Resolution of Generic Safety Issue 163
"Multiple Steam Generator Tube Leakage"

Division of Component Integrity
Office of Nuclear Reactor Regulation
United States Nuclear Regulatory Commission

1.0 INTRODUCTION

The U. S. Nuclear Regulatory Commission (NRC) opened Generic Safety Issue (GSI) 163, "Multiple Steam Generator Tube Leakage," in June 1992 (Reference 1) to address concerns of an NRC staff member raised in a Differing Professional Opinion (DPO) dated December 23, 1991 and, as modified, March 27, 1992 (References 2 and 3). By memorandum from B. Sheron to L. Reyes dated July 5, 2007 (Reference 4), GSI 163 was closed in the Generic Issues Program and was transferred to NRR for regulatory office implementation. The concerns (which constitute the principal assertion of this GSI) relate to the potential for multiple steam generator (SG) tube leaks during a non-isolatable main steam line break (MSLB) outside containment. This sequence of events could potentially lead to core damage as a result of the loss of all primary system coolant and of the safety injection fluid in the refueling water storage tank. The DPO was based on the discovery of widespread outer diameter stress corrosion cracking (ODSCC) at the SG tube support plates at the Trojan plant (which the author claimed could not be reliably detected), and also by the staff's approval of alternate repair criteria (ARC) which would allow many SG tubes known to contain such cracks to remain in service. Subsequent to opening GSI 163, the DPO author expanded the scope of the DPO concerns to include iodine spiking issues related to MSLB accidents, tube integrity concerns under severe accident conditions, and other issues (References 5 to 10).

GSI 163 is intended to address the adequacy of regulatory requirements related to the management of SG tube integrity; specifically, ensuring that SG tubes will continue to exhibit acceptable structural margins against burst or rupture under normal operating conditions and design basis accident (DBA) sequences (including MSLB), and that leakage from one or multiple tubes under DBA conditions will be limited to very small amounts, consistent with the applicable regulations for offsite and control room doses. Although GSI 163 was opened in response to the above referenced DPO concerns, resolution of GSI 163 is separate from resolution of the DPO.

The DPO concerns were reviewed by an Advisory Committee for Reactor Safeguards (ACRS) Ad Hoc Subcommittee that served as the DPO review panel. The Subcommittee's conclusions and recommendations were endorsed by the ACRS and transmitted to the NRC's Executive Director for Operations (EDO) on February 1, 2001 (References 11 and 12). In a memorandum to the DPO author dated March 5, 2001 (Reference 13), the EDO stated that the concerns raised in the DPO were concluded to be dispositioned and the DPO to be closed based on (1) the ACRS Ad Hoc Subcommittee's finding that the alternative repair criteria and condition monitoring program can adequately protect public health and safety, (2) the ACRS Ad Hoc Subcommittee's conclusion that no immediate regulatory actions were necessary, and (3) the NRC staff's development of an SG Action Plan (SGAP) to address the conclusions and recommendations in the ACRS Ad Hoc Subcommittee's report. The SGAP is documented in Reference 14, and the latest status of this program is in Reference 15.

This report documents the staff's resolution of GSI 163. Section 2 describes the background of the GSI and the DPO. Section 3 defines the specific scope of GSI 163 and how it relates to the DPO. Section 4 discusses new performance-based technical specifications governing the management of SG tube integrity. These new technical specifications have been in place at all U. S. pressurized water reactors (PWRs) since September 30, 2007. Although these technical specifications were not developed for the specific purpose of resolving GSI 163, these requirements directly address the principal assertion of the GSI and, thus, provide a key rationale supporting closure of the GSI. Section 5 addresses the ACRS Ad Hoc Subcommittee's conclusions and recommendations from the standpoint of demonstrating that NRC requirements relating to the management of SG tube integrity ensure that all tubes will exhibit acceptable structural margins against burst or rupture under normal operating conditions and DBAs (including MSLB), and that leakage from one or multiple tubes under DBAs will be limited to very small amounts, consistent with the applicable regulations for offsite and control room dose. Section 6 provides a summary and conclusions leading to closure of GSI 163.

2.0 BACKGROUND

2.1 SG Tube Integrity – Importance to Safety

The SG tubes function as an integral part of the reactor coolant pressure boundary (RCPB) and, in addition, serve to isolate radioactive fission products in the primary reactor coolant from the secondary coolant and the environment. Thus, the SG tubing serves a containment function as well as a RCPB function. SG tube leakage (i.e., primary-to-secondary leakage) or ruptures have a number of potential safety implications, including those associated with allowing fission products in the primary coolant to escape into the environment through the secondary system. In the event of an MSLB accident or stuck open SG safety valve, leakage of primary coolant through the tubes could contaminate the flow out of the ruptured steam line or safety valve, respectively. In addition, leakage of primary coolant through the SG tubing could deplete the inventory of water available for long-term cooling of the core in the event of an accident.

2.2 Regulatory Framework for Ensuring SG Tube Integrity

Title 10 of the *Code of Federal Regulations* (10 CFR) establishes the fundamental regulatory requirements with respect to the integrity of the SG tubes. Specifically, the General Design Criteria (GDC) in Appendix A to 10 CFR Part 50 state that the RCPB:

> shall have "an extremely low probability of abnormal leakage . . . and gross rupture" (GDC 14),
>
> "shall be designed with sufficient margin" (GDCs 15 and 31),
>
> shall be of "the highest quality standards practical" (GDC 30), and
>
> shall be designed to permit "periodic inspection and testing . . . to assess . . . structural and leak-tight integrity" (GDC 32).

To this end, 10 CFR 50.55a, Codes and Standards, specifies that components which are part of the RCPB must meet the requirements for Class 1 components in Section III of the American Society of Mechanical Engineers *Boiler and Pressure Vessel Code* (ASME Code). 10 CFR 50.55a further requires, in part, that throughout the service life of a pressurized water reactor (PWR) facility, ASME Code Class 1 components meet the requirements, except design and access provisions and pre-service examination requirements, in Section XI, "Rules for Inservice Inspection [ISI] of Nuclear Power Plant [NPP] Components," of the ASME Code, to the extent practical. This requirement includes the inspection and repair criteria of Section XI of the ASME Code. Section XI requirements pertaining to ISI of SG tubing is augmented by additional requirements in the plant technical specifications.

As part of the plant licensing basis, applicants for PWR licenses are required to analyze the consequences of postulated design-basis accidents (DBAs) such as an SG tube rupture (SGTR) and MSLB. These analyses consider primary-to-secondary leakage which may occur during these events and must show that the offsite radiological consequences do not exceed the applicable limits of 10 CFR 50.67 or 10 CFR Part 100 for offsite doses, GDC 19 criteria for control room operator doses, or some fraction thereof as appropriate to the accident, or the NRC-approved licensing basis (e.g., a small fraction of these limits).

Operating experience has proven SG tubing is subject to a variety of mechanically and corrosion-induced degradation mechanisms which may impair the structural and leakage integrity of the SG tubing. The licensee's plant technical specifications[1] (TSs) require the implementation of SG tube surveillance programs to ensure that tubes are repaired, or removed from service by plugging the tube ends, before the structural or leakage integrity of the tubes is impaired. The technical specifications include a generally applicable depth-based tube repair limit, typically 40-percent of the nominal tube wall thickness, beyond which the tubes must be repaired or plugged. This depth-based tube repair limit is intended to ensure that tubes accepted for continued service will not leak and will retain safety factors against burst consistent with the design basis (i.e., the stress limits in the ASME Code, Section III) with allowance for flaw depth measurement uncertainty and for incremental flaw growth prior to the next scheduled inspection. The plant TSs also include a limit on operational primary-to-secondary leakage, typically 150 gallons per day (gpd), beyond which the plant must be promptly shutdown. Should a flaw exceeding the tube repair limit not be detected during the periodic tube surveillance, the operational leakage limit provides added assurance of timely plant shutdown before tube structural and leakage integrity are impaired.

2.3 New Performance-Based Requirements for Ensuring SG Tube Integrity

As discussed above, NRC requirements for the ISI and repair of SG tubes are contained in the plant TSs. Until recently, these TS requirements were entirely prescriptive in nature, consisting of specified sampling plans for tube inspection, specified inspection intervals, and flaw acceptance limits (termed "tube repair limits") beyond which the tube must be removed from service by plugging or must be repaired. The TS defined the SGs to be operable when the facility met these requirements.

Although these requirements were intended to ensure SG tube integrity in accordance with the plant design and licensing bases (including the applicable regulations in 10 CFR Part 50), operating experience has shown that these earlier requirements did not necessarily ensure that facilities would meet this objective. For example, the required minimum tube inspection sample sizes and eddy current test (ECT) flaw detection performance were sometimes insufficient to ensure the timely detection of flaws before the desired margins against burst and the desired

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[1] See 10 CFR 50.36, Technical specifications, for basis.

degree of leak tightness were compromised. In addition, ECT measurement uncertainties and flaw growth rates sometimes exceeded those allowed for by the tube repair criteria. Also, when flaws were detected by ISI and were determined to exceed the tube repair criteria (dictating plugging or repair of the affected tubes), there was no requirement to demonstrate that the affected tubes retained the desired margins against burst and leakage integrity at the time these flaws were detected and plugged or repaired. Thus, implementation of the surveillance requirements alone did not necessarily ensure that the scope, frequency, and methods of inspection would be sufficient to ensure SG tube integrity. These earlier requirements did not directly ensure that the objective of GSI 163 was being met; namely, to ensure that all tubes will exhibit acceptable structural margins against burst or rupture under normal operating conditions and DBAs (including MSLB) and that leakage from one or multiple tubes under DBAs will be limited to very small amounts, consistent with the applicable regulations for offsite and control room dose.

As such, licensees experiencing significant degradation problems frequently found it necessary to implement measures beyond the minimum TS requirements in order to ensure the maintenance of adequate tube integrity consistent with the plant design and licensing bases. Until the 1990s, these measures tended to be ad hoc and licensee-specific. In the meantime, the industry and the NRC staff began initiatives to improve the effectiveness and consistency of the utility programs to ensure SG tube integrity. In 1997, the Nuclear Energy Institute (NEI) issued NEI 97-06, “Steam Generator Tube Integrity Guidelines” (Reference 16), which provided general, high-level guidelines for a programmatic, performance-based approach for ensuring SG tube integrity. NEI 97-06 references a number of detailed guideline documents from the Electric Power Research Institute (EPRI) for programmatic details concerning SG tube inspections, SG tube integrity assessment, in situ pressure testing, and monitoring of operational primary-to-secondary leakage. The NEI 97-06 approach was inspired by, and is similar to, an approach developed by the NRC staff in a draft regulatory guide, “Steam Generator Tube Integrity,” published as DG-1074 in December 1998 (Reference 17). All U.S. PWR utilities committed to NEI to implement the NEI 97-06 initiative no later than the first refueling outage starting after January 1, 1999.

Subsequent to the issuance of NEI 97-06, the NRC staff worked extensively with the industry to address issues associated with the industry initiative and to identify needed changes to plant TS to ensure maintenance of tube integrity. These efforts culminated in agreement between the NRC staff and the industry on a generic template for new TS (Reference 18) incorporating a programmatic, performance-based approach which is in general alignment with NEI 97-06. NEI recently updated NEI 97-06 (Reference 16) consistent with the TS generic template, and, as of September 30, 2007, new technical specifications for ensuring SG tube integrity, modeled on the generic template, are in place for all U. S. PWRs.

2.4 Voltage-Based Tube Repair Limits

The DPO concerns were first prompted by the finding of intergranular attack (IGA) and ODSCC at the tube-to-tube support plate (TSP) intersections at the Trojan NPP in 1991, the challenges that were encountered in reliably detecting such flaws, and consideration being given at the time to allowing some tubes with greater than 40-percent through-wall flaws to remain in service. At Trojan, and subsequently at many other PWRs with Westinghouse-designed SGs, ECT inspections identified hundreds of indications at the tube-to-TSP intersections. Examination of tube specimens removed from the field (i.e., pulled tube specimens) identified the degradation mechanism as stress corrosion cracking (SCC) initiating from the outer diameter surface of the tube (ODSCC), with varying degrees of general IGA. These examinations showed the ODSCC/IGA to be confined to within the 0.75 inch thickness of the TSPs. Burst testing of these specimens revealed the failure mode to be axial.

ECT techniques were not capable of accurately sizing the depth of the ODSCC/IGA flaws relative to the applicable TS tube repair limit of 40-percent of the nominal tube wall thickness. For this reason, it was necessary to assume that all detectable ODSCC/IGA indication exceeded the 40-percent tube repair limit, thus necessitating the plugging or repair of all affected tubes. However, the number of affected tubes at each plant ranged to hundreds and, sometimes, thousands of tubes. This had significant economic implications for the industry. Plugging such a large number of tubes would potentially significantly shorten the useful life of the SGs after which SG replacement would be necessary. Depending on the plant, the useful SG lifetime could potentially expire before replacement SGs were available. Sleeve repairs at each TSP intersection did not appear to offer a practical, cost effective alternative. For this reason, the industry began around 1990 to investigate alternative approaches to ensuring the integrity of tubing affected by ODSCC/IGA at the TSPs.

The 40-percent depth-based tube repair limit is intended to ensure that tubes accepted for continued service will not leak and will retain safety factors against burst consistent with the design basis (i.e., the stress limits in the ASME Code, Section III) with allowance for flaw depth measurement uncertainty and for incremental flaw growth prior to the next scheduled inspection. These safety factors include a factor of 3 relative to normal operating pressure differential (between primary system and secondary system pressures) and 1.4 relative to postulated accident pressure differentials. The 40-percent limit was developed with the conservative assumption that degradation results in uniform thinning of the tube wall thickness in both the axial and circumferential directions. Burst testing of pulled tube samples with ODSCC/IGA flaws showed the degrading effect of these flaws on tube burst pressure to be significantly less than is the case for tubes which are uniformly thinned to the same depth. This result is explained by the limited axial extent of the flaws, i.e., less than the thickness of the TSP (0.75 inches), the non-uniformity of the depth profile, and the often segmented rather than continuous nature of the cracks. In some cases, crack segments could penetrate up to 100-percent through the tube wall while maintaining structural safety margins consistent with the design basis.

It was also observed from burst and leak tests performed on the pulled tube samples that those ODSCC/IGA indications that had exhibited low voltage ECT signals in the field tended to exhibit high burst strengths and low potential for leakage compared to indications exhibiting higher voltage responses. This observation led the industry to develop a database from pulled tube specimens and lab specimens correlating voltage response of the ODSCC/IGA indications with burst strength, probability of leakage (POL) under MSLB differential pressure, and leak rate (given that leakage occurs) under MSLB differential pressure. This database was used as the basis for developing voltage-based alternate repair criteria (ARC). Statistical/mathematical models were developed for each of these correlations. The burst and leak rate correlations were represented by a mean regression curve and an associated variability distribution to capture the scatter or variability of the data. The POL correlation was modeled as a log-logistic function with an associated uncertainty distribution. Separate sets of correlations were developed for SGs with 7/8-inch diameter tubing and 3/4-inch diameter tubing respectively.

The voltage-based ARC was approved by the NRC on an interim basis for Trojan in 1992, and subsequently for other plants. In 1995, the staff issued Generic Letter 95-05, "Voltage Based Repair Criteria for Westinghouse Steam Generator Tubes Affected by Outside Diameter Stress Corrosion Cracking," with guidance for submitting applications for permanent voltage based ARC amendments (Reference 19). Over the next several years, the NRC approved voltage-based ARC TS amendments for 27 units. However, due to subsequent SG replacements at many of these plants, only 3 units continue to have TS which allow implementation of the voltage-based ARC.

The supporting data bases for the burst and leakage correlations are periodically updated as additional data becomes available. The conditional leak rate correlation for 7/8-inch diameter tubing has been, and continues to be, weak. For this reason, use of the linear regression fit of the conditional leak rate correlation is subject to demonstrating that the fit is valid at the 5-percent level with the "p-value" test. If this condition is not satisfied, the linear regression fit is assumed to be constant with voltage.

When implementing the voltage based ARC, an upper limit on voltage is established such as to provide a factor of 1.4 against burst under MSLB conditions. (The TSP constrains radial expansion of the tube under normal operating conditions ensuring that the factor of 3 criterion for normal operating conditions is met.) For MSLB, the TSP is conservatively assumed to be displaced axially by hydraulic blowdown loads. Thus, the TSP is assumed not to constrain radial expansion and burst under MSLB conditions. This voltage limit is deterministically based, corresponding to the voltage in the burst pressure versus voltage correlation where the lower 95-percent prediction interval burst pressure equals 1.4 times the MSLB differential pressure. This voltage is adjusted downward on a plant-specific basis to allow for voltage growth between inspections and for voltage measurement variability. The voltage growth value is a generic or plant specific value, whichever is larger. Plant specific values are based on the average value observed during the most recent one or two inspection intervals. The voltage measurement variability is an upper 95-percent cumulative probability estimate based on industry data.

Given the scatter and variability of the burst and leakage correlations, the growth rate distribution, and the voltage measurement variability distribution, there remains a non-negligible probability that an indication at the upper voltage limit may burst at a pressure less than 1.4 times MSLB pressure. For this reason, it must also be demonstrated that the conditional probability of one or more tubes bursting under MSLB conditions, from among the entire population of indications projected to exist at the next scheduled inspection, is less than 0.01 (operational assessment). This forward projection (using a Monte Carlo sampling method) is performed assuming that the probability of detection (POD) for ODSCC/IGA flaws during the current, or most recent, inspection is 0.6, independent of voltage amplitude. This conditional probability criterion was developed from the risk study described in Reference 20 to ensure that implementation of the voltage-based ARC would not significantly increase risk. In addition, a similar analysis is done during each inspection based on the as-found indications (without consideration of voltage growth) to confirm that the conditional probability criterion was met during the prior period of operation (condition monitoring assessment).

All tubes with bobbin coil indications exceeding the upper voltage criterion must be plugged. In addition, lower limits on voltage of 1 volt for 3/4-inch diameter tubing and 2 volts for 7/8-inch diameter tubing have been established for conservatism. Tubes with bobbin indications higher than the lower voltage limit, but less than or equal to the upper voltage limit, may be left in service if rotating probe inspections do not confirm the bobbin coil indication.

When implementing the voltage-based ARC, it must also be demonstrated that leakage under MSLB conditions will not exceed values assumed in the licensing basis accident analyses. The MSLB leakage assessment is performed in a similar manner as the conditional probability of burst analyses, except that the Monte Carlo sampling is performed on the POL and leak rate correlations instead of the burst correlation. This analysis yields a probability distribution of leak rates. The MSLB leak rate is the upper 95-percent percentile value from the distribution, evaluated at an upper 95-percent confidence bound.

3.0 SCOPE: GSI 163

GSI 163 is intended to address the adequacy of regulatory requirements relating to the management of SG tube integrity to ensure that all tubes will continue to exhibit acceptable structural margins against burst or rupture under normal operating conditions, as well as during postulated DBAs (including MSLB), and that leakage from one or multiple tubes during postulated DBAs will be limited to very small amounts, consistent with the applicable regulations for offsite and control room dose. As part of the closure of GSI 163, the staff has addressed each of the ACRS Ad Hoc Subcommittee's (DPO Review Panel's) conclusions and recommendations (References 11 and 12) to the extent necessary to ensure that GSI 163 is fully addressed.

4.0 NEW TS REQUIREMENTS FOR ENSURING SG TUBE INTEGRITY

The new TS requirements address the previous lack of a direct relationship between the TS surveillance requirements and SG tube integrity. The new TS requirements require implementation of an SG program which is directly focused on maintaining tube integrity and periodically verifying that the program continues to be successful in meeting this goal. This required SG program addresses the central objective of GSI 163 in that it is intended to ensure that all SG tubes will exhibit acceptable structural margins against burst or rupture under normal operating conditions, as well as during postulated DBAs (including MSLB), and that leakage from one or multiple tubes during postulated DBAs (including MSLB), will be limited to very small amounts, consistent with the applicable regulations for offsite and control room dose.

Section 4.1 provides an overview description of the new TS. Section 4.2 discusses how the NRC verifies the implementation of the new TS and the effectiveness of the required SG Program in ensuring that SG tube integrity is being maintained. Section 4.3 assesses the effectiveness of the SG Program in ensuring SG tube integrity

4.1 Overview

As discussed in Section 2.3, new performance-based TS requirements (see Reference 18 for details) have been in place at all U. S. PWRs since September 30, 2007. These requirements include a new Limiting Condition for Operation (LCO) that tube integrity shall be maintained with an associated surveillance requirement that tube integrity shall be verified in accordance with the SG Program. The key elements of the SG Program are defined in the TS Administrative Controls which specify that an SG program shall be established and implemented to ensure that SG tube integrity is maintained. The TS do not provide specific details on how this objective is to be met; it is the licensee's responsibility to ensure that the program will meet the stated objective. Industry guidelines in NEI 97-06 and other guidance referenced therein provide a resource to utilities for meeting this objective. However, the TS do define a general programmatic framework for the SG program, which must include the following programmatic elements:

- performance criteria for SG tube integrity
- provisions for condition monitoring
- provisions for tube repair criteria
- provisions for SG tube inspections
- provisions for monitoring primary-to-secondary leakage

The TS define three different types of performance criteria for evaluating SG tube integrity:

(1) structural integrity criteria,
(2) accident-induced leakage (primary-to-secondary) criteria, and
(3) operational primary-to-secondary leakage criterion.

The condition of the tubes relative to the structural integrity criteria and the accident-induced leakage criteria is evaluated periodically, based on inservice inspection results, in-situ pressure tests, or other means, prior to the plugging of tubes to confirm that these criteria are met for all tubes. This periodic evaluation is termed a condition monitoring assessment and is performed during each plant outage during which the SG tubes are inspected, plugged, and/or repaired. The operational leakage criterion corresponds to the TS LCO limit for primary-to-secondary leakage. Primary-to-secondary leakage is monitored while the plant is operating and should this leakage exceed the TS LCO limit, the plant must be shutdown in accordance with the TS.

The structural integrity criteria define the minimum factors of safety against burst or plastic collapse that must be maintained for all tubes under normal operating and DBA loading conditions. These safety factor criteria were developed to be consistent with the safety factors which are ensured by the stress limits in ASME Code, Section III (i.e., the design basis). These safety factor criteria include, for example, a factor of safety of 3 against burst under normal steady state full power operation primary-to-secondary pressure differential and a safety factor of 1.4 against burst applied to design basis accident primary-to-secondary pressure differentials.

Even if all tubes exhibit safety factors in accordance with the structural integrity performance criteria, tubes with localized flaws can leak under normal operating and accident conditions, without burst or collapse. The central DPO concern (References 2 and 3) was that such leakage from multiple tubes may lead to significant radiological releases and/or core melt. The accident-induced leakage criteria address this concern by limiting the allowable total accident-induced leakage in each SG (as determined during condition monitoring assessments) to values assumed in the licensing basis accident analyses to demonstrate that off site and control room doses meet applicable regulatory requirements. The accident-induced leakage criteria values are a small fraction of the values associated with a ruptured tube or values which affect peak clad temperature and the likelihood of core melt.

Given the TS LCO operational leakage limit, a separate performance criterion for operational leakage is unnecessary for ensuring prompt shutdown if the limit is exceeded. However, operational leakage is an indicator of tube integrity performance, although it is not a direct indicator. However, it is the only indicator that can be monitored while the plant is operating. Maintaining leakage within the limit provides added assurance that the plant is meeting structural and accident leakage performance criteria. Thus, inclusion of the TS leakage limit among the set of tube integrity performance criteria is appropriate from the standpoint of completeness of the performance criteria.

The new TS require that the SG program include periodic tube inspections. This includes a new performance-based requirement that the scope, methods, and intervals of the inspection ensure the maintenance of SG tube integrity until the next inspection. This performance-based requirement complements the requirement for condition monitoring from the standpoint of ensuring that tube integrity is maintained. The requirement for condition monitoring is backward looking in that it is intended to confirm that tube integrity has been maintained prior to the time the assessment is performed. The inspection requirement, by contrast, is forward looking as it is intended to ensure that tube inspections, in conjunction with plugging of tubes, are performed so as to ensure that the plant will continue to meet the performance criteria until the next SG inspection. Tube inspections would be followed again by condition monitoring at the next SG inspection to confirm that the performance criteria were in fact met, and so on.

The new TS performance-based requirements are supplemented by a number of prescriptive requirements relating to minimum sample sizes for tube inspections, maximum allowable inspection intervals, and tube repair criteria. Even though the new TS compel implementation of a performance-based program (including inspections and plugging) which ensures tube integrity, the prescriptive requirements pertaining to inspection sample sizes and inspection intervals provide added assurance of tube integrity should new or unexpected degradation mechanisms or changes in previously observed flaw growth rates occur. The tube repair criteria provide added assurance that degraded tubes will be plugged or repaired before the integrity of these tubes is impaired.

Regarding the tube repair criteria, the new TS retain the standard depth-based limit of 40-percent of the nominal tube wall thickness. In addition, any plant-specific requirements pertaining to the use of alternate repair criteria in the old technical specifications have been carried over to the new TS.

4.2 Verification

As of September 30, 2007, the technical specifications for all U. S. PWRs have been amended with the new requirements as described in Section 4.1 above. The NRC Regional Offices conduct periodic inspections (typically during each inspection outage) to assess the effectiveness of licensee programs for ensuring tube integrity in accordance with the technical specifications. These regional inspections are performed in accordance with the NRC Inspection Manual, Inspection Procedure 71111.08, “Inservice Inspection Activities” (Reference 21).

Failure to meet any of the TS tube integrity performance criteria is reportable pursuant to 10 CFR 50.72 and 50.73 in accordance with guidelines in NUREG-1022, “Event Reporting Guidelines 10 CFR 50.72 and 50.73” (Reference 22). In addition, the NRC regional office would follow up on such an occurrence as appropriate consistent with the NRC Reactor Oversight Program (Reference 23) and the risk significance of the occurrence.

Finally, the new TS requirements include a requirement that the following information be submitted to the NRC within 180 days of each SG inspection:

- a description of the inspections performed
- the results of these inspections
- the active degradation mechanisms found
- the number of tubes plugged or repaired, and
- the results of the condition monitoring assessments (vis-à-vis the tube integrity performance criteria)

The NRC staff reviews these reports for the purposes of monitoring SG tube degradation trends and assessing the effectiveness of licensee programs. These reviews, like the Regional Office inspection reports, are documented and publicly available.

4.3 Effectiveness – SG Program

Although the new TS requirements have only been in place since 2005 - 2007, depending on the plant, all PWR licensees have been implementing the basic performance-based elements of these requirements since 1999 - 2000 following their commitment to the industry's NEI 97-06 initiative. The NEI 97-06 initiative was an evolutionary change in licensee programs for ensuring tube integrity since the effectiveness of these programs have been constantly evolving and improving since the 1970s. Industry guidelines relating to secondary water chemistry control and inservice inspection have been available since this period and have been frequently updated to reflect research findings, technology developments, and operating experience. In the late 1980s, licensees became sensitized to the need to monitor operational primary to secondary leakage on as close to a real time basis as possible to provide added assurance of plant shutdown before rupture of a leaking tube. Industry guidelines for monitoring and responding to operational primary to secondary leakage have been available since the mid-1990s. Another trend dating to the 1970s was an ever increasing awareness among licensees of the need for their SG programs to address tube integrity in addition to satisfying TS surveillance requirements. Industry guidelines for tube integrity assessment became available in the mid-1990s and led to improved consistency, rigor, and completeness of licensee tube integrity assessments.

In parallel with these SG programmatic improvements, tube integrity reliability appears to have improved significantly since the 1970's. This is evidenced by the sharply declining trends in frequency of forced shutdowns due to SG leakage, as shown in Figure 1, and in SG tube rupture (SGTR) frequency, as shown in Figure 2. The forced outage data in Figure 1 was developed from industry data in Reference 24 (which covers forced outages through 1999) and from unpublished staff data for forced outages after 1999. The SGTR data in Figure 2 was compiled from Reference 25 and also includes the SGTR event at Indian Point 2 in 2000 (Reference 26) which occurred after publication of Reference 25. The use of tubing that is more resistant to stress corrosion cracking (i.e., thermally treated (TT) alloy 600 and 690 tubing in lieu of mill annealed (MA) alloy 600 tubing used in SGs manufactured through the late 1970s) in new (post-1970s) and replacement SGs has been responsible for some of this improvement as is indicated in these figures. However, as also can be seen in these figures, even plants with alloy 600 MA tubing have experienced sharply improved performance trends in forced outage and SGTR frequencies. The improving trends for the plants with alloy 600 MA tubing are due to a variety of factors relating to tube integrity management programs. These include more effective secondary water chemistry programs and steps taken to control copper and impurity ingress from the feed system. These improvements in water chemistry programs, however, are not the only reason for the improving tube integrity trends since even with the improved water chemistry programs plants with alloy 600 MA tubing have continued to experience extensive degradation, including stress corrosion cracking. As a result, it is clear that improved, more effective inspection programs and tube integrity management have played very important roles in reducing the frequency of forced outages due to SG leakage and SGTRs.

Even with the improved SG programs, however, operating experience continues to provide examples of tube flaws which were not detected by inservice inspection before these flaws were later discovered not to satisfy the required structural and accident leakage integrity margins. There have been three such occurrences since 2000, as follows:

- Indian Point 2 – SGTR event in February 2000 (Reference 26). This represented a failure to meet structural and leakage integrity performance criteria.

- Comanche Peak 1 – Failure to meet structural and leakage integrity performance criteria in Fall 2002 as determined by in-situ pressure testing during condition monitoring (Reference 27).

- Oconee 2 - Failure to meet structural integrity performance criteria in Fall 2002 as determined by in-situ pressure testing during condition monitoring (Reference 28).

Another occurrence, at Crystal River 3 in 2003, involved an apparent failure to satisfy the accident leakage criterion (Reference 29). The initial finding that the accident leakage rate exceeded the performance criteria was based on use of a leakage calculation model that was overly conservative. In 2005, the NRC staff approved a more realistic, but still conservative, leakage model than that used in the 2003 calculation (Reference 30).

The Indian Point SGTR event was due to a SCC indication that was missed during prior inspections due to excessive noise in the ECT data and failure to take action to mitigate the effects of the noise. The Comanche Peak and Oconee occurrences both involved an SCC indication missed in prior inspections due to masking dent signals. The industry has made numerous improvements to its inspection guidelines in response to these occurrences and other experience. In addition, the industry is evaluating additional needed enhancements to the guidelines on addressing noise in the ECT data.

Of these three occurrences, only the tube which ultimately ruptured under normal operating conditions at Indian Point would likely have ruptured had an MSLB event occurred during a several month period preceding the SGTR event. Given that there are 69 operating PWRs in the U. S., this experience indicates that the frequency at which tubes may be vulnerable to rupture (or leakage from multiple tubes comparable to a ruptured tube) under MSLB is well within a conditional probability value of 0.05 assumed in NRC risk studies in References 20 and 31.

Based on the above, the staff concludes that SG program improvements in the areas of inservice inspection and tube integrity management and assessment over the past 25 years have contributed significantly to improved SG tube integrity performance during this period.

Improved water chemistry practices and the increasing number of PWRs with SGs of improved design and more SCC-resistant tubing have also contributed to this trend. Since adoption of the

NEI 97-06 performance-based strategy in licensee SG programs around 2000 and the corresponding availability of more complete information concerning instances of failure to satisfy SG tube integrity performance criteria, actual incidences of failure to meet these criteria have been infrequent. This experience provides strong evidence that the potential for one or more tube ruptures (or leakage from multiple tubes of tube rupture proportions) under normal operating conditions or during postulated DBAs is well within that assumed in NRC risk studies to date and provides reasonable assurance that leakage during DBAs will not exceed values assumed in the licensing basis accident analyses.

5.0 DISPOSITION OF ACRS (DPO REVIEW PANEL) RECOMMENDATIONS

An ACRS Ad Hoc Subcommittee served as the NRC DPO Review Panel for the subject DPO, documenting their conclusions and recommendations in References 11 and 12 in February 2001. This section addresses the Subcommittee's conclusions and recommendations as they relate to the adequacy of NRC requirements to ensure that tube structural and leakage integrity will be maintained such that there is reasonable assurance that public health and safety will continue to be maintained.

5.1 Voltage-Based Alternate Repair Criteria (ARC) Issues

The ACRS Ad Hoc Subcommittee's conclusions were supportive of the technical adequacy of the voltage-based ARC, described in Section 2.4 above and in more detail in Reference 19, subject to two recommendations described later in this section. Specific conclusions (shown in bold) included the following:

1. **"There is a need for ARCs."** The Subcommittee did not focus on the economic benefits of ARCs (due to avoided tube plugging and repairs and to extended SG life), but rather on the need for different plugging criteria to address the different types of degradation being encountered in the field. The Subcommittee noted that ODSCC in the tube at the TSP intersections is difficult to detect and characterize relative to the standard 40-percent depth-based repair criterion. The Subcommittee noted the conservatism of the standard 40-percent depth-based criterion for this type of degradation and the attractiveness of voltage-based ARCs for this type of degradation, especially if supplemented by characterizations that ensure flaws producing the signal meet explicit and implicit assumptions about the possible growth and behavior of flaws. The staff notes that the voltage-based ARC includes specific requirements for verifying that these assumptions continue to be valid. For example, the assumptions that the ODSCC has a predominant axial orientation and that it is confined to within the thickness of the TSP is verified through laboratory examinations of representative tube samples which are periodically removed from the SGs and by rotating coil inspection of all tube-to-TSP intersections with bobbin coil responses exceeding 1 volt for 3/4-inch diameter tubing and 2 volts for 7/8-inch diameter tubing (Reference 19). As discussed in Section 5.1.2 (in response to the subcommittee's recommendation that the staff should develop a program to monitor the predictions of flaw growth for systematic deviations from expectations), the staff believes that any systematic deviations from expectations in flaw growth will be identified and addressed in the staff review of the

reports submitted after each outage during which the voltage-based ARC is implemented.

2. **"Plants will be operated with flaws in the SG tubes and this need not be risk significant."** The Subcommittee noted that, provided risk is managed properly, it is acceptable to operate plants with known, small flaws as well as undetected flaws in the SG tubes. As discussed in Section 4, the staff notes that the new technical specifications ensure low risk by requiring implementation of an SG program which ensures that all tubes satisfy the performance criteria for structural and leakage integrity. The staff also notes that the performance criteria associated with implementation of voltage based ARCs differ somewhat from those in the new generic technical specifications (which are applicable when not implementing the voltage based ARC), as discussed in Section 2.4. The ARC-specific performance criteria include a conditional probability criterion for induced tube rupture(s) to ensure that the conditional probability for induced rupture(s) is within values assumed in past risk assessments.

   The Subcommittee also noted that additional, defense-in-depth management of risk can be achieved by restricting known flaws in the tubes to those unlikely to grow significantly during an operating cycle. The staff agrees, noting there have been cases where preventive plugging of tubes not in violation of the voltage based repair criteria was performed to prevent high voltage growth from occurring during the next operating cycle.

3. **"The general features of the procedures that the staff has established to limit the number and size of flaws left in operating SG tubes are adequate."** The Subcommittee found no fault with the concept of voltage-based ARC and found the voltage repair criterion of 1 volt for 3/4-inch diameter tubing and 2 volts for 7/8 inch diameter tubing to be conservative. The Subcommittee did not attempt to reach conclusions concerning occasions when the staff granted exceptions to these criteria, except to note that these exemptions should have been accompanied by more complete risk analyses. The staff notes that the 1 and 2 volt criteria above are lower threshold limits and that all indications below these limits are acceptable (Reference 19). However, the voltage based ARC includes higher upper bound voltage threshold limits which are determined in accordance with the voltage based ARC methodology in Reference 19. This methodology is based on satisfying the voltage based ARC performance criteria, including the criterion on conditional probability of induced rupture(s) during MSLB, with allowance for voltage measurement variability and voltage growth rate distribution. As noted by the Subcommittee, the staff approved an increase in the lower voltage threshold limit to 3 volts for three plants (with 3/4-inch diameter tubing) where a number of tubes were expanded against the tube support plates for purposes of limiting axial support plate deflection under MSLB conditions. These changes are no longer in effect, since these plants have undergone SG replacement and the provisions for implementing voltage-based ARCs have been eliminated from the TS for these plants. Under these changes, the licensees were required to demonstrate that the conditional probability of burst criterion continued to be met. Thus, the staff believes there were no risk implications associated with the 3 volt criterion.

4. **“The general features of the condition monitoring program are adequate.”** The Subcommittee found the general approach used to assess the probabilities of leakage and tube burst to be conservative. The development of empirical correlations of burst pressure and leakage with voltage amplitude was felt by the subcommittee to be technically defensible. The Subcommittee found no evidence that the supporting databases were flawed in any non-conservative, systematic way. The Subcommittee felt that the constant POD assumption in the voltage based ARC methodology approved by the staff could potentially deter technical improvements, but acknowledged that the staff would consider approving alternative POD assumptions that recognize that POD can depend on flaw size (with a sufficient technical justification). In fact, the NRC staff has approved an alternative (Reference 32) to the constant POD model which replaces the POD parameter with a parameter known as the “probability of prior cycle detection” (POPCD). This empirical, plant-specific parameter is voltage dependant and it relates the total number of indications found during a given inspection in a given voltage bin to the subset of these indications that were also detected during the previous inspection.

   The Subcommittee concluded that the condition monitoring program that licensees adopt in conjunction with the ARC, although not perfect, can produce a better understanding of the conditions and vulnerabilities of steam generators and afford additional protection to the public than has been possible in the past. The staff agrees with this conclusion and notes that the voltage-based ARC was an important step that contributed to the ultimate development of the performance-based strategies in DG 1074 (Reference 17), NEI 97-06 (Reference 16), and the new TS for ensuring SG tube integrity.

   The Subcommittee did not attempt to investigate the quality with which the condition monitoring is being implemented by licensees. The Subcommittee stated that it is aware of recent events that may suggest that implementation does not meet expectations of the staff. This Subcommittee comment was made during the aftermath of the SGTR event at Indian Point 2 in February 2000 (Reference 26). This event is attributable to several shortcomings in the licensee’s program implemented during the outage prior to the SGTR event. These shortcomings included failure of condition monitoring (due to inspection data acquisition and analysis shortcomings) to recognize the size and significance of an PWSCC flaw in the u-bend region and the need for corrective action to ensure that tube integrity would be maintained during subsequent operation. The staff notes that failure of condition monitoring to detect conditions challenging the tube integrity criteria or failure of operational assessment to anticipate the condition of the tubes relative to the performance criteria at the next scheduled inspection is typically accompanied by a failure to implement needed corrective actions on a timely basis. Without timely corrective action, the condition of the tubes worsen until, ultimately, the condition of the tubes becomes obvious as a result of future ISIs, tube leakage, or an SGTR event. As discussed in Section 4.3, operating experience shows that failure to satisfy the tube integrity performance criteria is an infrequent occurrence; thus testifying to the overall effectiveness of licensee programs, including condition monitoring.

The above conclusions by the ACRS Ad Hoc Subcommittee were accompanied by two recommendations as discussed in Sections 5.1.1 and 5.1.2 below.

5.1.1 ACRS Ad Hoc Subcommittee's Recommendation (Reference 12) - "The databases for 7/8-inch diameter tubes need to be greatly improved to be useful."

The subcommittee observed that the correlation of leakage with voltage for the 7/8-inch diameter tubes does not correspond well with that for 3/4-inch diameter tubes. The subcommittee could identify no mechanistic reasons why this should be the case. The subcommittee felt that the lack of a relationship may reflect stochastic scatter and limited size of the database and, therefore, felt the staff should consider requiring a near-term expansion of the database.

The staff evaluated this recommendation under item number 3.7 of the NRC SG Action Plan (SGAP) (References 14 and 15). The staff's findings are documented in Reference 33 and include the following:

1. Evaluation of the leakage data has not led to a conclusive explanation for the poor correlation of the 7/8-inch diameter tube leakage data compared to 3/4-inch diameter tube leakage data.

2. The poor correlation not withstanding, the methodology for assessing leak rate is conservative for the following reasons:

    a. Pre-pull voltage responses are used for the correlations. If the crack tears as a result of the tube pull operation, the measured voltage is expected to be higher than if the tube were not damaged.

    b. The leak rate analysis yields a probability density function of total leak rate (using Monte Carlo sampling of the input parameter distributions and leak rate distributions as a function of voltage) for a given population of voltage responses. This probability density function is evaluated at the upper 95th percentile value at an upper 95-percent confidence bound vis-à-vis the applicable performance criterion for accident leakage.

    c. If a statistical correlation between leak rate and voltage cannot be demonstrated to within criteria specified in Generic Letter 95-05 (Reference 19), Generic Letter 95-05 specifies that leakage shall be treated as independent of voltage, which is conservative (since most indications left in service are relatively low voltage indications, which tend to leak less than the mean).

Based on the above, the staff concluded in Reference 33 that item number 3.7 (the leakage correlation issue) is adequately addressed and is, therefore, closed. In addition, the staff stated that it would continue to assess the leakage correlations as more data are added to the database.

The ACRS reviewed these findings in Reference 34. The ACRS continues to believe that the leakage correlation for 7/8-inch diameter tubing should not be used, which is contrary to the staff's position, as stated above. As previously noted, the voltage based ARC, including the leakage correlation, continues to be used at one plant with 7/8-inch diameter tubes (as of February 2009) and is approved for use at two additional such plants (but not currently implemented). However, the ACRS stated that it agrees with the staff that the choice of a 2 volt limit for 7/8-inch diameter tubes is conservative with respect to the risk posed and that item number 3.7 should be closed.

5.1.2 ACRS Ad Hoc Subcommittee's Recommendation (Reference 12) - "The staff should establish a program to monitor the predictions of flaw growth for systematic deviations from expectations."

One step in the voltage-based ARC methodology is the prediction of the change in the voltage distribution over an operating cycle. The subcommittee noted that this is done assuming a linear change in the distribution with time. The subcommittee noted that this is inconsistent with behavior of stress corrosion cracks observed in NRC research. These studies show that cracks grow slowly until they interlink, after which it is possible for flaws to grow very quickly. Flaw growth is, then, inherently non-linear and can be treated as linear with time only in a bounding manner. Even then, the subcommittee stated that stochastic variability means that occasionally individual cracks can violate even very conservative linear bounds. Thus, the subcommittee found that it will be important for the staff to be vigilant in monitoring the implementation of the ARC to watch for such systematic errors in the crack growth predictions.

The staff evaluated this recommendation under item number 3.8 of the SGAP (References 14 and 15). The staff's findings are documented in Reference 35 and are summarized in the following paragraphs.

In accordance with GL 95-05, licensees submit information related to the structural and leakage integrity of the tubes within 90-days (the 90-day report) of completion of the steam generator tube inspections. The information submitted includes the actual voltage distribution and the projected voltage distribution for the next operating cycle. It also includes the tube burst probability and calculated leakage under main steam line break differential pressure conditions. The projected voltage distribution with the resultant tube burst probability and leakage estimates account for flaw growth.

The staff has routinely reviewed these 90-day reports and compares the tube burst probability and leakage to the criteria specified in GL 95-05. In addition, the staff compares the predicted values to actual values. If the predicted values are conservative, the flaw growth distribution used in the prediction is typically considered to be within expectations. If the predicted values are not conservative when compared to the actual values, the staff evaluates the root cause and ensures appropriate corrective actions are taken by the licensee.

In summary, the staff concluded in Reference 35 that any systematic deviations from expectations in flaw growth will be detected and addressed in the staff review of the 90-day reports. The staff also concluded that with the GL 95-05 guidance and staff's review process, the monitoring of flaw growth specified in the SGAP item number 3.8 is adequately addressed. The staff considers item number 3.8 closed.

In Reference 34, the ACRS recommended that SGAP item number 3.8 should not be closed until progress has been made on developing the cracking model under item number 10 of the SGAP (References 14 and 15). Item number 10 involved development of models for predicting cracking behavior of SG tubing in an operating environment and attempting to explain the observed relationship between changes in eddy current signal and crack growth. In response

(Reference 36), the NRC Executive Director for Operations reiterated the staff's position in Reference 35 that the staff is monitoring operating experience as it relates to flaw growth and considers item number 3.8 to be closed. In addition the staff will continue to monitor research associated with SGAP item number 3.10.

For the reasons stated above, the staff concludes that crack growth rates will continue to be adequately monitored as part of the implementation of the voltage based ARC and considers the SGAP item number 3.8 closed.

5.2 Damage Progression Issues

5.2.1 ACRS Ad Hoc Subcommittee's Recommendation (Reference 12) - "Risk analyses that the staff considers need to account for progression of damage in a more rigorous way."

This recommendation stemmed from a DPO concern that dynamic loads induced in steam generator tubes by an MSLB or other secondary-side breaches would lead to growth of cracks and increased steam generator tube leakage or ruptures outside the range of analyses and experiments performed by the NRC staff. In addition, an MSLB may impose dynamic loads on the TSPs beyond simply those associated with differential pressure loads, and these loads could be transferred to the tubes. The Subcommittee noted that this concern affects any consideration of SG tube integrity and is not unique to use of voltage based ARCs.

The staff opened a new generic issue, GSI 188, "Steam Generator Tube Leaks or Ruptures Concurrent with Containment Bypass from Main Steam Line or Feedwater Line Breaches," in part[2], to address this concern. This work was performed under item number 3.1 of the SGAP (Reference 14 and 15) and has been completed. Resolution of GSI 188 and the technical basis thereof are documented in References 37 and 38, respectively. Key conclusions of the staff included:

1. Dynamic loads and resonance vibrations following an MSLB are low and have little impact on growth of existing cracks beyond the effects of differential pressure stress alone.

2. Dynamic loads from an MSLB or feedwater line break (FWLB) do not affect the structural integrity of tubes in service and do not lead to additional leakage or ruptures beyond what would be determined using differential pressure loads alone.

3. Therefore, the principal assertion of GSI 188 is closed, and no changes to existing regulations and guidance are recommended.

4. <u>The dynamic load effects from an MSLB or FWLB need not be taken into account in evaluating the potential for multiple tube ruptures under GSI 163.</u>

[2] GSI 188 also addressed a second issue outside the scope of DPO issues reviewed by the ACRS Ad Hoc Subcommittee; namely multiple SG tube leaks or ruptures could cause the secondary side to over-pressurize and cause a steam line break that could then result in additional SG tube leaks or ruptures.

The ACRS reviewed the technical basis for these findings in Reference 34 and concluded that item number 3.1 of the SGAP is appropriately closed out. Confirmatory information requested by the ACRS in Reference 34 was subsequently provided to the ACRS as discussed in Reference 37.

5.2.2 Jet Impingement Issue

The ACRS Ad Hoc Subcommittee considered a DPO concern that particulate-laden fluids flowing from a cracked SG tube can pierce adjacent tubes. The staff evaluated this concern as item number 3.2 of the SGAP (Reference 14 and 15). This item addressed both MSLB and severe accident conditions. In its review of the DPO concerns in Reference 12, the ACRS Ad Hoc Subcommittee concluded that the staff had undertaken adequate research (under item number 3.2 of the SGAP) to address this issue. The Subcommittee stated that although it is necessary to carry this research to an appropriate conclusion, early results suggest that damage progression by the jet cutting mechanism is not likely.

Item number 3.2 has been completed (Reference 39). The detailed results of this study for MSLB conditions are documented in Reference 40. This study was based on tests that provided a conservative simulation of an MSLB to determine the susceptibility of SG tubes to erosive damage from impacting jets of superheated steam leaking from adjacent tubes. This study showed that the likelihood of failure propagation by jet erosion is low under these conditions.

The detailed results for severe accident conditions are documented in Reference 41. Erosion tests were conducted in a high temperature, high velocity erosion rig using micron-sized nickel and aluminum oxide particles mixed in a high temperature gas. The erosion results, together with analytical models for crack opening area and jet velocities, were used to estimate the erosive effects of superheated steam with entrained aerosols from the core during severe accidents. It was determined that failure of an adjacent tube by jet impingement would take more than 10 hours after the subject crack had undergone significant crack opening displacement by creep at high temperature. However, once the system has reached these high temperatures, failure of some primary system component, including unflawed SG tubes, would be expected to occur in less than 1 hour. Thus, jet impingement is very unlikely to contribute in any significant way to severe accident risk.

In Reference 34, the ACRS agreed with the staff’s conclusion that the probability of damage progression via jet cutting of adjacent SG tubes is low and need not be considered in accident analyses. The ACRS also agreed that SGAP item number 3.2 should be closed.

5.2.3 Crack Unplugging Issue

The ACRS Ad Hoc Subcommittee considered a DPO concern that forces involved with MSLB blowdown and leakage through cracks can cause cracks plugged with corrosion products to leak. In addition, the DPO was concerned that corrosion products in the annular gap between the tubes and TSP holes can be expelled, allowing otherwise occluded cracks to leak. The subcommittee stated in Reference 12 that it found no evidence that the “unplugging” of cracks is a damage progression mechanism of concern. The subcommittee made no recommendations concerning any follow-up study of this issue, and no such work has been included as part of the SGAP. The staff does not believe such work is necessary. Models used to predict leak rate under accident conditions tend to be mechanistic models (based in part on crack geometry) that have been benchmarked against test data (from pulled tube specimens and/or laboratory specimens) or empirical models such as that used for the voltage based ARC. In both cases, the test data is expected to reasonably reflect the leakage that would be expected for cracks in the free span under actual accident conditions

5.3 Risk Issues Pertaining to Tube Ruptures or Leakage During MSLB

A central concern of the DPO was that MSLB can lead to primary to secondary leakage of tube rupture proportions sufficient to deplete the reactor water storage tank (RWST) inventory via emergency core cooling system (ECCS) injection lost to the secondary side of the SGs (and therefore not available for recirculation from the containment sump) thereby leading to core damage with containment bypass. This concern relates to primary-to-secondary leakage from one or more tube ruptures and/or relatively large numbers of tubes, which have not burst, such that the total leakage from all tubes is comparable to one or more tube ruptures.

The DPO estimate of core damage frequency (CDF) and containment bypass frequency associated with SG tube leakage as a consequence of an MSLB was $1.0x10^{-4}$/reactor year (RY) (Reference 3). This estimate is based on the assumptions of (1) an MSLB frequency of $1.0x10^{-4}$/RY, (2) a conditional probability of 1.0 that primary-to-secondary leakage will be of tube rupture proportions under MSLB conditions, and (3) a conditional probability of 1.0 for failure to successfully mitigate the event before core damage occurs.

Staff PRAs considered by the ACRS Ad Hoc Subcommittee assumed that the frequency of initiating secondary side depressurization events is dominated by stuck open SG relief valves, with a frequency of $1x10^{-3}$/RY estimated from operational event data. The frequencies of MSLB and main feed line break (MFLB) are estimated to be $6.8x10^{-4}$/RY and $1.8x10^{-4}$/RY, respectively, for a 4-loop plant. The DPO did not appear to have any concerns relative to these estimates, nor did the ACRS Ad Hoc Subcommittee state any concern relative to these estimates.

5.3.1 Conditional Probability of SG Tube Rupture during MSLB

The DPO concern relates to plants with widespread SCC, and particularly those plants with ARC TS that allow many tubes with such cracks to remain in service, and that, because of eddy current limitations in reliably detecting such cracks, leakage of tube rupture proportions is the expected outcome. As discussed in Section 5.1, the ACRS Ad Hoc Subcommittee acknowledged that eddy current test techniques are not capable of 100-percent accuracy in detecting flaws (though noting the technical advances that have led to improved detection performance). However, the Subcommittee stated that this does not degrade the protection afforded to the public health and safety, provided the risk is properly managed.

Staff PRAs considered by the ACRS Ad Hoc Subcommittee assumed the conditional probability of rupture(s), or leakage from multiple tubes of tube rupture proportions, to be equal to or less than 0.05. The ACRS subcommittee did not make specific comments regarding the staff's assumption, but concluded that if the risk can be managed properly, it is acceptable to operate plants with known, small flaws as well as undetected flaws in the SG tubes. As an example of managing risk, the ACRS Ad Hoc Subcommittee cited the voltage based ARC methodology that requires that the conditional probability of rupture be demonstrated periodically to be 0.01 or less (for tubes degraded by ODSCC at the tube to TSP intersections).

Looking beyond voltage-based ARCs, the performance-based strategy for ensuring tube integrity in the new technical specifications (i.e., ensuring, and periodically demonstrating, that all tubes satisfy the structural and accident leakage integrity performance criteria developed consistent with the design and licensing bases) is a risk management strategy. Meeting the performance criteria on a consistent basis ensures that the conditional probability of tube leakage of tube rupture proportions under MSLB is low relative to values assumed in PRAs. This conclusion is supported by operating experience as discussed in Section 4.3.

5.3.2 Accident Mitigation/Human Factors Issues

ACRS AD Hoc Subcommittee's Conclusion (Reference 12): "Analyses of human performance errors during design basis accidents appear consistent with current practices." The Subcommittee reviewed the DPO concern that the staff's estimate of the probability that the operators will fail to perform tasks needed to establish the long term cooling of the core (i.e., 10^{-3} or 1 in 1000) is overly optimistic. The subcommittee concluded that the staff estimate appears consistent with the state of current understanding of human performance errors when only a single tube ruptures. In developing assessments of risk concerning these DBAs, the Subcommittee stated that the staff must consider the probabilities of multiple tube ruptures until adequate technical arguments have been developed to show that damage progression is improbable (Reference 12).

DPO and ACRS Ad Hoc Subcommittee's concerns pertaining to damage progression were evaluated under item numbers 3.1 and 3.2 of the SGAP, as discussed in Section 5.2 above. Again, as discussed in Section 5.2 above the ACRS has concurred with the staff's conclusions drawn from the results of these studies and with the staff's closure of these item numbers. The staff concludes that the damage progression mechanisms cited in the DPO are unlikely to increase the probability of multiple tube ruptures beyond that which has already been considered in staff PRAs.

The ACRS Ad Hoc Subcommittee also observed that the staff needs to develop defensible analyses of the uncertainties in its risk assessments, including uncertainties in its assessments of human error probabilities. As the staff develops a better understanding of the dynamic processes associated with depressurization during an MSLB, the Subcommittee noted that the staff may want to revisit estimates of operator error probability in light of the considerable distraction that might occur during such events. In response to the comments, the staff is developing improved methods for risk assessment under item number 3.5 of the SGAP (References 14 and 15). This item number is considered outside the scope of GSI 163 since its focused on severe accidents and its completion is not expected (based on early results) to identify needed improvements to the current regulatory framework for ensuring SG tube integrity. With respect to operator distraction which may occur during such an event, the staff notes that the dynamic effects of the event will happen quickly. No mandatory operator actions are needed while the plant is experiencing these short-lived dynamic effects.

5.4 Severe Accident Risk Issue

The ACRS Ad Hoc Subcommittee considered a DPO concern that severe accident sequences in which the primary system remains pressurized are more likely to evolve into steam generator tube rupture accidents than the staff predicts in Reference 31.

ACRS Ad Hoc Subcommittee's Conclusion (Reference 12): "Substantial uncertainties remain in the understanding of steam generator tube performance under severe accident conditions." The subcommittee stated,

> "The staff has not developed persuasive arguments to show that the steam generator tubes will remain intact under conditions of risk-important accidents in which the reactor coolant system remains pressurized. The current analyses dealing with loop seals in the coolant system are not yet adequate for risk assessments. The treatment of mixing of flows in the inlet plenum to a steam generator under conditions of countercurrent natural convection flow are optimistic and are not substantiated by applicable data from experiments. Sensitivity studies have not explored the plausible ranges of parameter values or the space of uncertainties adequately. Finally, the Ad Hoc Subcommittee notes that analyses of failure of other locations in the coolant system subject to natural convection heating have not included a systematic examination of vulnerable locations in the system."

The ACRS Ad Hoc Subcommittee's concerns relating to severe accidents are being addressed under item number 3.4 of the SGAP (References 14 and 15). This item is outside the scope of GSI 163 since should any action be determined necessary to address severe accident risk concerns, these actions would likely be directed toward accident mitigation rather than modification of the current regulatory framework for ensuring SG tube integrity.

5.5 Iodine Spiking and Source Term Issues

As part of the voltage-based tube repair criteria (Reference 19), licensees must demonstrate that primary-to-secondary leakage that may potentially occur under MSLB conditions does not exceed values assumed in the licensing basis safety analyses to demonstrate that the associated dose consequences meet applicable regulations (i.e., 10 CFR 50.67 or 10 CFR 100, GDC-19). In accordance with the NRC Standard Review Plan (NUREG-0800), these dose calculations are based on an initial coolant equilibrium iodine concentration equal to the allowable limit in the technical specifications (typically 1.0 μCi/g) and an iodine spiking factor of 500. As part of their license amendment request for voltage-based tube repair criteria, a number of licensees requested (and the staff approved) reduced limits in the technical specifications on allowable equilibrium iodine concentrations in the primary coolant. This reduction in the allowable equilibrium iodine concentration means that a higher level of primary-to-secondary leakage can be tolerated, assuming the same iodine spiking factor of 500, consistent with the applicable regulatory dose limits, thus enabling additional degraded tubes to remain in service (provided all other requirements of the ARC are met).

The ACRS Ad Hoc Subcommittee reviewed a DPO concern that data (primarily from reactor trips, but including SGTR events) indicate that spiking factor increases with decreasing steady state iodine concentration. Thus, there was a concern that the spiking factor used for the licensing basis accident analysis is too low when the technical specification limit on the iodine concentration in the primary coolant has been reduced.

ACRS Ad Hoc Subcommittee's Recommendation (Reference 12) - "The staff should develop a more technically defensible position on the treatment of radionuclide release to be used in safety analyses of design basis events." This recommendation was addressed under item number 3.9 of the SGAP and was discussed at the 509th meeting of the

ACRS, February 5-7, 2004. In a letter dated May 21, 2004 (Reference 34), the ACRS stated: "The staff continues to treat iodine spiking in a conservative, empirical fashion. We recommend that the staff develop a mechanistic understanding of iodine spiking so that analyses reflect current plant operations and the capabilities of modern fuel rods." The ACRS went on to say, "the staff has not accepted our recommendation to develop a mechanistic understanding of the iodine spiking issue. The staff continues to use a conservative, empirical estimate of iodine spiking for accident consequence analyses. This estimate is based on historical data that may not reflect current practices in plant operations or the capabilities of modern fuels to prevent coolant contamination. We again encourage the staff to take advantage of iodine studies available in the literature and develop a mechanistic understanding of the phenomenon."

Based on these comments from the ACRS, the staff proposed a new generic issue; Generic Issue (GI) 197, "Iodine Spiking Phenomena." This issue was screened (Reference 42) by a review panel in accordance with NRC Management Directive 6.4, "Generic Issues Program." As documented in Reference 42, the review panel found the issue to be of low safety significance and concluded that it should not be continued as a safety issue. The review panel found that there is no evidence that the current regulatory approach is not bounding, even in event of a combined MSLB and SGTR and that the current regulatory approach to iodine spiking, in spite of its empirical nature, is adequate. By Reference 42, GI 197 and item number 3.9 of the SGAP are closed. In Reference 43, the ACRS stated it had considered the results of the staff's screening of GI 197 and had no objection to dropping this issue from further consideration.

6.0 SUMMARY, CONCLUSIONS, AND CLOSURE

This report documents the staff's resolution of GSI 163, "Multiple Steam Generator Tube Leakage." This GSI involves a DPO concern (principal assertion) by an NRC staff member that multiple SG tube leaks during a non-isolatable MSLB outside containment could lead to core damage that could result from the loss of all primary system coolant and safety injection fluid in the refueling water storage tank.

To address this concern, the staff evaluated the adequacy and effectiveness of industry practice and regulatory requirements relating to the management of SG tube integrity to ensure that all tubes will exhibit acceptable structural margins against burst or rupture under normal operating conditions and DBAs (including MSLB), and that leakage from one or multiple tubes under DBAs will be limited to very small amounts, consistent with the applicable regulations for offsite and control room dose. As part of this effort, the staff considered the conclusions and recommendations of the ACRS Ad Hoc Subcommittee, which served as the DPO Review Panel, and the staff's follow up actions taken in response to these findings as part of its evaluation of the adequacy and effectiveness of regulatory requirements.

As of September 30, 2007, new performance-based technical specification requirements were in place and being implemented at all US PWRs. These requirements are intended to ensure that all tubes exhibit adequate structural margins against burst or rupture for the spectrum of normal operating and DBA conditions, consistent with the original design basis. In addition, these requirements are intended to ensure that total leakage from tubes at a plant will not exceed values assumed in licensing bases accident analyses, even if no tubes actually rupture under these conditions. In addition, licensees are required to periodically demonstrate that these structural margin and accident leakage criteria are satisfied for all tubes or, if not met, to report the occurrence in accordance with 10 CFR 50.72/73.

Although these technical specification requirements have been implemented only recently, the basic elements of the required performance-based approach have been in use by U. S. PWR licensees since 2000 as part of the industry's NEI 97-06 initiative. NEI 97-06 itself was an evolutionary development since tube inspection technologies, inspection practices, and tube integrity management practices had been undergoing significant improvement since the mid-1970s. These improvements have contributed significantly to improved SG tube integrity performance during this period. Improved water chemistry practices and the increasing number of PWRs with steam generators of improved design and more stress corrosion crack resistant tubing have also contributed to this trend. Since adoption of the NEI 97-06 performance-based strategy in licensee SG programs and the corresponding availability of more complete information concerning instances where there was a failure to satisfy the SG tube integrity performance criteria, actual incidences of failure to meet these criteria have been infrequent. This experience provides strong evidence that the potential for one or more tube ruptures (or leakage from multiple tubes totaling tube rupture proportions) during normal operation or DBAs is well within that assumed in NRC risk studies to date.

The staff has completed all SGAP tasks that were opened to address the ACRS Ad Hoc Subcommittee's conclusions and recommendations stemming from their review of the DPO concerns relating to voltage based ARCs, damage progression mechanisms, and iodine spiking. Based on the results of these tasks, the staff concludes that the DPO concerns relating to these issues are not substantiated and that no changes to existing requirements are needed to ensure public health and safety. The ACRS has concurred with the closure of these issues. In response to ACRS Ad Hoc Subcommittee conclusions and recommendations, the staff is continuing to evaluate risk issues associated with accident sequences involving ruptured/leaking SG tubes as part of SGAP item numbers 3.4 and 3.5. These studies are primarily focused on severe accidents and are not expected to identify needed changes to existing requirements for managing SG tube integrity and are, therefore, outside the scope of GSI 163.

Based on the above, the staff concludes that the technical specification requirements relating to SG tube integrity provide reasonable assurance that all tubes will exhibit acceptable structural margins against burst or rupture during normal operation and DBAs (including MSLB), and that leakage from one or multiple tubes under DBAs will be limited to very small amounts, consistent with the applicable regulations for offsite and control room dose. Thus, the staff concludes that the GSI principal assertion and related concerns in the DPO are not substantiated and that actions for the GSI are completed.

The staff met with the ACRS on May 7, 2009, to discuss the staff's technical basis for resolution of GSI 163. In a letter dated May 20, 2009, to Gregory B. Jaczko, Chairman, NRC, the ACRS concluded that GSI 163 can be closed as proposed by the staff (Reference 44).

7.0 REFERENCES

1. Memorandum from E. Beckjord to T. Murley, "A New Generic Issue: Multiple Steam Generator Tube Leakage" (ADAMS Accession No. 9212040356), dated June 16, 1992.

2. Memorandum from T. Speis to J. Hopenfeld, "Your Differing Professional Opinion Dated 12/23/91" (ADAMS Accession No. 9212290195), dated February 19, 1992. This memorandum encloses (Enclosure 1) J. Hopenfeld's Differing Professional Opinion dated December 23, 1991.

3. Memorandum from J. Hopenfeld to E. Beckjord, "A New Generic Issue: Multiple Steam Generator Leakage" (ADAMS Accession No. ML003709116), dated March 27, 1992.

4. Memorandum from B. W. Sheron to L. A. Reyes, "Generic Issues in Regulatory Office Implementation Status" (ADAMS Accession No. ML071630094), dated July 5, 2007

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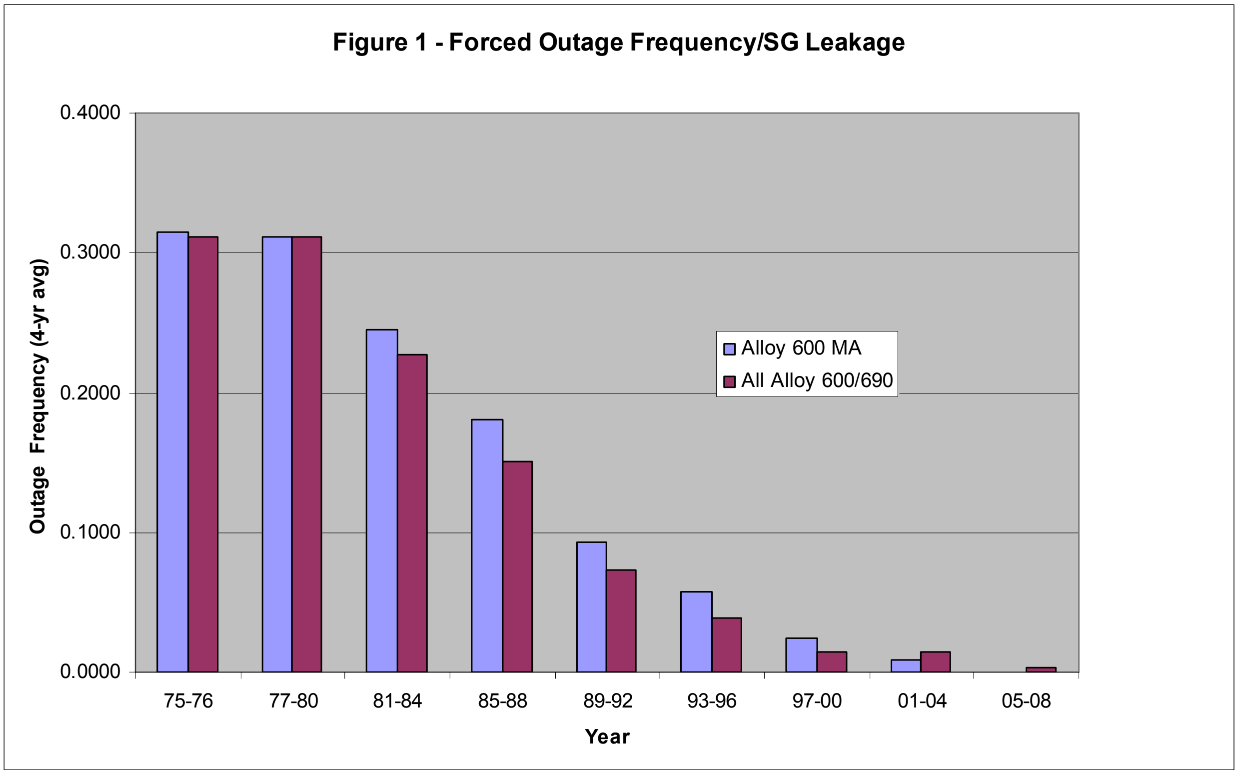
Figure 1 - Forced Outage Frequency/SG Leakage
0.4000
0.3000
0.2000
0.1000
0.0000
Outage Frequency (4-yr avg)
Alloy 600 MA
All Alloy 600/690
75-76
77-80
81-84
85-88
89-92
93-96
97-00
01-04
05-08
Year

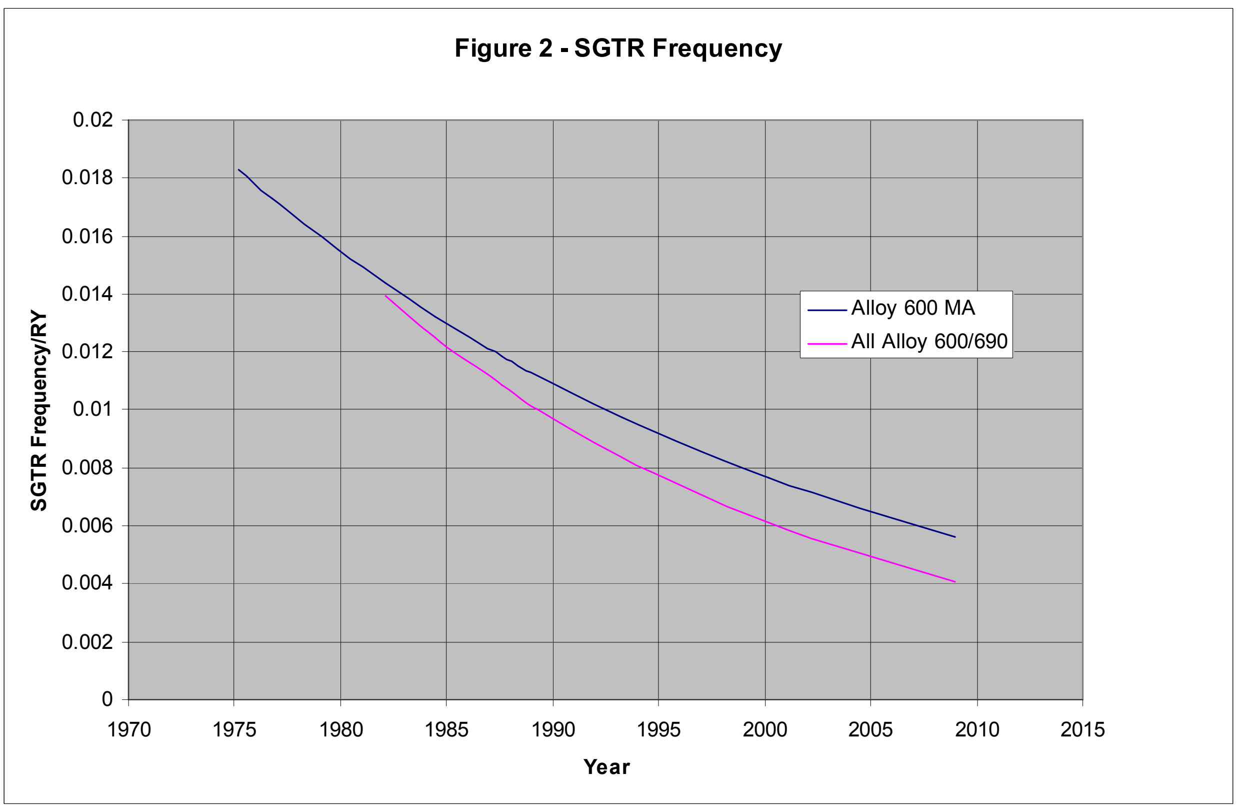
Figure 2 - SGTR Frequency
0.02
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
SGTR Frequency/RY
Alloy 600 MA
All Alloy 600/690
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
Year