstration. The staff's guidance in DG-1074 (Reference B6) highlights the importance of performance demonstration data for purposes of quantifying NDE detection performance. Unfortunately, no such performance demonstration has been performed for actual u-bends with actual inner diameter cracks in the presence of copper bearing deposits such as exists at IP-2. The licensee has only now initiated such a program but will not have results until after the steam generators have been replaced. The EPRI Appendix H qualification of the high frequency probe is not considered acceptable for quantifying detection and sizing performance for PWSCC since it was performed mainly on test samples with EDM notches with only two samples containing actual cracks. EDM notches exhibit higher voltage responses than cracks due to their larger volume and, therefore, are easier to detect and to size.

In the absence of directly applicable POD data, the licensee utilized POD versus crack depth curves obtained from a formal performance demonstration program performed with the mid-range plus point for PWSCC at non-symmetrical dents. The licensee believes that the dents comprise a detection and sizing challenge comparable to that of the u-bends and that use of the available POD data for the mid-range probe at dents should be conservative for the high frequency probe at the u-bends.

In its initial June 2, 2000 submittal (Reference B1), the licensee utilized POD curves plotted as a function of crack depth. By letter dated July 7, 2000 (Reference B2), the licensee submitted a supplemental operational assessment for the small radius u-bends. The supplemental assessment is based on an alternative POD curve plotted as a function of crack effective area. Again, the POD curve is based on data for dented intersections. The licensee believes that the voltage response and detection can reasonably be expected to correlate better with crack effective area than with crack depth or crack length individually. This approach allows for deep but very short flaws to have a low POD similar to long but very shallow flaws, but long, deep flaws to have a relatively high POD. The staff agrees that relating POD to crack area represents a more realistic approach than relating it to crack depth.

The staff notes, however, that there are differences in attributes between dented tube locations and u-bends which may affect relative noise levels and signal to noise ratios and which, therefore, may affect relative detection performance. These attributes include (but are not necessarily limited to) OD surface deposits, ID surface imperfections, tube ovality, and the tight radius of curvature in the small radius u-bends.

To address this issue, the licensee submitted by letter dated August 4, 2000 (Reference B4) a comparative study of the noise levels present in the small radius u-bend high frequency probe 800 KHz data versus that present in the POD data set. The licensee reported that the average vertical noise component was 0.21 volts for the row 2 u-bends and 0.17 volts for the row 3 u-bends. These compare with average vertical noise components in the POD data set of 0.20

volts at the edge of the support plate and 0.13 volts at the center. Peak-to-peak noise amplitudes were generally twice as high for the u-bends as for the edge and center locations of the POD data set and over three times that of the flaw sizing data set. Comparison of the vertical noise components is most relevant to assessing relative detection capabilities. The licensee concludes that the vertical noise components are in good agreement between the u-bends and POD data set and support application of the POD curves deriving from that data set to the IP-2 u-bends.

The staff's review of the POD data set indicates that the noise levels along the 1-inch length of the support plate intersection spike at the edges and the middle of the intersection due geometric discontinuities. The noise signals considered by the licensee for the POD data set appear to correspond to these spikes. It is the staff's opinion that these spikes only affect crack detection in cases of very short cracks (< 0.2 inches) located at the spike location. Although the staff reviewed the data for only a few of the samples in the data set, it is the staff's expectation that most of the cracks in the data set are longer than 0.2 inches and that significant portions of these cracks would be present between the noise spikes. Thus, it is the noise level between the spikes rather than at the spikes which will typically govern the delectability of these flaws and which is of primary interest for purposes of comparing with noise levels in the u-bends. The staff concludes that the licensee's August 4, 2000 submittal does not resolve the staff's concerns relating to the comparative noise levels between the IP-2 u-bends and the POD data set.

To account for uncertainties relating to the use of POD data for dents, the licensee has included the uncertainty distribution about the POD curve in its supplemental operational assessment. This uncertainty distribution reflects the uncertainty of fitting the POD data set and does not reflect the uncertainty of applying the POD curve to the IP-2 u-bend inspections. The staff is concerned that this POD curve may be biased in the non-conservative direction because of higher noise levels in the u-bends.

The licensee has also performed analyses assessing the sensitivity of the analysis to the assumed POD function. Based on the POD function assumed in the analysis, the licensee's analysis would indicate the 95% lower bound burst pressure for the most limiting undetected indication to be 5620 psi at the time of restart. (The staff extrapolated this value from values actually reported by the licensee for .333 EFPY and 1.7 EFPY after restart.) Shifting the POD curve in the conservative direction by a factor of 1.5 decreases the limiting burst pressure from 5620 to 4979 psi. A factor of 2 shift would decrease the limit burst pressure to 4675 psi, just meeting the 3 delta P criterion of 4668 psi. The licensee states that the 1.5 shift is a good approximation of the POD fit to the POD data set evaluated at the 95% confidence level. The factor of 2 shift is comparable to a 99% confidence level fit to the POD data set. The staff concludes that the results of the analysis are quite sensitive to the assumed POD function. How much of a shift in the POD curve would be appropriate for the IP-2 u-bends is uncertain given the absence of validating data from destructive examinations.

The assumed POD function was used to infer undetected indications based on indications actually detected with the high frequency plus point probe. For each indication found, a fractional undetected flaw was assumed to exist with the same crack profile including the associated maximum and average depth and length. The value of the fraction was determined consistent with a formula given in NRC Generic Letter 95-05 (Reference B7):

Fraction = 1/POD - 1

The POD was determined from the POD curves based on the measured average depth in the initial analysis and based on the measured flaw area in the revised analysis. These fractions ranged from being quite small for the larger indications found to greater than one for the smaller indications found. The fractional undetected indications were then sorted in descending order in terms of average depth (initial analysis) and crack effective area (revised analysis). Starting at the top, the fractional indications were grouped such the sum of the fractional indications in each group equaled one. Each "POD group" essentially constitutes an assumed BOC flaw with a distribution of possible crack profiles matching those associated with fractional undetected flaws in the group. The frequency distribution of the flaw profiles within the group is weighted by the fractional contribution of each profile to unity. During each Monte Carlo simulation of a given BOC flaw (POD group), the frequency distribution of crack profiles belonging to the group is randomly sampled and one is selected.

The staff finds that the above ("fractional flaw") approach may be a source of significant non-conservatism for IP-2. Approved methods using the NRC Generic Letter 95-05 utilize a constant POD assumption rather than a POD which varies as a function of crack depth or area. A general concern with the fractional flaw approach when a variable POD is employed is that it makes the analysis relatively insensitive to the size of the fractional flaws. A sensitivity analysis conducted by the licensee indicated that consideration of flaw size measurements based on the 800 KHz data instead of the 400 KHz data resulted in essentially no change in the projected burst pressures at the end of cycle even though calculated burst pressures associated with the 800 KHz data are 18% higher than those associated with the 400 KHz data. This means that the size of flaws found during an inspection (within at least an 18% range) has no implications regarding the size of flaws which can be expected at the end of the next cycle. The staff considers this counter-intuitive and unrealistic.

The staff also notes that the above methodology with a variable POD effectively excludes from consideration an undetected flaw with a length in the range of 0.97 inches to 2.4 inches. The assumption of no fractional undetected flaws associated with R2C5 (during the 2000 inspection) derives from the fact that the POD was effectively 1 for flaws looking exactly like R2C5 as it existed immediately prior to the failure. Thus, the fractional flaw approach appears to unduly distort the length distribution of fractional undetected flaws toward shorter lengths. However, the staff does not have a basis to evaluate the degree of potential non-conservatism associated with the use of the fractional flaw approach for IP-2.

In certain situations, the fractional flaw approach appears to lead to a paradox when used in conjunction with a variable POD. As an illustration, plant A experiences a tube rupture near the end of its operating cycle after a flaw grows to 90% through wall. A look back analysis of the failed tube indicates that a 70% through wall flaw was present during the previous inspection but was missed. No other indications are found. Because the POD of a 90% through wall flaw is essentially 1, no corresponding fractional flaw needs to be considered in the operational assessment. On the other hand, plant B shuts down for its planned inspection outage. The inspection reveals one flaw, 60% through wall. A look back analysis indicates that a 40% through wall flaw was present during the previous inspection but was missed. The POD for a 60% flaw is less than 1, so a corresponding fractional flaw must be assumed in the operational assessment. Plant B's operational assessment will predict a larger flaw to be present at the end of the next operating cycle than plant A's.

When using a variable POD assumption, it appears that an alternative to the "fractional flaw" approach above is needed to provide for a realistic analysis. The staff does not have a basis to evaluate the degree of potential non-conservatism associated with the use of the fractional flaw approach for IP-2.

Westinghouse considers that the above methodology accounts for undetected indications down to the minimum crack size detected during the inspection which Westinghouse defines as the minimum detection threshold. The licensee states that the minimum average depths actually detected included one measurement at 14% and another at 23% through wall. The licensee thus concluded that an assumed minimum detection threshold of 25% should be conservative. The staff notes that the first measurement is for R2C74 and was discredited by the in-situ pressure test result (Section 3.3.1). The second of these measurements is for R2C4 for which sizing measurements must be considered highly uncertain by virtue of the low voltage response at both 400 and 800 KHz. The staff's independent sizing measurements for this tube indicates that the crack depth exceeded 40% of the portion of the crack length where there was a sufficient voltage response to render the tube detectable during a field analysis. The staff estimates the minimum detection threshold to be closer to 40%.

The licensee has considered a distribution of 100 undetected flaws whose average depth is below the minimum detection threshold. Undetected flaws in this region were assigned a shape distribution of average crack depths which appear to the staff to be largely arbitrary. The shape of the crack profiles was determined during each Monte Carlo simulation by sampling an assumed distribution of crack shapes intended to be representative of the variety of crack shapes observed for detected indications at IP-2. For a given average depth, maximum depth was determined during each Monte Carlo simulation by sampling an assumed distribution of maximum depth to average depth. This distribution was determined from the NDE measured crack profiles for IP-2 in the u-bends. Similarly, crack lengths were assigned during each Monte Carlo simulation by randomly sampling a length distribution which is based on fitting NDE crack length measurements for detected indications at the IP-2 u-bends. The staff observes that specifics of this part of the model does not significantly affect the outcome of the overall analysis.

B.2 Flaw Size Measurement Error

As discussed in Section B.1, the BOC flaw distribution was based in part on the NDE measured depth profiles for detected cracks over their measured length. During each Monte Carlo simulation for each BOC indication, the BOC crack depth profile and length were adjusted to account for NDE measurement error during the 2000 u-bend inspection program. The operational assessment employed separate error distributions for average depth, maximum depth, and length. For structural integrity analyses, the average depth error distribution was randomly sampled and the flaw depth profile was uniformly adjusted over its length consistent with the sampled error value. For accident leakage calculations, the process was the same except that it was the error distribution for maximum depth that was sampled. This approach is based on the fact that structural (burst) integrity is more a function of average depth than maximum depth whereas leakage integrity tends to be more a function of maximum depth. For both the structural and leakage analyses, the error distribution for crack length was sampled. The sampled error value is applied locally to nodes near the crack tips. The above approach is consistent with an approach approved previously by the staff (Reference B8) and is acceptable for this (IP-2) application.

Ideally, as is the case for POD, error distributions for NDE flaw size measurements should be determined on the basis of a performance demonstration program with u-bend samples containing IP-2 representative surface deposits and ID cracks. The staff's draft guidance in DG-1074 (Reference B6) highlights the importance of performance demonstration data for purposes of quantifying NDE measurement error. Unfortunately, such a program has only just been initiated and the results will not be available until after the steam generators have been replaced. Error distributions were assumed consistent with the results of the previously discussed performance demonstration data for PWSCC at dents ("sizing data set"). The standard deviation of each of the distributions were increased by 25% to allow for any potential non-conservatisms. This increased the assumed standard deviations from 7.8% to 9.8% through wall for average depth, 14.2% to 17.8% through wall for maximum depth, and from 0.139 to 0.175 inches for length. As is the case for POD, the staff considers the applicability of the data from dents to be highly uncertain, even with the 25% adjustment. The assumed distribution for average depth includes a small bias to reflect a small tendency in the sizing data set to overcall defect depth (by 3% for a flaw which is 50% through wall). The bias for the length distribution is essentially zero.

Whereas the vertical component of noise is the parameter of interest from the standpoint of evaluating relative detection performance, it is the staff's opinion that peak-to-peak (p-p) voltage is the main parameter of interest in evaluating relative sizing performance. This is because the depth of the flaw is determined from the relative value of the vertical amplitude to the horizontal amplitude of the signal response. The licensee's noise study in Reference B4 indicates average noise levels in the IP-2 row 3 u-bends of 1.03 volts (p-p) and 0.60 volts (p-p) at 800 KHz and 400 KHz respectively. This compares to a much smaller noise level existing in the sizing data set; an average of 0.29 volts (p-p) suggesting that the IP-2 u-bends pose a significantly more challenging noise environment from the standpoint of flaw sizing.

The reported noise levels for the u-bends at 400 KHz were described in Reference B4 as being from the mid-range probe. The licensee's operational assessment is based primarily on sizing measurements performed with the mid-range probe at 400 KHz. The licensee's noise study indicates that mid-range probe 400 KHz data exhibits less noise and higher signal-to-noise on a peak-to-peak basis than does the high frequency probe. This was a surprise to the staff based on its observations during independent review of the eddy current data. It had been the staff's observation that the 800 KHz data exhibited much better signal to noise and much less signal distortion than the mid-range 400 KHz data. Thus, it had been the staff's opinion that the high frequency data at 800 KHz should provide better sizing accuracy than the mid-range probe at 400 KHz. Based on an August 16, 2000 phone call with the licensee, it now appears that the reported noise data at 400 KHz is actually from the high frequency probe. The staff notes that expected noise levels at 400 KHz with the mid-range probe would be expected to be significantly higher than that with the high frequency probe due to mechanical differences between the probes. The mid-range probe produced significant signal distortion due to the shoe material of the surface riding coil, its contact area, and the length of the cable which lead to friction, slowing of the probe motor, and cable whipping. The high frequency probe exhibited significantly improved data quality due to a different shoe material and less contact area leading to less friction, as well as a shorter cable resulting in less of a wind-up effect.

Staff concerns about NDE measurement errors are most acute for low voltage signals. For the high frequency probe data, low voltage refers to signal amplitudes of approximately one volt or less. For the 400 KHz data low voltage includes voltages extending beyond one volt due to higher noise levels. The staff finds that establishing flaw depth profiles for these flaws to be a highly judgmental process prone to considerable error. These errors may be substantially more significant than is assumed in the analysis. Tube R2C74 serves as a case in point. As discussed in Section 3.3.1, the in-situ pressure test of the tube reveals that the measurement error for this tube was substantially beyond what could be reasonably expected based on the performance implicit in the assumed measurement error. The staff considers that high measurement errors relative to that indicated for dented tubes should be the expectation, not the exception, particularly for the 400 KHz data by virtue of their low signal-to-noise ratio. The staff expects that sizing measurements based on the 800 KHz data can reasonably be expected to be more accurate than measurements based on the 400 KHz data due to the much improved signal to noise ratio. Where comparative information is available, the 400 KHz measurements tend to be consistently smaller than the 800 KHz measurements resulting in burst pressure estimates which are an average of 18% higher than indicated by the 800 KHz data. However, the staff notes that sizing measurements based the 800 KHz can also involve significant error, outside the bounds assumed in the analysis. This is particularly the case for indications with relatively low voltage responses; i.e., maximum voltages around one volt with voltages significantly below this value over much of the profile.

The licensee analyzed the sensitivity of the operational assessment to the standard deviation of the assumed measurement error distributions. These analyses indicate that the operational assessment is moderately sensitive to the assumed standard deviation. Increasing the assumed standard deviations by 75% (For average flaw depth, this means increasing the standard deviation from 9.8% to 17.2%) reduces the calculated limiting burst pressure by 4%. Whether this bounds the additional error due to the relatively high noise level in the u-bends is speculative. In addition, the sensitivity study assumes that the uncertainty of the measurement error distribution is entirely associated with the standard deviation of the distributions. However, the systematic discrepancy of the sizing measurements with the high frequency 800 KHz data compared to the mid-range 400 KHz data underscore the potential that the sizing measurements with one or both of these probes may involve significant systematic errors, beyond the very small bias built into the assumed distributions. The analyses would be expected to be more sensitive to such systematic errors than random errors. Overall, the staff finds there is little basis to conclude that the assumed measurement error distributions bound the uncertainties associated with the NDE flaw sizing measurements.

B.3 Crack Growth Rate

After adjusting for measurement error during each Monte Carlo simulation, the BOC crack profile was adjusted to account for crack growth over the planned operating interval. The operational assessment employed separate growth distributions for average depth, maximum depth, and length. For structural integrity analyses, the average depth growth distribution was randomly sampled and the flaw depth profile was uniformly adjusted over its length consistent with the sampled growth value. For accident leakage calculations, the process was the same except that it was the growth distribution for maximum depth that was sampled. For both the structural and leakage analyses, the growth distribution for crack length was sampled. The sampled growth value was applied uniformly over the length of the profile. The above approach is consistent with an approach approved previously by the staff (Reference B8) and is acceptable for this (IP-2) application.

The growth rate distributions for average depth and length were derived from comparative 400 KHz data for the 2000 and 1997 inspections as obtained with the mid-range probe. Although the 1997 data were not actually detected in 1997, it was possible with the benefit of hindsight gained from the 2000 results to "dig out" the 1997 indications from the noise and to perform phase angle measurements (for flaw depth). A log-normal function was fit to the data. The data indicated a growth rate of 3.8% through wall per EFPY in terms of average depth and 0.03 inches per EFPY in terms of crack length. The individual growth data ranged from negative 1.35% to positive 11.1% for average depth and from negative 0.09 inches to positive 0.10 inches for crack length. These apparent growth rates include the effect of NDE measurement error as evidenced by the negative values at the lower end of the distribution.

The licensee performed Monte Carlo analyses to extract a "true" (corrected) growth rate distribution from the apparent distribution. The Monte Carlo analysis was constrained by the assumption that the average true growth rate plus any average NDE measurement error (bias) equals the apparent average growth rate. (Generally there should be no bias when the same inspection technique is employed for both inspections and the comparative sizing measurements have been performed by the same analysts as was done for IP-2.) The licensee assumed that measurement error was biased in the negative (conservative) direction by approximately 2% in terms of average depth and by 0.02 inches in terms of crack length. The true growth distribution (assumed log normal) was considered to have been obtained when application of the NDE uncertainties to the true growth distribution yielded agreement with the log normal fit of the actual data.

The licensee believes that a best estimate approach would be to assume no measurement error bias which would significantly reduce higher growth rates in the tail of the distribution. The staff notes that had a negative bias to the measurement error distributions not been applied when adjusting for the true distribution, the apparent growth rate in terms of average depth for R2C5 (11.3%/EFPY) would be predicted to be approximately a 99% cumulative probability value. There is little justification to assume that the R2C5 growth rate is such an extreme value considering there are only nine data points in the growth rate distribution or alternatively to assume that the true growth rate for R2C5 is substantially smaller than what was measured for this tube. This suggests that for best estimate purposes, the adjustment for true growth should be constrained by the assumption that the true growth rate for R2C5 equals the apparent growth rate for R2C5 at a cumulative probability value of 92%. This is consistent with what is predicted with Bernard's median ranking when applied to the as measured growth rate data. However, the licensee's consideration of a negative bias to the NDE measurements largely mitigates this concern since it has the effect of restoring the measured growth rate value for R2C5 to a 92% cumulative probability value.

The licensee did not discuss alternatives to its use of the log normal function for purposes of fitting the growth rate data, other than to note that growth data can be generally fit by a log normal distribution. However, the licensee did evaluate the sensitivity of the analysis to a 25% increase in growth rates relative to the reference (true) growth rate distributions, which should reasonably accommodate the uncertainty associated with the assumed fitting function.

The staff notes that potential non-conservatism in the assumed NDE measurement error distributions, discussed in Section 3.6.1.2, lend significant additional uncertainty to the growth rate distributions used in the IP-2 operational assessment. The staff notes that much of the growth data is based on comparative voltage responses involving low voltage signals, particularly the 1997 data. Apart from the accuracy of the data, there is considerable judgement involved in how to interpret it. As an example, crack number 1 in tube R2C69 exhibited a relatively low 1.3 volt signal at 400 KHz in 1997 and a 2.7 volt signal in 2000. The licensee calculated apparent growth rates of -6.76%/EFPY and -3.04%/EFPY in average depth over the total crack and burst effective lengths, respectively. The staff's analysis of the data indicated that the 1997 data exhibited much poorer signal to noise than the 2000 data for this tube. The profiling performed from the 1997 data was found by the staff to be a highly judgmental process not capable of providing a reliable depth estimate. Focusing on a small portion of the length of the 1997 signal where the signal to noise was best, the staff estimated an average depth growth rate of +6.8%/EFPY. Thus, apart from modeling considerations discussed in previous paragraphs, the comparative growth rate data itself incorporates significant uncertainty which may not be bounded by the licensee's consideration of a 25% increase in growth rates in the aforementioned sensitivity study.

Perhaps the most significant concern regarding the licensee's estimated growth rates involves the estimated growth rates in terms of crack length. Whereas the licensee considered the apparent growth rates for average depth and burst average depth for R2C5 in the depth growth rate distributions, the licensee did not consider the apparent growth rate for R2C5 in terms of burst effective length. The licensee estimates the post failure through wall length of the R2C5 crack to be 2.2 to 2.5 inches with no evidence of crack extension. The licensee's best estimate burst effective length for this crack in 1997 is 1.87 inches, indicating a length growth rate of between 0.22 inches and 0.42 inches/EFPY. Since this is one of nine growth rate estimates, Barnard's median ranking would make the R2C5 growth rate a 92% cumulative probability value for the distribution of apparent growth rates. By omitting consideration of R2C5, the maximum apparent growth rate of the remaining eight estimates is 0.08 inches/EFPY. The "true" growth rate considered by the licensee was approximately 12% at a 92% cumulative probability value. The omission of the apparent growth rate for the R2C5 crack potentially represents a significant non-conservatism in the licensee's analysis since it is the upper tail of the growth rate distribution which directly impacts the calculation of minimum burst pressure at end of cycle.

Finally, growth rate distributions for maximum depth were not derived from comparative sizing measurements between 2000 and 1997. The licensee observed that the comparative data for maximum depth were not consistent with expectations. The licensee stated that maximum depths are more difficult to size accurately than average depths and that a more accurate estimate of the maximum depth growth rate distribution can be obtained by multiplying the average depth distribution by a ratio of 1.3. This ratio is based on a regression fit of measured maximum depths plotted as a function of average depths as measured at 800 KHz and 400 KHz for the IP-2 u-bend indication profiles, but is noted to be consistent with industry pulled tube and NDE data. The staff agrees that the maximum depth sizing measurements are very uncertain as are the average depth and length measurements. The staff has insufficient information to conclude whether the above approach provides for an improved assessment of maximum depth or maximum depth growth rate.

B.4 Material Properties

The licensee's analysis in Reference B1, as supplemented by Reference B2, utilized a material flow stress value of 75.7 ksi (hot) for the row 3 tubes. The licensee describes this as a lower bound estimate based on burst tests conducted on laboratory u-bend specimens. This estimate accounts for the added strength in the row 3 u-bends compared to the straight leg portions of tubing due to strain hardening effects associated with the tube bending process. The licensee estimates the total strain associated with the bending process for row 3 tubes to be 9%.

Although requested by the staff, the licensee has not described the precise basis for the flow stress value assumed in the analysis. However, the licensee submitted a supplemental analysis in Reference B3 which considered a distribution of flow stress based on the Certified Material Test Report (CMTR) data for all IP-2 tubes in Row 3, as adjusted for strain hardening. For each heat of tubing, the corresponding yield and ultimate strengths from the CMTRs were used to construct a stress strain curve for that heat. Basically, this involved scaling a typical stress strain curve provided in Reference B1. These stress strain curves were interrogated at the 9% total strain value to obtain the strain hardened value of yield stress. The corresponding strain hardened flow stress was then taken as one-half the sum of the strain hardened yield stress and the ultimate stress. Reference cases for the operational assessments in References B1 and B2 were rerun using the above distribution of flow stress which was randomly sampled during each Monte Carlo iteration. The results of these supplemental analyses indicate that the reference analyses were in fact conservative from a flow stress standpoint.

B.5 Burst Pressure

The NDE measurement error adjustment to the assumed BOC flaw profiles discussed in Section B.2 and growth rate adjustment discussed in B.3 provided an estimate of the projected flaw profiles at EOC. A burst pressure was calculated for each projected EOC flaw determined during each Monte Carlo simulation. The licensee's initial operational assessment (Reference B1) utilized a burst prediction model documented in Reference B9. Pressure test results for another plant have recently led the industry to reexamine its testing procedures used as part of the development of the Reference B9 model. It is not known at this time what, if any, impact this reexamination may have on this model. In the meantime, the staff requested that an alternative burst prediction model be employed for the IP-2 assessment. In response, the licensee employed an alternative burst model in its supplemental operational assessment (Reference B2) based on an empirical equation developed by Argonne National Laboratory (ANL) (Reference B10). The ANL model is a model for predicting ligament tearing. The licensee made some minor modifications to the model in Reference B9. The ANL model includes an associated uncertainty distribution which is sampled for each indication. The staff approved use of this model for Sequoyah for predicting ligament tearing pressures as part of a leakage analysis (Reference B8). The staff concurs that its use for predicting burst pressure at IP-2 should be conservative since ligament tearing may precede burst such as in the case of short, deep cracks.

Both the Reference B9 burst model and the ANL equation for ligament tearing idealize cracks as being rectangular. The licensee employed an iterative procedure to determine the equivalent rectangular shape for each EOC crack profile. The equivalent rectangle is that portion of the crack length which, when considered in conjunction with the average depth over that length, yields the minimum burst (initial analysis) or ligament tearing pressure (supplemental analysis) among the universe of potential rectangles for a given crack profile. The length of the equivalent rectangular crack is termed the burst effective length and the depth is termed the burst average depth. For the supplemental analysis, the associated ligament tearing pressure was conservatively assumed to be the burst pressure.

As discussed earlier, an EOC crack profile and associated burst pressure is generated for a given BOC crack profile during each Monte Carlo simulation. Thousands of simulations were performed for each BOC indication resulting in a distribution of burst pressures for a given BOC indication. These distributions were evaluated at a 95% lower quantile value determined with 95% confidence for purposes of comparing with the limiting structural performance criterion (i.e., acceptance limit).

For purpose of this discussion, the reference analysis is considered to be the supplemental analysis documented in Reference B2 using the area-based POD assumption discussed in Section B.1 and the ANL ligament tearing model for predicting burst. For this reference case, predicted EOC burst pressure for the most limiting tube is 5450 psi for a 0.333 EFPY operating interval and 4674 psi for a 1.7 EFPY operating interval. Extrapolation of the predictions leads to a predicted burst pressure of 5710 psi at BOC. These predictions satisfy the applicable 3 delta P criterion of 4668 psi. However, the analysis contains a number of potential non-conservatisms relating to the assumed POD function (see Section B.1), the fractional flaw methodology when used in conjunction with a variable POD function (see Section B.1), the assumed flaw size measurement error distributions (see Section B.2), and the assumed crack growth rates, particularly with respect to crack length (see Section B.3). The analysis does assume a ligament tearing model for burst which the licensee's analysis indicates reduces the predicted burst pressure by about 8% when compared to the Westinghouse burst model in Reference B9. However, it is not known at this time whether the Westinghouse model is an appropriate benchmark for evaluating the conservatism of the ligament tearing approach pending the outcome of the ongoing industry effort to resolve issues relating to supporting data for the Westinghouse model. The flow stress assumed in the licensee's analysis was also conservative, but only had a 2% affect on the calculated burst pressures (see Section B.4). These conservatisms do not significantly mitigate the staff's concerns relating to the potential non-conservatisms in the licensee's analysis. Although the licensee has performed sensitivity analyses relating to the major modeling and input parameter uncertainties of the reference analysis, there is little basis to estimate a quantitative lower bound on these uncertainties relative to the 3 delta P limit, either at BOC or later into the operating interval.

B.6 Accident Induced Leakage

The EOC crack distribution used to assess potential leakage during a postulated main steam line break (MSLB) accident is similar to that used for the burst analyses except that the BOC crack profiles were adjusted on the basis of measurement error and crack growth rate distributions based on maximum depth rather than average depth. During each Monte Carlo simulation, a leak rate estimate was made for each projected EOC flaw in the steam generator which are summed to yield a total SG leak rate estimate. Many simulations were performed resulting in a distribution of calculated total SG leak rates under MSLB conditions. This distribution was evaluated at the upper 95% quantile value determined with 95% confidence for purposes of comparison with the applicable performance criterion of 1 gpm for IP-2.

The leak rate estimates were determined by applying the ANL ligament tearing model (see Section B.5) to each EOC crack profile. An iterative procedure was followed to determine the longest one or more ligaments that would tear entirely through wall under MSLB conditions. For each ligament determined to tear through wall, the licensee calculated a corresponding leak rate using the Westinghouse CRACKFLO code. Actual leak rates tend to exhibit significant variances from what is expected on the basis of codes such as CRACKFLO. Therefore, the CRACKFLO code was calibrated to actual leakage data with a regression correlation. A statistical model was developed to characterize the scatter of the test data about the regression correlation. This leak rate prediction model has been approved previously by the staff for application at Sequoyah (Reference B8) and is acceptable for use at IP-2.

Based on the approach outlined above, the licensee's analysis indicates that no leakage is expected under MSLB conditions. However, the staff notes that the accident leakage analyses are subject to the same potential non-conservatisms as were discussed in the context of burst in Section B.5. The potential non-conservatisms relate to the assumed POD function (see Section B.1), the fractional flaw methodology when used in conjunction with a variable POD function (see Section B.1), the assumed flaw size measurement error distributions (see Section B.2), and the assumed crack growth rates, particularly with respect to crack length (see Section B.3). The licensee has performed sensitivity analyses relating to the major modeling and input parameter uncertainties of the reference analysis as discussed previously. Each of these sensitivity analyses, including consideration of the factor of 2 shift on the area-based POD function, indicated zero leakage. Thus, the potential non-conservatisms in the analysis appear to be of less concern from a leakage standpoint than from a burst standpoint. Resolution of the issues relating to burst margins would therefore also resolve issues relating accident induced leakage.

B.7 Relative Susceptibility of Row 3 U-Bends to PWSCC

As discussed earlier, the licensee's operational assessment assumes the row 3 tubes to be equally susceptible to PWSCC as row 2 tubes for which no PWSCC indications have been identified to date. However, the licensee performed analyses using finite element techniques and Monte Carlo simulations to assess the relative susceptibility of the row 3 u-bends to PWSCC compared to the row 2 u-bends in order to provide insight on the degree of conservatism associated with the assumption of equal susceptibility in the operational assessment. The licensee states that the key differences between row 2 and row 3 tubes in terms of their susceptibility to PWSCC are the differences in degrees of cold work relating to the tube bending process and differences in the sensitivity of hoop stress at the apex of the u-bends to a given amount of hourglass deformation of the upper TSP flow slots.

The licensee utilized a relationship developed at Brookhaven National Laboratory (BNL) as documented in Reference B11 to estimate the relative time to crack initiation. For stresses above yield, constant load data on tensile specimens showed that the that the time to crack initiation is inversely proportional to the 4.3 power of stress divided by the yield stress. The licensee utilized a power of 4.0 which is slightly more conservative than 4.3. This relationship is based on laboratory tests. The data scatter band presented in Reference B11 was considered in the Monte Carlo analysis by assuming a triangular distribution of data within the reported scatter band.

Finite element models of the upper support plate and row 2 and row 3 tubes were employed to evaluate hoop stress (actually, hoop stress divided by yield stress) at the inner surface at the u-bend apex/extrados location as a function of the amount of hourglass deformation at the adjacent upper TSP flow slot and as a function of the material properties of the tubing. The u-bend models incorporated pressure and thermal loadings associated with normal operating conditions, residual stresses associated with the tube bending process during fabrication, and non-linear stress-strain properties. The residual stresses were determined experimentally from laboratory u-bend specimens. The analysis considered the full range of yield strengths in rows 2 and 3 respectively as determined from the Certified Material Test Reports (CMTR) records for IP-2. The reported upper bound, average, and lower bound yield strengths for row 2 are approximately the same as for row 3. The stress strain properties beyond yield were determined experimentally from a tensile test of a test coupon cut from a straight length of tubing. The resulting stress strain curves were adjusted to reflect the strain hardening effects associated the tube bending process. The induced elongation during the bending process is about 12% in row 2 and 9% in row 3. The strain hardening effect provides a slightly larger increase in yield stress for row 2 than for row 3.

The Monte Carlo analysis considered each tube in row 2 and row 3, except those plugged before 2000, and the associated variability of yield strength. Three different sets of assumptions were considered regarding the degree of hourglass deformation at each flow slot. As previously discussed, an hourglass measurement was only performed for the flow slot adjacent to R2C5 in SG 24. One case assumed all flow slots to be deformed equally to that adjacent to R2C5; namely 0.47 inches. The other two cases considered different distributions of hourglass deformation ranging from 0.2 inches to 0.7 inches. The Monte Carlo analysis yielded a distribution of hoop stress to yield stress ratios from which a distribution of time to failure was derived for both row 2 and row 3 tubes.

The results of this analysis indicate that the time to crack initiation for the most susceptible row 3 tube is 1.7 times as long as for the most susceptible row 2 tube and that 50 tubes in row 2 would be expected to initiate cracks before the most susceptible tube in row 3. The licensee stated that the literature indicates that the relative time to cracking would be accentuated by the higher degree of cold work in row 2 than row 3; however, there is insufficient laboratory evidence to quantify this effect.

The licensee did not address the significance of these results in terms of when row 3 tubes could be expected to initiate and grow to just below the threshold of crack detection. The staff finds that these results provide little insight on whether cracks may or may not have initiated in row 3 due to uncertainties in how long significant hourglass deformation (leading an abnormally high state of stress at the apex of the u-bends) may have been present and uncertainty as to when cracks first initiated in row 2. The average crack growth rates calculated by the licensee for the row 2 indications (4%/EFPY in terms of average depth) suggest that initial crack initiation may date back 10 or 15 EFPY, to the early 1980's or late 1970's. There is no direct evidence for how long significant hourglass deformation has been present in the upper TSP flow slots, but significant hourglass deformation was observed in the lower TSPs in the late 1970's suggesting the possibility the upper TSPs may also have contained significant hourglass deformation at that time. Even though the time to crack initiation may be 1.7 times longer for row 3 than row 2, crack initiation under this scenario may have occurred very quickly in row 2 such that initiation in row 3 may have occurred only shortly thereafter with the cracks in row 3 only now approaching the threshold of detection. This discussion is highly speculative and is intended solely to illustrate that the licensee's analysis does not provide a clear picture of the potential for undetected cracks in row 3. The staff acknowledges that the crack growth rate data is highly uncertain and that crack initiation in row 2 may have been much more recent. The advent of significant hourglass deformation in the upper TSP flow slots may also have been more recent. If so, the potential for undetected cracks in row 3 would depend on how quickly cracks initiated in row 2 relative to the onset of significant hourglass deformation of the upper TSP flow slots.

The staff notes that nine row 2 tubes (including R2C67 in 1997) have been identified with u-bend cracks. Whether nine tubes or 50 row 2 tubes with identified cracks would precede a crack in row 3 approaching the detection threshold is probably stretching the precision of the analysis. The staff does acknowledge, however, that given the absence of detected row 3 tubes to date, the growth of an undetected row 3 indication to just below the detection threshold at the precise time that R2C5 failed and the inspection program was conducted would appear to be a relatively unlikely coincidence. The staff finds this to be a major element of conservatism.

References:

B1. Letter from John F. Groth (ConEd) to William Travers (NRC), dated June 2, 2000, "2000 Refueling Outage Steam Generator Inspection Condition Monitoring and Operational Assessment Reports"

B2. Letter (No. NL#00-085) dated July 7, 2000 from James S. Baumstark (ConEd) to NRC Document Control Desk, "Response to Staff Request for Additional Information (RAI) Regarding Steam Generator Operational Assessment Report."

B3. Letter (No. NL-00-099) dated July 27, 2000 from James S. Baumstark (ConEd) to NRC Document Control Desk, "Responses to NRC's Request for Additional Information (RAI) Regarding Steam Generator Operational Assessment Report."

B4. Letter (No. NL-00-104) dated August 4, 2000 from A. Alan Blind (ConEd) to NRC Document Control Desk, "July 28, 2000 Steam Generator Inspection Meeting - Additional Question Responses."

B5. Letter (No. NL-00-107) dated August 8, 2000 from James S. Baumstark (ConEd) to NRC Document Control Desk, "July 28, 2000 Steam Generator Inspection Meeting - Additional Question Responses."

B6. Draft Regulatory Guide DG-1074, "Steam Generator Tube Integrity," December 1998.

B7. NRC Generic Letter 95-05, "Voltage-Based Repair Criteria for Westinghouse Steam Generator Tubes Affected by Outside Diameter Stress Corrosion Cracking," August 3, 1995.

B8. Letter dated March 8, 2000 from Ronald W. Hernan (NRC) to J. A. Scalice (TVA), "Sequoyah Nuclear Plant, Units 1 and 2 - Issuance of License Amendments Regarding Steam Generator Tube Alternate Repair Criteria."

B9. Letter from TVA to NRC dated February 24, 2000, "Sequoyah Nuclear Plant (SQN) - Westinghouse Electric Company Topical Report WCAP-15128, Revision 2."

B10. NUREG/CR-6575, "Failure Behavior of Internally Pressurized Flawed and Unflawed Steam Generator Tubing at High Temperatures - Experiments and Comparison with Model Predictions," March 1998.

B11. NUREG/CR-5752, "Assessment of Current Understanding of Mechanisms of Initiation, Arrest, and Reinitiation of Stress Corrosion Cracks in PWR Steam Generator Tubing," February 2000.