November 8, 2005

Mr. Christopher M. Crane
President and Chief Executive Officer
AmerGen Energy Company, LLC
4300 Winfield Road
Warrenville, IL 60555

SUBJECT: THREE MILE ISLAND NUCLEAR STATION, UNIT 1 - STEAM GENERATOR TUBE KINETIC EXPANSION INSPECTION AND REPAIR CRITERIA (TAC NO. MC7001)

Dear Mr. Crane:

The Nuclear Regulatory Commission (NRC) staff has completed its review of the information submitted by your letters dated October 4, 2002, August 16, 2004, May 3, 2005, August 11, 2005, August 23, 2005, and October 14, 2005, on the subject issue. The NRC staff's review results are delineated in the enclosed safety evaluation.

The NRC staff found that the proposed kinetic expansion inspection acceptance criteria, inspection scope and methods, flaw growth assessment methodology, and accident leakage methodology ensure that the structural and leakage integrity of the kinetic expansion joints will be maintained in accordance with the applicable regulations without undue risk to public health and safety.

If you have any questions, please contact me at 301-415-1451.

Sincerely,

\RA

Peter S. Tam, Senior Project Manager
Plant Licensing Branch III-1
Division of Operating Reactor Licensing
Office of Nuclear Reactor Regulation

Docket No. 50-289

Enclosure: Safety Evaluation

cc w/encl: See next page

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SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

AMERGEN ENERGY COMPANY, LLC

THREE MILE ISLAND NUCLEAR STATION, UNIT 1 (TMI-1)

STEAM GENERATOR TUBE KINETIC EXPANSION INSPECTION AND REPAIR CRITERIA

DOCKET NO. 50-289

1.0 INTRODUCTION

By letter to the Nuclear Regulatory Commission (NRC) dated October 4, 2002 (Agendywide Document Access and Managmenet System (ADAMS) Accession No. ML 022840503), as supplemented by letters dated August 16, 2004 (Accession No. ML042370131), May 3, 2005 (Accession No. ML051300602), August 11, 2005 (Accession No. ML052350122), August 23, 2005 (Accession No. ML052350912), and October 14, 2005 (Accession No. ML052940347), AmerGen Energy Company, LLC (AmerGen) (the licensee) submitted the updated inspection acceptance criteria and updated leakage assessment methodology for the TMI-1 once-through steam generators (OTSG) kinetic expansions. This information was submitted for NRC review and acceptance in accordance with IWB-3630 of the American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME Code), Section XI.

2.0 BACKGROUND

TMI-1 received its operating license in April 1974. It is a two-loop pressurized-water reactor (PWR) with original equipment OTSGs manufactured by Babcock & Wilcox. OTSGs differ from recirculating steam generators (RSGs) of the type manufactured by Westinghouse and other manufacturers in that the tubes are straight extending from the tube inlets at the upper tubesheet to the tube outlets at the lower tubesheet. During the original fabrication of the OTSGs, the tube ends were roll expanded over a 1-inch length against the upper and lower tubesheets, respectively. Each tube was also welded at the primary faces of the upper and lower tubesheets. The tubes are Alloy 600 Mill Annealed.

Widespread inside diameter (ID) intergranular attack (IGA) was identified in the early 1980s, mostly near the upper end of the OTSG tubing at TMI-1. The licensee determined that the degradation was due to a chemistry excursion that occurred while the plant was in a shutdown condition during that period. The licensee performed repairs on all inservice tubes by forming a new tube-to-tubesheet joint within the upper tubesheet using a kinetic expansion (KE) process. Most of these KE joints were formed over the top 17 inches of the 24-inch thick tubesheet. A smaller number were formed over the top 22 inches of the tubesheet. These expansions were

Enclosure

intended to span defects in the tubesheet region with at least a 6-inch defect free zone at the bottom of the expansions. Developmental testing demonstrated that this 6-inch zone (qualification zone) is sufficient to ensure the structural and leakage integrity of the joints. The NRC staff reviewed and approved the licensee's repair in NUREG-1019, "Safety Evaluation Report Related to Steam Generator Tube Repair and Return to Operation – Three Mile Island Nuclear Station, Unit No. 1," dated November 1983.

In 1996, NRC inspectors identified concerns regarding inservice inspection practices being implemented for the KE joints by GPU Nuclear Corporation, the then licensee for TMI-1 (later changed to GPU Nuclear, Inc. (GPUN)). Among these concerns was that GPUN did not appear to have a program to ensure the continued structural and leakage integrity of the KE joints. During a meeting on July 25, 1997, GPUN representatives agreed to provide the NRC staff the technical basis for inspection and repair criteria that were to be applied to indications in the KE joints during the next refueling outage inspection. The licensee provided this information by letters dated August 8 and November 26, 1997. By letter dated June 17, 1999, the NRC staff stated that the inspection and repair criteria implemented by GPUN required regulatory approval. After reviewing GPUN comments pertaining to this position, the NRC staff reached a final determination by letter dated August 24, 2001, that the repair criteria implemented by GPUN require regulatory approval. In addition, any future modifications to the subject acceptance criteria shall be submitted to the NRC for review and approval prior to implementation. As a result of the sale and license transfer of TMI-1 to AmerGen on December 20, 1999, and as documented by letter from AmerGen to the NRC on January 26, 2000, AmerGen (the licensee) engrossed all issues and requests that were pending with the NRC at the time of the license transfer.

3.0 REGULATORY EVALUATION

Steam generator tubes function as an integral part of the reactor coolant pressure boundary (RCPB) and, in addition, serve to isolate radiological fission products in the primary coolant from the secondary coolant and the environment. For the purposes of this safety evaluation, tube integrity means that the tubes are capable of performing these functions in accordance with the plant design and licensing basis.

Title 10 of the *Code of Federal Regulations* (10 CFR) establishes the fundamental regulatory requirements with respect to the integrity of the SG tubing. 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" (GDC 15 and 31), shall be of "the highest quality standards possible" (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 specifies that components which are part of the RCPB must meet the requirements for Class 1 components in Section III of the ASME Code. Section 50.55a further requires, in part, that throughout the service life of a 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 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 are augmented by additional SG tube surveillance requirements in the plant technical specifications (TSs).

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 main steamline break (MSLB). These analyses consider the primary-to-secondary leakage through the tubing which may occur during these events and must show that the offsite radiological consequences do not exceed the applicable limits of the 10 CFR Part 100 guidelines 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).

Under the plant TSs SG surveillance program requirements, the licensee is required to monitor the condition of the SG tubing and to plug or repair tubes as necessary. Specifically, the licensee is required to perform periodic inspections of and to repair or remove from service by plugging all tubes found to contain flaws with sizes exceeding the acceptance limit, termed "repair limit." The tube repair limits were developed with the intent of ensuring that degraded tubes (1) maintain factors of safety against gross rupture consistent with the plant design basis (i.e., consistent with the stress limits of the ASME Code, Section III); and (2) maintain leakage integrity consistent with the plant licensing basis while, at the same time, allowing for potential flaw size measurement error and flaw growth between SG inspections. The required frequency and scope of tubing examinations and the tube repair limits are specified in TMI-1 TS 4.19, “OTSG Tube Inservice Inspection.”

The TMI-1 TSs define a tube inspection as an inspection of the tube from the bottom of the upper tubesheet to the top of the lower tubesheet. The TMI-1 requirements are unique in that they do not contain inspection requirements for the portions of tubing within the thickness of the tubesheets. The specified repair limit is equal to 40% of the nominal tube wall thickness. In addition, the TMI-1 TSs define an alternative repair criteria (ARC) applicable to ID IGA in the unexpanded portions of tubing. The TMI-1 TSs do not address inspection and repair limit criteria applicable to the KE joints in the upper tubesheet.

Despite the absence of TS requirements, the portions of tubing located within the thickness of the tubesheets, including the KE joints, are part of the RCPB and, as such, are subject to Section III and XI of the ASME Code. IWB-3521.2, “Allowable Flaws for Straight-Tube Steam Generators,” of the ASME Code, Section XI currently states that inspection acceptance standards are “in the course of preparation.” IWA- 3100(b) of the ASME Code, Section XI states that “[i]f acceptance standards for a particular component , Examination Category, or examination method are not specified in this Division, flaws that exceed the acceptance standards for materials and welds specified in this [ASME Code] Section III edition applicable to the construction of the component shall be evaluated to determine the disposition. Such disposition shall be subject to review by the enforcement authority having jurisdiction at the plant site.” As discussed in detail in a letter to the licensee dated August 24, 2001, the NRC staff has found that flaws detectable by eddy current testing would likely exceed the ASME Code, Section III standards. For these reasons, the NRC staff informed the licensee that the repair criteria being implemented for the KE joints require regulatory approval.

The evaluation standard by which the NRC is reviewing the licensee's inspection acceptance criteria and accompanying leakage assessment methodology is that the criteria and methodology are adequate to ensure that the structural and leakage integrity of the KE joints will be maintained consistent with the design-basis structural safety margins against gross failure and licensing basis accident analyses leakage assumptions.

The licensee has evaluated all reactor system transient and accident scenarios and determined that an MSLB accident would create the transient primary and secondary parameters that resulted in the most limiting OTSG tube loads. The licensee has provided the results of its MSLB thermal-hydraulic analysis that could be used as input to define the OTSG tube loads and to calculate the leakage from each KE flaw. This information is needed to support the NRC staff's evaluation of SG integrity.

4.0 EVALUATION

4.1 Inspection Acceptance Criteria

4.1.1 Summary - Inspection Acceptance Criteria

The licensee's inspection acceptance criteria and leakage assessment methodology are documented in the licensee's report No. ECR #02-01121, "Inspection Acceptance Criteria and Leakage Assessment Methodology for TMI OTSG Kinetic Expansion Examinations." The most recent revision of this report is Revision 2, which was submitted by the licensee's letter dated October 14, 2005, and which is the specific revision that is the subject of this safety evaluation. This report is applicable only to the kinetically expanded tubing within the upper tubesheets and is not applicable to unexpanded tubing within the TMI-1 upper tubesheets or to the transition between the unexpanded and kinetically expanded tubing. The licensee stated that other licensee documents describe the examinations performed for unexpanded tubing within the TMI-1 tubesheets and the disposition of the examination results. For example, the licensee's report No. ECR TM 01-00328 (referenced in the TMI-1 TSs) describes examination requirements and acceptance criteria for unexpanded tubing within the upper tubesheets.

The licensee's proposed inspection acceptance criteria consist of the following:

- Inspection acceptance criteria that define the minimum required length of defect-free tubing that must be present above the bottom of the fully expanded tubing. These minimum required lengths are summarized in Table 1 of ECR #02-01121 and vary as a function of tube radial location from the center of the bundle. The minimum required lengths vary from 3.4 inches at the center of the tube bundle to 2.1 inches at the periphery of the bundle for tubes with 17-inch-long KEs and from 8.4 inches to 3.2 inches for tubes with 22-inch expansions. The defect-free lengths need not be continuous. One may have two or more defect free length segments, each separated by a flaw.

- Flaw dispositioning criteria. These criteria are summarized in Table 2 of ECR #02-01121 and include criteria defining the length of expanded tube affected (influenced) by a given flaw. In addition, the circumferential component of an individual ID volumetric flaw may not exceed 0.52 inches in length (measured on the outside diameter (OD) and equivalent to 96 degrees circumference). For multiple flaws separated by less than an axial distance of 1 inch, the circumferential lengths are combined and must be less than 0.64 inches. If separated axially by more than an inch, each circumferential length is treated independently and must be less than 0.52 inches.

- Tubes with flaws in the KE failing the above acceptance and dispositioning criteria must be plugged or repaired. Also, tubes with flaws other than ID volumetric indications (e.g., axial or circumferential cracks) must be plugged or removed from service. Any tubes with newly identified flaws must be plugged or removed from service.

The licensee's proposed implementation of these acceptance and dispositioning criteria include the following elements:

- Demonstrate that the as found KE flaws do not contribute unacceptably to leakage that may occur during a postulated MSLB.
- All KE joints are to be inspected with a motorized rotating pancake coil (MRPC) (including a +Point coil) during each inspection.
- A flaw growth assessment will be performed during each inspection to confirm zero growth of the KE flaws since the previous inspection.

4.2 Structural Design Basis of the KE Joints

The licensee stated that the purpose of the proposed inspection acceptance and dispositioning criteria is to ensure that the design capability of the KE joints is maintained.

The KE repair of the TMI-1 OTSGs was approved by the NRC in NUREG-1019 (dated November 1983). The design basis for these repairs was that no tubes shall break within the KE joint or separate from the tubesheet under MSLB conditions. To this end, the licensee enforced a no-axial slip criterion for the expanded tube relative to the tubesheet for a design basis MSLB axial load of 3140 lbf.

Similarly, the proposed inspection acceptance and dispositioning criteria are intended to prevent axial slip and severance of the expanded tube relative to the tubesheet. The NRC staff notes that axial fishmouth burst under primary-to-secondary pressure differentials is precluded due to the radial constraint provided by the tubesheet on the expanded tubing. In addition, the licensee states that applied bending loads are very low in magnitude at the KEs. The staff believes this to be a reasonable assumption given that the 22-inch KE joints are located at least 3 tube diameters in from the lower tubesheet face, and in view of the very limited clearance between the unexpanded tubing and tubesheet below the tube expansion.

The derivation of the 3140 lbf axial load for MSLB is documented in a Babcox & Wilcox (B&W) topical report BAW-10146 (dated October 1980), and is an elastically calculated load with a corresponding axial strain of 0.16%. It is a thermally induced load due to the temperature difference between the OTSG shell and tubing during the transient. For tubes with relatively small wall thicknesses and/or yield strengths, the axial stress under MSLB may exceed the elastic limit of the tube material. An elastic-plastic analysis by the licensee shows that a tube with a minimum wall and yield strength would only develop a 2400 lbf axial load at the applied 0.16% axial strain. For this case (assumed minimum tube thickness and material strength), the acceptance criteria in terms of minimum required defect length is based on ensuring no slip under a load of 2400 lbf. This means that a factor of safety of 1.0 is being enforced relative to the no slip criterion for MSLB. However, the NRC staff finds that the no slip criterion is conservative from a structural integrity standpoint for OTSGs since the applied axial load is thermally induced and self-limiting (since any slippage acts to relieve the axial load, limiting slippage). In addition, the tubes are roll-expanded and welded to the lower tubesheet, providing additional assurance against parting or pull out of the tube from the tubesheet (i.e., gross structural failure). The NRC staff finds this safety factor relative to no slippage to be acceptable as a basis for development of the inspection acceptance criteria for ensuring structural integrity. The acceptability of these criteria for ensuring accident leakage integrity is addressed in Section 4.4 below.

The 2400 to 3140 lbf MSLB load was actually calculated for tubes at the periphery of the tube bundle. This load becomes progressively smaller toward the interior of the bundle due to the effects of tubesheet bow discussed in Section 4.3 below. The proposed inspection acceptance criteria take advantage of this reduction in load for the interior tubes in ensuring no slippage. This is acceptable to the NRC staff since it ensures a consistent margin (i.e., safety factor of 1) relative to slippage for these tubes.

The licensee stated that consideration of the minimum wall thickness and minimum material strength is the limiting case in terms of satisfying the no slip criterion under MSLB. Although relatively thick-walled tubing with relatively high material strength may develop as much as 3140 lbf axial force, the load needed to cause slippage will actually be higher than 3140 lbf.

With the exception of axial loads associated with certain large-break loss-of-coolant accidents (LBLOCA), the licensee stated that axial loads associated with other accidents or transients (feed line break, small-break LOCA (SBLOCA), heat up and cool down transients) as a result of differential thermal expansion are significantly smaller than for the assumed MSLB accident.

At present, LBLOCA is not directly part of the design basis for repair methods and alternate repair criteria that have been approved for any plant with B&W OTSGs. The licensee stated that it is currently working with other B&W plant owners to revise Topical Report BAW-2374, which deals with LBLOCA, to address LBLOCA for all aspects of the SGs' design and maintenance. The NRC staff acknowledges this activity and has been working with the B&W Owners Group (BWOG) to identify needed changes to the plant design and licensing basis to address this issue.

In the meantime, the NRC staff finds that the LBLOCA issue is not a significant safety issue with respect to the KE joints. The magnitude of the LBLOCA axial load is approximately 3300 lbf based on typical stress strain properties of alloy 600 material which is only slightly larger than the 3140 lbf MSLB load used to develop the dispositioning criteria to ensure no slippage or severance. Even if a LBLOCA should lead to slippage or severance of a tube or tubes in the KE region, the lower tube-to-tubesheet joint ensures that any such severance in the upper tubesheet will not result in pull out of the tube from the upper tubesheet. The consequences of such a severance, therefore, would be very limited due to (1) the restricted leakage path existing from the point of severance in each affected tube past the remainder of the KE joint below the severance; and (2) the very small primary-to-secondary pressure differentials which would be the driving force for primary-to-secondary leakage and resulting dose consequence. In addition, the licensee committed in its October 14, 2005, letter to perform a best estimate leakage assessment for LBLOCA to demonstrate that leakage will not exceed acceptable limits and to report the results of this assessment in its 90-day report following each SG inspection.

4.3 Inspection Acceptance and Dispositioning Criteria

An elastic-plastic finite element analysis (FEA) model of the KE joint was used to develop the acceptance criteria for the axial component of ID IGA flaws. This model includes the lower 6 inches of the KE joint including the 0.5-inch joint expansion transition. This 6-inch long model matched the 6-inch long KE joint test specimens used during the original qualification testing of the KE joint design. The results of the original qualification testing were used to benchmark the FEA model, leading to consistent results. The FEA model was then used to extend the results of the original qualification tests to consider the presence of axial flaws in the tube and the effects of tubesheet bow under primary-to-secondary pressure differential, neither of which was considered in the original qualification tests.

The FEA model conservatively assumed that contact pressure between the tube and tubesheet was completely released by the presence of an axial flaw over an axial length equal to the length of the flaw plus 0.25 inch and extending 360 degrees around the tube circumference. The additional 0.25 inch was determined from the FEA results and accounts for the distance over which contact pressure transitions from zero to its nominal value for an unflawed tube. The basic approach of the analysis was to determine the maximum axial flaw length (including the 0.25-inch influence adjustment) which can be allowed without resulting in joint slippage under the applied axial load. This allowable axial flaw length varies as a function of each tube’s radial location within the tube bundle. This is due to the effect of tubesheet bow. Tubesheet bow tends to reduce axial load with decreasing radial tube location within the tube bundle. In addition, tubesheet tends to tighten the KE joint above the neutral plane of the tubesheet (located about midway between the primary and secondary tubesheet faces) and to loosen the KE joint below the neutral plane. Both the 17-inch and 22-inch KE joints extend to below the neutral plane. This effect on joint tightness is greatest near the center of the tube bundle where tubesheet flexure due to bowing is greatest, but is small near the periphery of the bundle.

The acceptance criteria for minimum required length of defect free tubing was determined by subtracting the maximum allowable flaw length at each radial location within the bundle plus an allowance for eddy current measurement error (discussed in Section 4.5 below) from 5.5 inches. 5.5 inches is the length of fully expanded tubing considered in the FEA model and located at the bottom of the KE joint. The allowance for eddy current measurement error is discussed in Section 4.5 below. The FEA analyses demonstrate that the required length of defect-free tubing need not be continuous and that multiple axial flaws may be tolerated. For multiple flaws, however, a 0.25-inch influence adjustment must be added to the measured length of each flaw except the first. The first is excepted since the acceptance criteria for minimum defect length already includes such an adjustment for one axial flaw.

The NRC staff concludes that the above FEA analyses provide a conservative and acceptable basis for the proposed acceptance criteria applicable to flaws in the KE joints with an axial component.

The licensee's proposed acceptance criteria for the circumferential component of volumetric IGA flaws is based on an allowable length of 0.64 inches or 130 degrees circumference, irrespective of the measured depth. This allowable length is based on tube parting (severance) considerations for an axial load of 3140 lbf. The NRC staff finds this to be a conservative criterion for MSLB since it assumes that flaws are 100% through-wall, that they occur in peripheral tubes where the axial loads are the highest, that they occur at the very bottom of the fully expanded portion of the expanded tubing before some or most of the load has been transferred to the tubesheet by friction at the tube-to-tubesheet interface, and that the tubes are of relatively high strength material and relatively thick-walled. The licensee stated it will plug or repair tubes with individual ID IGA flaws with a circumferential component exceeding 0.52 inches in length, to allow for measurement error as discussed in Section 4.5 of this safety evaluation.

For multiple circumferential flaw components, a circumferential length criterion of 0.64 inches (with no allowance for eddy current measurement error as discussed in Section 4.5 below) is applied to the sum of the individual lengths for flaws with an axial separation distance of less than 1 inch. The licensee stated that flaws with more than 1 inch axial separation behave independently of one another. The 1-inch axial separation distance ensures that shear stress will be limited to 60% of the axial membrane stress at each flaw plane consistent with ASME Code, Section III philosophy and, therefore, is acceptable to the NRC staff.

4.4 Accident Leakage Assessment Methodology

The licensee's accident leakage assessment methodology consists of evaluating the primary-to-secondary leakage under an MSLB relative to maximum values that meet the offsite dose criteria of 10% of 10 CFR Part 100 limits for the 2-hour exclusion area boundary and 30-day low population zone. The dose consequences and, hence, total allowable leakage were approved by the NRC on October 2, 1997 (Amendment No. 204 to the TMI-1 operating license). The allowable leakage is as follows:

1. Integrated primary coolant leakage @ 2 hours = 3228 gallons
2. Total integrated primary coolant leakage = 9960 gallons

The MSLB loads considered in this leakage assessment are based upon a revised, TMI-1-specific MSLB analysis rather than the "generic" analysis documented in Topical Report BAW-10146 which was part of the original design basis for the KE repairs and was the basis for the loads used to develop the acceptance criteria discussed above. The TMI-1-specific analysis reduces the maximum axial load of 3140 lbf. from the generic analysis to 1300 lbf. in the faulted SG. In addition, the maximum differential pressure from the TMI-1 specific analysis does not exceed 1400 psi compared to the 2500 psi from the generic analysis. This TMI-1 specific MSLB analysis is evaluated in Section 4.5 of this safety evaluation.

For leakage assessment purposes, the licensee has modeled the flaws in the KE region as freespan flaws. The NRC staff concurs that this is a conservative approach since it ignores the resistance to axial crack opening displacement provided by the radial constraint of the tubesheet, the resistance to circumferential crack opening displacement due to the friction between the tube and tubesheet, and the resistance to leakage between the tube and tubesheet due to the limited leakage area afforded by the expanded tube to tubesheet joint. The degree of conservatism will depend on tube radial location and crack axial location within the tubesheet since tubesheet bow effects can affect the degree of joint tightness.

The licensee has modeled volumetric ID IGA flaws as a composite axial and circumferential crack of dimensions equal to the axial and circumferential components of the volumetric flaw. The idealized axial and circumferential cracks are assumed to behave independently of one another. The leak rate for each volumetric indication is the sum of the idealized axial crack and circumferential crack leak rates. The NRC staff finds this to be an acceptable approach considering that the constraint provided by the tubesheet should prevent the IGA from becoming “hole-like.”

Because the KE indications are conservatively being treated as freespan cracks, leakage rate is a function of crack opening area. The licensee calculated the leak opening area (for 100% throughwall cracks) using the methodology in NUREG/CR-3464, “The Application of Fracture Proof Design Methods Using Tearing Instability Theory to Nuclear Postulating Circumferential Through-Wall Cracks,” September 1983. Crack opening area for axial cracks is a function of crack length and the applied primary-to-secondary pressure loading which varies as a function of time. Crack opening area for circumferential cracks is a function of crack length and axial load which varies as a function of radial location within the tube bundle (due to the effects of tubesheet bow) and time.

The licensee determined leakage rate for a given crack opening area and pressure using the PICEP (Pipe Crack Evaluation Program) code developed by Electric Power Research Institute (EPRI). Using PICEP in conjunction with the crack opening area, the licensee evaluated leak rate as a function of crack length and orientation, differential pressure, and radial location within the tube bundle (which determines axial load). These analyses were basically integrated over time to yield 2-hour and 30-day leakage values in tabular form for a given crack as a function of crack length and orientation and radial location. These tables then are used to determine the leakage for each indication, and the total leakage for the population of indications is the sum of the individual indications.

The NRC staff finds that the above approach (PICEP in conjunction with crack opening area models) for evaluating leakage to be a relatively standard analytical approach. However, it is the NRC staff’s judgment that the approach should not be viewed in and of itself as an accurate or even conservative predictor of leakage from freespan cracks. An EPRI perspective documented in EPRI Topical Report NP-6897s-L, “Steam Generator Tube Leakage Experiments and PICEP Correlations,” states that improved fracture and fluid mechanics models and experiments are necessary for accurate SG tube leakage predictions. EPRI stated that experimental scatter in leak rates is largely due to crack plugging, residual stresses, and other poorly understood mechanisms that make analytical predictions difficult. This is consistent with the NRC staff’s experience.

The NRC staff recognizes that the flaws in the KE joints are not freespan flaws. Overall, it is the NRC staff’s judgment that the licensee’s leakage assessment model is conservative for the KE region. Leakage tests conducted by the licensee confirm that typical contact pressures between the tube and tubesheet reduce leakage relative to the “no contact pressure” case by over 95%. The licensee’s leakage methodology takes no credit for this. The license states that only the lowermost quarter inch of the 17-inch expansions and lowermost 8 inches of the 22-inch expansions near the center of the tube bundle do not have significant contact pressure due to the effects of tubesheet bow. Relatively few tubes have 22-inch expansions. Of 31,062 tubes in the TMI-1 OTSGs, only 431 have 22-inch kinetic expansions.

Another important conservatism in the licensee’s leakage assessment model is that all flaws with measured depths greater than 67% are treated as 100% through wall and, thus, are assumed to contribute leakage. It is the NRC staff's judgment based on the licensee's eddy current performance demonstration work and available EPRI Appendix H databases that the vast majority of flaws measuring between 67% and 100% through wall will not be 100% through-wall. Even among flaws measuring 100% through-wall, it is the NRC staff's judgment that some will be less than 100% through-wall.

The above leakage model addresses MSLB leakage associated with indications within the zone of the KE joints that is inspected, but does not address leakage from indications that are located above the inspection zone. The licensee has attempted to bound the leakage from above the inspection zone based on leakage tests performed on expanded tube samples under normal operating conditions. The assumed leak rate under normal operating conditions was an upper 0.99 probability estimate based on the leakage data evaluated at a 0.99 confidence level. This estimate was factored upward by 3 to account for the fact that the testing considered a 6-inch defect-free expansion length whereas the inspection zone in the KE joint can be as little as 2.1 inches (for 17-inch KEs located at the periphery of the tube bundle). This latter estimate is factored up by the square root of 2 from Bernoulli's equation to account for a factor of 2 increase in differential pressure when going from normal operating to MSLB conditions. This estimate in turn is multiplied by the total number of tubes remaining in service to yield a 2-hour and 30-day duration leakage estimate of 15 and 170 gallons/SG, respectively. These numbers are added to the calculated leakage for all other sources, including calculated leakage from the identified flaws in the KE inspection zone. Although small, these leakage estimates for MSLB for the region of tubing above the KE inspection zone are consistent with detectable leakage being present under normal operating conditions (about 26 gallons per day). The licensee stated that there is no evidence that the KE joints have leaked over the past several cycles. Based on this experience, the NRC staff concludes that the above mentioned use of an upper 0.99/0.99 bounding estimate of the leakage test data for normal operating conditions is conservative.

On the other hand, the NRC staff notes two incidents of non-conservatism in the licensee's MSLB leakage estimate for flaws above the inspection zone. The estimate does not account for the effects of tubesheet bow nor does it account for axial tensile load, both of which may act to loosen the KE joint (in the 2.1-inch-long zone mentioned in the previous paragraph) relative to the conditions tested. The NRC staff has performed independent estimates of the importance of these incidents of non-conservatism based on test and analytical results pertaining to the relationship between leakage and joint tightness, between tubesheet bow and joint tightness, and between axial load and joint tightness that were provided to the NRC staff in the context of the tube end cracking alternate repair criteria TS amendment for Crystal River 3. Based on these estimates, the NRC staff concludes that the effect of these potential incidents of non-conservatism is negated by the conservatism discussed in the previous paragraph. Thus, the NRC staff finds the licensee's estimate of leakage for flaws above the KE inspection zone to be acceptable.

The licensee stated that MSLB is the most limiting accident from the standpoint of ensuring that resulting primary-to-secondary leakage is within that assumed for the accident analyses. The licensee has excluded SBLOCA, with a maximum axial load of 2097 lbf, as a limiting accident in view of the very small (and even negative) primary-to-secondary pressure differentials existing during the accident. For feedline break (FLB), the licensee stated that the tubes are in axial compression which works to tighten circumferential cracks and to restrict leakage. For MSLB, the axial loads are in tension which tends to open circumferential flaws producing more leakage. In addition, because the axial load associated with FLB is compressive, the axial load works to tighten the KE joint due to the Poisson effect in contrast to the tensile load associated with MSLB where the Poisson effect works to loosen the joint. Thus, the licensee concludes that the KE joints are significantly tighter during an FLB than is the case during an MSLB. The tighter joint during FLB increases the resistance of the KE joint to leakage compared to MSLB. Although maximum differential pressure during an FLB is about 2500 psi and, thus, is significantly higher than the maximum 1400 psi assumed for MSLB, the licensee believes MSLB to be more limiting from an accident leakage standpoint.

Although the licensee did not perform a quantitative analysis to support this conclusion, the NRC staff notes that the licensee’s treatment of the KE flaws as freespan flaws in its MSLB leakage model is very conservative. Leak rate from freespan flaws is very sensitive to differential pressure not just because pressure is the driving force for leakage, but because differential pressure acts to significantly open up the flaw opening area of the axial and circumferential flaw components. It is the NRC staff’s judgment that the radial contact between the tube and tubesheet limits the flaw opening to a very small fraction of what would be the case for actual freespan flaws. In addition, the compressive axial force during FLB acts to tighten rather than to open up the circumferential component of KE flaws. The NRC staff estimates that for a given (or constant) leakage area (using standard Bernoulli model), the increase in leak rate for freespan cracks under the maximum FLB pressure differential is only 33% higher than under the maximum MSLB pressure differential. The licensee’s leakage model conservatively neglects the resistence to leakage between the flaw and the bottom of the KE joint which, in the NRC staff’s judgment overwhelms the 33% higher leakage arising from consideration of FLB differential pressures. The NRC staff concludes that the licensee’s MSLB leakage model predictions bound actual leakage which would occur under FLB conditions.

4.5 MSLB Analysis

The licensee's MSLB analysis was performed in two phases, a short-term phase and a long-term phase. The short-term phase duration was 10 minutes following the initiation of the event. This part of the transient was calculated using the NRC-approved transient code RETRAN-02, Mod 5. The long-term phase thermal-hydraulic conditions were developed by applying assumed operator actions, consistent with TMI-1 procedures for accident mitigation. The long-term analysis began at 10 minutes and extended to the end of the transient (approximately 24 hours).

For the short-term analysis, and consistent with the TMI-1 licensing basis, no operator actions were assumed in the first 10 minutes of the transient. RETRAN-02, Mod 5 computer code and a TMI-1 plant model were used to perform the most complicated and dynamically changing thermal-hydraulic attributes during this transient period. The TMI RETRAN model has been approved by the NRC for applying in TMI-1 licensing applications (letter, U.S. NRC to C. Lehman, “Acceptance for Referencing of the RETRAN-02, MOD005.1 Code,” dated April 12, 1994). The licensee has used analysis assumptions and initiate conditions that would generate a conservative reactor coolant system (RCS) overcooling and pressure transient for the MSLB event and resulting SG tube loads.

For long-term analysis (i.e., following the first 10 minutes), the licensee assumed that operator action would be taken to terminate emergency feedwater (EFW) to the affected OTSG and to begin a controlled cooldown and depressurization to decay heat removal (DHR) initiation conditions using the unaffected OTSG. The limitations imposed by cooldown pressure-temperature limits and tube-to-shell differential temperature limits would be observed during this transient period.

The combined results of the licensee’s short-term and long-term analysis are reflected in Figure 14 (RCS temperature and average SG shell temperature) and Figure 15 (RCS pressure and OTSG pressure) of Attachment 1 to the licensee’s May 3, 2005, submittal. These transient data are applicable for determining OTSG tube loads.

The NRC staff reviewed the licensee’s thermal-hydraulic analysis of an MSLB relative to SG tube load and finds that the results of the licensee's analysis are acceptable and the transient data reflected in Figure 14 and Figure 15 in Attachment 1 are applicable for determining OTSG tube loads. The bases of the NRC staff's conclusion are: (1) the licensee's analysis was performed using NRC-approved computer code and methodology; (2) the analysis was performed using assumptions and initial conditions that would generate the most conservative transient conditions for determining OTSG tube loads; and (3) the assumed operator actions 10 minutes into the transient are consistent with plant procedures for accident mitigation.

4.6 Inspection Scope and Methods

Beginning in the upcoming 1R16 refueling outage inspection, and in all subsequent refueling outage inspections, the licensee committed to perform an MRPC inspection on all (100%) inservice KE joints. The extent of each KE inspection will include the KE expansion transition and will extend up into the fully expanded tube a sufficient distance to demonstrate that there is a sufficient defect-free length to satisfy the minimum requirement in this regard. This appears to include a nominal inspection length of 6 inches, including the 0.5-inch expansion transition. However, the inspection may proceed beyond the 6 inches if necessary to demonstrate an acceptable defect-free length exists. Although the original joint qualification tests and the more recent FEA analyses were based on an assumed 6-inch joint, the NRC staff agrees that meeting the same acceptance criteria over a longer than 6-inch length will ensure that the no slip criterion is met.

The MRPC probe includes a mid-frequency (300 kHz) +Point coil and a 0.080-inch-diameter high frequency (600 kHz) shielded pancake coil. The 300 kHz +Point coil data is used for the detection and depth sizing of detected flaws in the KE region. Depth sizing is needed to support implementation of the leakage methodology discussed in Section 4.4. The mid-frequency +Point coil data is also used for the length sizing of KE circumferential or axial crack-like indications. While tubes with crack-like indications must be plugged or repaired, the NRC staff notes this information is needed for condition monitoring assessments.

The high frequency 0.080-inch diameter pancake coil data is used for measuring the axial and circumferential extent of ID volumetric flaws.

The licensee stated that the mid-frequency +Point has been EPRI Appendix H-qualified for the detection of axial and circumferential primary water stress-corrosion cracking (PWSCC) for several tube sizes not including the OTSG tube size. In addition, the licensee stated there are no industry Appendix H qualifications directly applicable to expanded tubing. The licensee has evaluated the expected performance the mid-frequency +Point for TMI-1 KE application using tube samples with machined axial and circumferential notches and machined volumetric pit-like flaws. These studies were supplemented with 9 ID IGA flaws from a TMI-1 pulled tube specimen and with 6 specimens with axial PWSCC flaws created in the laboratory. The licensee stated that tube noise studies and site validations performed for TMI-1 have confirmed that the TMI-1 KE region eddy current data is similar to the Appendix H qualification data and TMI-1 tubes with freespan ID IGA that were previously in-situ pressure-tested. The licensee concluded that similar performance is expected for the OTSG KE region and that the 300 mid-range +Point coil is considered Appendix H-qualified for TMI-1.

The NRC staff has not been provided with sufficient information to accept the licensee's conclusion that the +Point is Appendix H-qualified and, thus, is not relying on this conclusion in making its own finding. In particular, the NRC staff has not been provided information on the signal amplitude and signal-to-noise ratios of the machined flaw specimens versus actual field flaws and laboratory PWSCC flaws of a given depth and length. Thus, the NRC staff does not know how representative these flaws are of actual flaws at TMI-1.

The limited data from the laboratory PWSCC specimens indicates reasonably good depth sizing performance, with a maximum undercall of 19%, as compared to a maximum undercall of 34% based on the machined volumetric pits. The NRC staff notes that the EPRI Appendix H databases (consisting mostly of laboratory PWSCC specimens and some pulled tube specimens) for non-OTSG tubing sizes indicated that depth undercalls were bounded by 23%. Thus, the NRC staff concludes that the licensee's assumption that PWSCC or ID IGA flaws with a measured depth of 67% of the nominal wall thickness or greater are actually 100% through-wall to be conservative. It is the NRC staff's judgment that with this assumption, flaws which are less than 100% through-wall are much more likely to be treated as 100% through-wall than vise versa.

With respect to PWSCC, the licensee provided its length sizing performance data for axial cracks only. These consisted largely of machined specimens and 6 laboratory PWSCC specimens with axial lengths ranging to about 0.25 inch. This data showed that the +Point consistently overcalls the axial length. The licensee stated that it performed its performance studies on relatively short flaws because this is what is typically found at TMI-1. However, the NRC staff notes that it is more appropriate to include flaws of lengths sufficient to challenge or exceed the applicable acceptance limits, consistent with EPRI Appendix H philosophy. EPRI Appendix H databases for non-OTSG tubing sizes include data for axial cracks ranging from zero to 0.9 inches and circumferential cracks ranging from about 40 to 360 degrees circumference indicate that +Point does not consistently overcall crack lengths. The licensee will plug all tubes found to contain PWSCC. Length sizing of PWSCC flaws is still important, however, to support condition monitoring assessments of PWSCC indications found. The NRC staff finds that PWSCC length sizing performance with the mid-frequency +Point coil is adequate to ensure the structural and MSLB leakage integrity of the KE joints. The basis for this finding is identical to the rationale enumerated below regarding the adequacy of the high frequency pancake for length sizing of ID IGA flaws.

With respect to the high frequency pancake coils used to measure the axial and circumferential components of volumetric ID IGA, the licensee performed its performance study with the machined pit-like flaw specimens and the 6 ID IGA flaws in the TMI-1 pulled tube specimen. The licensee stated that there are no Appendix H qualifications to compare with the licensee's performance studies and that it considered that the high frequency pancake to be qualified to the intent of EPRI Appendix H for purposes of length sizing of ID IGA flaws. The NRC staff disagrees that the licensee's performance study meets the intent of EPRI Appendix H since the data set do not include a significant sample of flaws with lengths which meet or exceed the proposed acceptance criteria and, thus, the NRC staff has taken no credit for the high frequency pancake as being EPRI Appendix H-qualified in reaching the conclusions of this safety evaluation.

The licensee's acceptance and dispositioning criteria for length of ID IGA flaws provides a 0.5-inch allowance (minimum) for under calling the total length of axial flaws, a 0.22-inch allowance for under calling the length of individual circumferential flaws, and no allowance for under calling the total length of circumferential flaws within 1 inch of each other. The NRC staff does not have a sufficient basis to conclude that these allowances are sufficient to address potential under calls of ID IGA flaw lengths with respect to ensuring no parting or slippage of the tube within the KE joint under MSLB axial loads of 2400 to 3140 lbf. However, the acceptance and dispositioning criteria for ensuring no parting or slippage include significant conservatism as discussed in Section 4.3 above. In addition, should such parting or slippage occur (for either PWSCC or ID IGA), it would not constitute a gross structural failure as previously discussed.

MSLB leakage for PWSCC and ID IGA flaws is evaluated for a more realistic MSLB axial load of 1300 lbf, but this evaluation assumes no parting or joint slippage. The NRC staff notes that under calls of flaw axial and circumferential lengths on the order of 50% can be tolerated without creating the potential for parting or slippage under a 1300 lbf load. It is the NRC staff's judgment based on both the eddy current performance data provided by the licensee and the NRC staff's experience that the inspection methods to be employed for length sizing of PWSCC and ID IGA flaws are adequate to ensure no tube parting or slippage under a 1300 lbf load.

The licensee's MSLB leakage analysis uses measured PWSCC and ID IGA flaw lengths directly since the licensee concluded that eddy current testing will systematically over-call these lengths. Although the NRC staff has insufficient basis to concur with this conclusion, the NRC staff finds the MSLB leakage assessment to be conservative overall. This is due to the conservative treatment of the KE flaws as free span flaws and the treatment of all flaws with measured depths greater than 67% through-wall as being 100% through-wall.

4.7 Flaw Growth Rates

The licensee stated that observed degradation in the KE region to date are dominantly ID IGA flaws and, to a much lessor extent, ID circumferential flaws. Based on successive MRPC examinations performed in the KE region since the late 1990s, the licensee believes that these flaws have not been growing over this period (i.e., are inactive). The licensee believes that these indications may have been present since before the KE repairs were performed, and that the exp0ansions enhanced flaw detectability. "New" indications that have been found are attributed to improvements in analyst and technique sensitivity (data quality).

The licensee's proposed inspection acceptance criteria, therefore, are premised on the flaws in the KE region remaining inactive. The acceptance criteria make no allowance for flaw growth. The licensee monitors flaw growth to verify that the no-growth assumption remains valid. This is similar to the approach already incorporated into the TMI-1 TSs for monitoring ID IGA indications in the unexpanded portion of tubing per ECR TM 01-00328. However, in the event that future TMI-1 KE field data indicate that growth is greater than a small positive value change from the historical value, or apparent growth as evidenced by the inability to demonstrate statistically insignificant growth, the licensee stated that it will be necessary to develop a cycle-specific growth model. The licensee further stated that such cycle-specific growth model will require a revision to ECR #02-01121, Revision 2, which is the subject of this safety evaluation, and that this revised report will be submitted to the NRC well ahead of the subsequent refueling outage with any actions to address potential growth. In Attachment 3 of the licensee's October 14, 2005 letter, the licensee committed that any changes to criteria and methods in ECR #02-01121, Revision 2, will be submitted to NRC for review and approval. This commitment is acceptable to the NRC staff.

The licensee stated that it will use a statistical procedure to assess ID IGA growth. Data from individual indications will be compared back to the first outage with acceptable MRPC data for these statistical tests. The procedure consists of initial screening of the data for extreme values, followed by two statistical tests, a sign test and a paired t-Test, applied to axial length measurements and separately to circumferential length measurements (total of 4 statistical tests). If all 4 tests are passed, it will be concluded that the KE ID IGA population is not growing.

The data is first screened with the use of an extreme value test that compares the largest growth values with the 5% critical value. If the largest growth value is less than the critical value, it will be concluded that the extreme values of ID IGA growth are not statistically significant. The sign tests will determine if the axial and circumferential growth of the ID IGA indications are each bounded by small, positive reference values of 0.01 inch. For the paired t-Tests, the mean change in the ID IGA axial and circumferential lengths must each be less than a small, positive reference value of 0.01 inch. The extreme value tests, sign tests, and paired t-Tests are identical to the statistical tests which the NRC staff has previously approved for TMI-1 as part of the ARC for ID IGA in unexpanded tubing.

The NRC staff notes that ID IGA axial and circumferential length are the only flaw size parameters which are relevant to the structural acceptance criteria. These acceptance criteria conservatively assume that all detected indications are 100% through-wall. For the accident leakage assessment, only flaws with a measured depth exceeding 67% through-wall are assumed to be potential leakers. However, the licensee is not proposing to monitor depth growth rates. The NRC staff considers this to be acceptable for several reasons. TMI-1 will only be operated for another two fuel cycles prior to SG replacement in 2009. The MSLB leak rate based on the as-found indications in the KE region during the most recent SG inspection in 2004 was trivially small (i.e., 6 gallons for 2 hours and 55 gallons for 30 days). The licensee will report the accident leak rate based on the as-found condition in the KE region in its 90-day report following each future SG inspection. Any significant increase in this leak rate from one inspection to the next would be a potential indicator of growth in the depth of previously detected indications or the occurrence of new indications, providing the NRC staff with the opportunity to discuss growth rate implications with the licensee on a timely basis.

Beginning in the Fall 2005 refueling outage inspection, the licensee will plug or repair all tubes with indications in the KE region that were not detected or detectable during the 1997 through 2001 refueling outage inspections. In addition, all tubes with circumferential indications (rather than volumetric) will be plugged or repaired, including circumferential indications that were detected during prior 1997 through 2003 outage inspections that remain in service. These are clearly conservative actions and are acceptable to the NRC staff.

5.0 CONCLUSION

As set forth above, the NRC staff finds that the proposed kinetic expansion inspection acceptance criteria, inspection scope and methods, flaw growth assessment methodology, and accident leakage methodology ensure that the structural and leakage integrity of the kinetic expansion joints will be maintained in accordance with the applicable regulations without undue risk to public health and safety.

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