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U. S. Nuclear Regulatory Commission
Attn: Document Control Desk
Washington, DC 20555-0001

Three Mile Island Unit I (TMI Unit 1)
Operating License No. DPR-50
Docket No. 50-289

Subject: Additional Information Regarding Kinetic Expansion Inspection and Repair Criteria

References:
1) NRC Letter, Colburn to Warner, "Assessment of the Three Mile Island Nuclear Station, Unit 1 (TMI-1) Once-Through Steam Generator Kinetic Expansion Inspection and Repair Criteria (TAC M99388)", August 24, 2001.

2) GPU Nuclear Letter #6710-97-2348, J. W. Langenbach to U.S.Nuclear Regulatory Commission, "Once-Through Steam Generator Kinetic Expansion Inspection Acceptance Criteria", August 8, 1997.

3) GPU Nuclear Letter #6710-97-2441, J. W. Langenbach to U. S. Nuclear Regulatory Commission, "Leakage Assessment Methodology for TMI-1 Once-Through Steam Generator (OTSG) Kinetic Expansion Examination", November 26, 1997.

In response to Reference 1, this letter provides updated inspection acceptance criteria and updated leakage assessment methodology for the TMI-1 kinetic expansion examinations. This information supersedes the information that was previously provided to the NRC in References 2 and 3. In addition, this letter provides responses to questions posed by the NRC staff in Reference 1. This information is submitted for NRC's review/acceptance in accordance with Section IWB-3630 of ASME Code Section XI.

If you have any questions or require further information, please contact us

Very truly yours,

Michael P. Gallagher

Michael P. Gallagher
Director, Licensing & Regulatory Affairs
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Attachment A: Inspection Acceptance Criteria And Leakage Assessment Methodology For TMI OTSG Kinetic Expansion Examinations

Attachment B. Responses to Prior NRC Issues / Questions

cc: H. J. Miller, USNRC, Administrator Region I,
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File No. 02077

ATTACHMENT A

Inspection Acceptance Criteria
And
Leakage Assessment Methodology
For TMI
OTSG Kinetic Expansion Examinations

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ECR #02-01121, Rev. 0

INSPECTION ACCEPTANCE CRITERIA AND LEAKAGE ASSESSMENT METHODOLOGY FOR TMI OTSG KINETIC EXPANSION EXAMINATIONS

ORIGINATOR(S)

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INSPECTION ACCEPTANCE CRITERIA AND
LEAKAGE ASSESSMENT METHODOLOGY
FOR TMI OTSG KINETIC EXPANSION EXAMINATIONS

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1.0 Purpose

TMI-1's OTSG tubes were repaired in 1982 – 1985 by forming a new tube-to-tubesheet joint within the upper tubesheet using a kinetic expansion process. In 1997 GPU Nuclear (the prior owner of TMI-1) developed inspection criteria for use during ECT inspection of the kinetically expanded regions and these criteria were submitted to the NRC (References 25 and 26). This single AmerGen document is an update of those two submittals.

These inspection criteria identify the minimum required length of defect-free kinetically expanded tube that must be present, and provide acceptance criteria for any flaws that may be encountered in order to ensure that the design capability of the joints is maintained. These criteria also ensure that margin is provided in depth against unacceptable performance of the joint as by slipping, parting of the tube, or unacceptable accident induced leakage.

The purpose of this document is also to provide a summary of the conservative methods that are used to inspect and disposition the kinetically expanded joints. An assessment of the material condition of the joint is presented as regards the benefit of the residual stresses from formation of the joint in mitigating stress corrosion cracking. It is also shown that NDE performance characteristics for the several forms of potential damage in the joint are applied conservatively.

This document is only applicable to the kinetically expanded tubing within the upper tubesheets of the TMI-1 steam generators The inspection criteria and leakage assessment methodology described herein are not applicable to unexpanded tubing within the TMI-1 upper tubesheets, or to the transitions between the unexpanded and kinetically-expanded tubing. (Other documents describe examinations of unexpanded tubing within the TMI-1 upper tubesheets and disposition of those exam results. For example, TMI-1 ECR TM 01-00328 (Referenced in T.S. 4.19) describes examination requirements and acceptance criteria for unexpanded tubing within the TMI-1 upper tubesheets).

2.0 System Performance/Kinetic Expansion Structural Integrity Analysis

The design basis performance for the kinetically repaired TMI-1 OTSG tubes is that, as a result of a Main Steam Line Break (MSLB), no tube shall break or separate from the tubesheet (Reference 27) In the following analysis, this performance requirement is practically applied as first, a condition that the tube is not permitted to part within the kinetically expanded joint (or at any other location). In addition, the repaired tube is expected to sustain a design basis axial load of 3140 lbs with no slippage (Reference 28).

For the kinetic expansion areas within the upper tubesheet, it is necessary to consider only the axial load applied through the tube to the joint as a result of the MSLB. The axial tube loads that occur during normal operations, for example those resulting from a normal cooldown transient, are much lower and will not exceed about 35% of the faulted condition Since the kinetically expanded tubing is captured within the steam generator upper tubesheets, applied bending loads are very low in magnitude, and bending stresses do not develop within the joint because no rotation can occur.

2.1 Finite Element Modeling/Benchmarking

A finite element analysis model of the kinetically expanded tube-to-tubesheet joint was developed The analysis model of the tube-to-tubesheet joint consisted of a tube, the tubesheet, and a contact element representing the interference/connection between the tube and tubesheet. (Reference 24).

The analysis model had the additional feature that tube material behavior in both the elastic and plastic regions was modeled using actual tube stress-versus-strain data. Also, tube internal pressure could be included in the analysis model. Finally, the effect of tubesheet bow was captured (The tubesheet may bow slightly due to the combined effects of axial tube load and primary-to-secondary pressure difference.)

Test results from the original kinetic expansion qualification program (Reference 29) were used as the basis for benchmarking the finite element analysis model results. The benchmark process used qualification program tubes with high yield strength (57 ksi) and wall thickness slightly larger than design minimum tube wall (0 038" vs. 0.034"). Qualification test results were available for expansion lengths equal to four, six and eight inches. High yield strength tube material was exclusively used for only the 4" and 8" expansions. Test results indicated that the joint's capacity to resist slip is the same for the 6" expansion as it is for the 8" expansion data

The model parameters that describe the performance of the expansion are the contact interference between the tube and the tubesheet that was achieved by the kinetic expansion, and the coefficient of friction. Use of a contact interference dimension equal to 0.0003" in the model produced the best agreement with the joints' original qualification test results when using a coefficient of friction equal to 0.2. The analysis model results accurately matched the minimum test results obtained for the 4" expansion and underpredicted the performance of the 6" and 8" expansions. The same contact interference and coefficient of friction were used throughout the analysis reflecting the assumption that the kinetic expansion was equally effective over the range of expansion lengths. No parameter adjustments were made to produce results matching the pullout capacities for the 6" and 8" expansions as accurately as that obtained for the 4" expansion This avoided overpredicting the pullout capacity of a shorter expansion in order to more accurately represent the longer expansions. The analysis results are conservative for the longer expansions as a consequence of not adjusting the expansion parameters. The pullout resistance of the 4" expansion is predicted to be 3260 lbs. where minimum test data was 3100 lbs , 4030 lbs. for the 6" expansion where minimum test data was 5000 lbs , and 4110 lbs. for the 8" expansion where minimum test data was 5000 lbs

2.2 Finite Element Model Results

The key performance features of the kinetically expanded joint are shown in Reference 24, which documented the finite element analysis Figure 3-2 of Reference 24 shows the finite element analysis model results for a 6" expansion using high yield strength tube material. [The 6" expansion of the analysis model actually contained 5.5 inches of expanded tubing and a 0.5" expansion transition The 0.5" transition does not contribute to the pullout strength of the kinetic expansion joint since the transition tubing is not in contact with the tubesheet Actual profilometry data from a qualification test block indicated that a typical kinetic expansion has a transition of 0.5" length] The residual contact pressure is shown in Figure 3-2 as a function of distance above the transition region for both the condition of no applied load (dashed line) and the condition when slip begins (solid line) As described above, the effective length of the expansion is less than 6" because of the transition, which gradually tapers away from the tubesheet. (The analysis model ignored the fact that 17" and 22" long kinetic expansions were actually installed in the steam generator tubes.) Without applied load, the joint's residual contact pressure reaches a plateau a short distance away from the transition at a pressure equal to about 3300 psi The residual contact pressure abruptly decreases near the end of the expansion because of the effect of the free edge. The free edge is more flexible than the interior portion of the expansion so that the reaction at the edge is less for the same interference. The influence length of the effect of the free edge is determined by analysis to be approximately 0.25", which is reasonable in that this dimension is about three times the "decay length" of 0.08" based on widely used approximations of the structural influence of local discontinuities in thin tubes such as OTSG tubes (decay length = $0.78\sqrt{Rt}$, where R is the tube inner radius and t is the tube minimum wall thickness).

Under slip load conditions, the model demonstrated that residual contact pressure redistributes due to Poisson contraction of the tube wall. The reduction of residual contact pressure is less with increasing distance above the transition. This is because the tube reaction decreases with increasing distance above the transition due to the increasing total contribution of the friction reaction The pullout capacity of the joint is the product of the total residual contact pressure, the contact area, and the coefficient of friction

The design basis MSLB load for the OTSG tubes of 3140 lbs. was determined by assuming that all tubes remain fully elastic (Reference 17). It was necessary to adjust the results obtained for high yield strength tubes and greater wall thickness for consideration of minimum yield strength and nominal wall thickness tubes that may be present in the steam generators. The tubes in the OTSG having the lower bound yield strength (41 ksi per Reference 29) are expected to be in the plastic range for the design basis MSLB load The 3140 lb load corresponds to an axial membrane stress equal to 49.5 ksi and a design basis tube strain of 0.16% A stress-strain curve for the lower bound yield strength material was developed using actual tube material stress-strain data. Using the design basis tube strain (0.16%) and the stress-strain curve for the lower bound yield strength material the maximum axial load that must be considered was 2400 lbs. The design basis load is caused almost entirely by an applied thermal displacement since the OTSG shell is at a higher temperature than the OTSG tubes after a MSLB

The analysis model results indicated very little increase in pullout capacity for expansion lengths greater than 4". This is because the low yield strength tubing begins to yield at a load equal to 2400 lbs. Poisson contraction of the tube wall relieves the contact interference between the tube and tubesheet, particularly after the tube begins to yield. As an axial load is applied to a tube, Poisson contraction begins to relieve contact interference, and hence decreases contact pressure, and proceeds further into the expansion in proportion to the load. The relief of contact pressure due to local yielding permits a higher applied load to reach further into the expansion because the benefit of the friction reaction is reduced at the beginning of the expansion as higher loads are applied. Local yielding occurs further into the expansion so that contact pressure is relieved there as well, and so on, so that ultimately there is very little additional capacity achieved for the 6" and 8" expansion with regards to the 4" expansion This trend of results was reported during the original 1980's joint qualification program, and is also present in the Reference 24 analysis model In short, there is decreasing utility in increasing the length of the joint above 4". The analysis model also showed a change in the performance of the joint from friction limited, when the intact expansion is at a minimum, to yield strength limited when the intact length is longer and the applied axial load is higher. This was an expected result, since the joints must yield as applied load is increased

2.3 Flaw Dispositioning Criteria Development

A flaw dispositioning criteria was analytically built, in part, on these performance features of the kinetically expanded joint The analysis model was able to conservatively evaluate the performance of the intact and flawed kinetically expanded joints. For example, Reference 24, Section 3, Figure 3-12 shows the expected distribution of contact pressure in a 6" expansion [i e., 5.5" of expanded tube and a 0.5" transition] after a 2" 100% through-wall axial defect is introduced midway through the expansion length. The axial defect completely relieves contact pressure along its length and, in fact, influences the contact pressure for a length greater than 2" because of the "edge" effect as previously described. The expected pull out load for this configuration is 2509 lbs. which compares well with the capacity of the 4" expansion from Figure 3-11 (2516 lbs.) of Reference 24. Thus, a 2" axial defect in a nominal 6" expansion, without including tube internal pressure, forms an equivalent 4" expansion that also satisfies the qualification program criterion for resisting slip. The general conclusion from this and other similar calculations is that the kinetic expansions are flaw tolerant of axial defects (and for circumferential defects of limited extent also, as will be shown below) with respect to pull-out load. The required intact expansion for slip/pull-out load may be continuous or distributed in segments anywhere within the expansion length, provided the tube condition prevents tube parting.

The prescriptive conditions that were used to develop the design basis axial load for the MSLB include primary pressure equal to 2500 psi (Reference 17). Tube internal pressure should be included in the tube-to-tubesheet analysis model in order to identify the increase in contact pressure, in addition to residual contact pressure from formation, due to "pressure tightening". As the internal pressure within the tube increases, the tube is tightened within the tubesheet. When this pressure tightening was included in the analysis model, the analysis model results (Reference 24, Section 3, Figure 3-11) indicated that, for a lower bound yield strength tube having the design wall thickness, slightly less than a 2" expansion depth is required to resist pullout in a peripheral tube

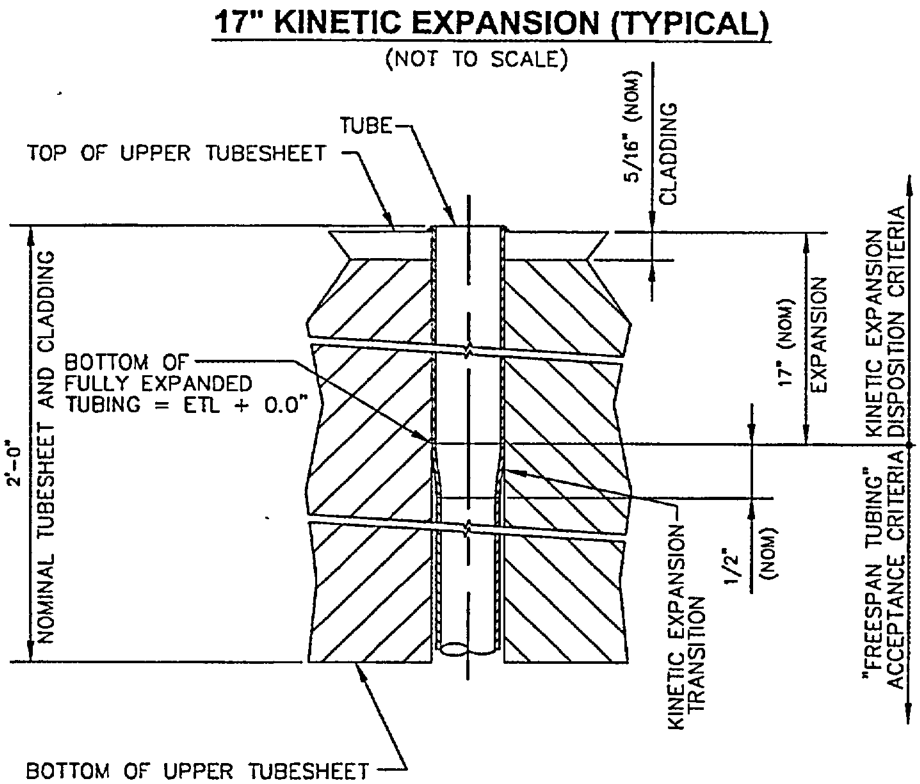
2.3.1 Required Length of Expansion

The Reference 24 analysis model defined the maximum axial flaw length that could be present within a kinetic expansion and still meet the requirement to resist pullout (as a function of the radial location of the tubes.) Since the analysis model assumed that the flawed lengths of kinetic expansion do not contribute to the pullout capacity, subtracting the length of the maximum allowable flaw from the expansion length provided the minimum necessary length of defect-free expansion to resist pullout. Table 3-5 of Reference 24 provides results of analyses that were based on finite element modeling of a 6" expansion (5.5" kinetic expansion length plus a 0.5" expansion transition) [Note 4 of that table states, "These criteria are only applicable for the fully-expanded region from 0.5" to 6" above the bottom of the kinetic-expansion joint " The length of the kinetic expansion transitions at the bottom of the kinetic expansions is approximately 0.5".] Table 3-5 provides "allowable defect lengths" within the 5.5" fully expanded length. For example, for a given tube location Table 3-5 may report that the allowable defect length is 4.4". Another way to state this is that a minimum of (5 5" minus 4.4", or) 1.1" of the kinetic expansion must be "defect free". In summary, the "required defect-free" lengths of the kinetic expansions, based on the finite element analysis, is the 5.5" modeled length of the kinetic expansions minus the calculated "allowable defect length".

The minimum required length of kinetic expansion, as described in the above paragraph, is based on finite element analysis only; the required expansion lengths were increased to conservatively account for field examination uncertainties. (Reference 24 determined structural requirements for the kinetic expansions based on structural analysis only and did not consider examination uncertainties.) For the inspection acceptance criteria additional length was added to the dimensions calculated in Reference 24 to conservatively account for the expected uncertainty in locating eddy current indications along the axial length of the kinetic expansion with respect to the expansion transition, and any uncertainty in locating the transition reference point itself. When applied in the field the minimum "defect free" length is 2.1" for a peripheral tube. Table 1 provides the resulting list of minimum required lengths of defect-free expansion, $AKEL_{MIN}$, for the various kinetic expansion lengths and their radial locations within the OTSG tube bundles. Table 1 provides AKELmins that include the results of the finite element analysis plus additional length for conservatism and to account for possible examination errors.

Figure 1 provides an illustration of a typical 17" deep kinetic expansion within the TMI-1 upper tubesheet. As described above, TMI-1 uses required kinetic expansion lengths that are conservative and are longer than those defined by the analysis model. TMI inspects and dispositions only these required expansion lengths. (Refer to Table 1.) A TMI-1 eddy current analyst reviews the tube's MRPC signal to locate the top of the kinetic expansion transition (i.e., that point where the tube is fully kinetically expanded against the tubesheet bore). This point is designated by the eddy current analyst as location ETL+0.00". (ETL = Expansion Transition Location) The analyst reviews the eddy current signals from the fully-expanded section; if no flaws are detected over the minimum required defect free length then the tube is dispositioned as "NDD" (i e., No Detectable Degradation). If a flaw is detected, it is characterized, located with respect to the ETL+0.00" reference point, and additional kinetic expansion length is reviewed by the analyst to detect/characterize any other flaws that might be present. If the additional analyzed length contains flaws such that sufficient defect free tubing is not identified, the tube is repaired. If the additional kinetic expansion length is analyzed and sufficient defect free tubing length is identified, the expansion then may be left in service (provided it meets all other criteria to remain in service)

FIGURE 1



17" KINETIC EXPANSION (TYPICAL)
(NOT TO SCALE)
TUBE
TOP OF UPPER TUBESHEET
5/16" (NOM)
CLADDING
NOMINAL TUBESHEET AND CLADDING
2'-0"
BOTTOM OF FULLY EXPANDED TUBING = ETL + 0.0"
17" (NOM)
EXPANSION
KINETIC EXPANSION DISPOSITION CRITERIA
"FREESPAN TUBING" ACCEPTANCE CRITERIA
1/2" (NOM)
KINETIC EXPANSION TRANSITION
BOTTOM OF UPPER TUBESHEET

The kinetic expansion acceptance criteria apply only to tubing that has been fully kinetically expanded As described above, the plant's analysis guidelines require that that point at which the tubing is fully expanded against the tubesheet bore is identified and is given the ETL + 0 00" reference point This provides a reference point to locate any indications that may be present. (See Figure 1 above.) All kinetic expansion examination results are referenced to the ETL+0.00" reference point. All minimum axial kinetic expansion lengths ($AKEL_{MIN}$s) are measured from the ETL+0.00" reference point.

2.3.2 Evaluation of Circumferential Indications

Evaluation of circumferential defects in the kinetic expansions was performed based on tube parting considerations. A tube may have a through-wall circumferential defect of 130° (0 64", as measured on the ID) in extent and still have a sufficient ligament to resist the design axial load (36 percent of the tube circumference is permitted to be flawed). This evaluation assumed that the defect is located at the bottom of the expansion region where the axial force is at its maximum. (At higher elevations within the expansion region, part of the axial force would be transmitted to the tubesheet by the friction restraining force, thereby reducing the axial force in the tube wall As a result, the allowable circumferential defect in higher areas of the expansion region would be greater than 0.64".)

For multiple circumferential defects in the expansion region, the allowable combined length of the defects would be 0.64" if the elevation difference is less than a separation criteria. These separation criteria were conservatively evaluated as part of the analytical work. The resulting flaw combination criteria are based on providing the required shear path between defect elevations in order to transfer the total load. It is conservative to include total load for shear transfer since membrane transfer also occurs A reasonable separation distance was judged to be 1" considering that 1.13" of intact tube length is required at the plane of the defect for membrane stress A 1" separation provides 2" of shear transfer path (1" at each side of a defect) at an allowable stress of 60% of that for membrane stress. For example, if two circumferential defects are separated by an axial distance greater than 1", each one may not exceed 0.64" in length. These criteria will ensure that the tube within the expanded region will not part.

The "edge" effect is an additional factor that must be included when evaluating the impact of circumferential defects. The edge effect of a circumferential defect degrades the pullout capacity of the tube much like an axial defect, as discussed above. For purposes of developing a flaw dispositioning criteria, a 0.25" axial influence will be added to each circumferential defect. In this way, the results for the contact pressure redistribution in the presence of only an axial defect form the basis for the comprehensive dispositioning criteria with respect to pullout resistance. The resulting inspection acceptance criteria for the OTSG kinetic expansion region are given in Table 1 and Table 2. Note that criteria differ for periphery, mid-bundle, and center tubes due to the effect of tubesheet bow, to be described below. As a result, the Table 1 and Table 2 values for a given tube are a function of the radial location of that tube within its OTSG tube bundle.

The loads, methods, and assumptions that were used in the analysis are conservative. The 3140 lb. axial load that was used to develop the inspection criteria is from a conservative analysis based on conservative assumptions with respect to TMI-1 regarding main steam line size, and maximum emergency feedwater flow and duration. For example, more recent analyses addressing expected MSLB thermal/hydraulic conditions and tube loads (described in Section 5.0) indicate that the maximum axial tube load is about 1300 lbs. as opposed to 3140 lbs. Thus, the use of the axial tube load from the analysis in the development of the inspection criteria incorporates a conservative factor of about 2 0

Each kinetic expansion defect was assumed to locally relieve the tube-to-tubesheet contact pressure to the same extent as a 360° cut regardless of its circumferential extent. Therefore, the relief of contact pressure due to any acceptable circumferential defect is overestimated and actual pull-out capacity is higher than that calculated. In addition, with regard to acceptable circumferential defect location, no credit is taken for the reduction in applied axial tube load within the expansion due to friction. The assumption provides more conservative results for defects that are further within the expanded zone, (i.e , the full axial load is assumed to be imparted on a circumferential defect, regardless of its location within the expansion) These analyses of joint integrity assumed that all defects are 100% through-wall. Any difference between actual depth and the assumed 100% through-wall depth of the analysis model represents an additional conservatism

2.4 Fatigue Analysis

The analysis of the joints also evaluated the possibility that defects that are acceptable for the faulted condition could propagate by fatigue during normal operation. The important contribution to propagation by fatigue is the axial tube load due to the cooldown, because bending stress, such as that due to flow induced vibration or due to local bending at the elevation of a defect, does not occur in the expanded tube above the transition Crack propagation by fatigue was conservatively evaluated previously during the repair of the OTSGs considering a defect located in the free span. The previous calculation was useful for guidance because, while it did not identically match the kinetic expansion condition, it was representative. The previous calculation considered a smaller through-wall, circumferential defect (0.36" circumferential extent), but also included local bending stress. The sum of these is practically the same as the membrane stress for the kinetic expansion analysis (i e., the kinetic expansion analysis had a longer defect and no bending stress). The results indicated that, on a per cooldown cycle basis, the expected crack propagation is about 10^{-4} inches in circumferential extent per cycle Assuming six cooldown cycles per year for two years of operation, propagation by fatigue results in practically no increase in circumferential extent. It is, therefore, not necessary to reduce the extent of the acceptable critical defect size in the expanded tube because of expected propagation due to fatigue during the forthcoming operation cycle. In addition, re-inspection of representative indications left in service in the kinetic expansions will take place during subsequent refueling outages in order to verify that flaw extent is not increasing to unacceptable size. (Additional discussion regarding the possibility of growth of existing flaws in the kinetic expansions is provided below.)

2.5 Tubesheet "Bow" Analysis

The analysis model (and the resulting inspection criteria) for the OTSG tubes includes an additional feature of the performance of the joint: tubesheet bow (due to tube axial load and due to primary-to-secondary pressure differences during an MSLB) is assumed to open the tubesheet bores below the tubesheet center plane and close them above. The tubesheet bore dimension was adjusted in the analysis model to reflect the expected bending strain distribution at the elevations of the expansion due to tubesheet bowing. The effect is greatest for a center tube where bowing is maximum. There is no effect for a peripheral tube. As a result of the upper tubesheet bowing inward, the applied axial tube load on the affected tubing is reduced, with the minimum occurring at the center. However, as another result of tubesheet bow, the contact pressure of the tube-to-tubesheet joint is reduced due to enlargement of the tubesheet hole in the area of the joint

The greatest impact of tubesheet bowing is for the 22" deep expansions where the original 6" qualification length was further below the tubesheet center plane than for the 17" expansions In fact, for a 22" expansion at the center, tubesheet bow eliminates most of the residual contact pressure even when considering tube internal pressure. (The effects of tubesheet bow were not evaluated during the original kinetic expansion qualification program of the early 1980's.)

The kinetic expansion inspection criteria identify the minimum required defect-free kinetically expanded tube that must be present within the inspected distance (Table 1) as well as the flaw, or combination of flaws, allowable within the inspected distance (Table 2). The inspection may continue beyond the nominal qualification length, if necessary, in order to demonstrate the presence of a satisfactory joint since the tubes were kinetically expanded over the entire length of the tubesheet above their original 6" qualification length. The absence of consideration of the effects of tubesheet bow as part of the original qualification program will not impact nuclear safety as long as the 22" expansions within the center and mid-radius locations of the tubesheet are inspected to the same elevation as the 17" expansions and evaluated to similar criteria. (Note that lengths of the center and mid-bundle 22" kinetic expansions that are 5" above ETL + 0.00" are also evaluated as freespan tubing, and is discussed below.)

2.6 Implementation of the Inspection and Repair Criteria

The inspection of a kinetic expansion always includes a concurrent inspection of its transition (This is required by the plant's eddy current guidelines and is also necessary to determine the location of the ETL+0.00" reference point as described above.) All kinetic expansion examination results are referenced to the ETL+0.00" reference point at the top of the expansion transition. All $AKEL_{MIN}$ minimum axial kinetic expansion lengths (for both 17" and 22" expansions) are measured from the ETL+0.00" reference point. Section 4.0, which follows, provides details regarding the eddy current inspection of the kinetic expansions.

Volumetric indications are dispositioned by combining the results that were derived separately for axial and circumferential defects. That is, the criteria for axial defects shall be used for the axial extent of the volumetric indication and the criteria for circumferential defects shall be used for the measured circumferential extent of the volumetric indication (The majority of TMI-1 OTSG kinetic expansion flaws are volumetric ID IGA indications, similar to those found in the freespan tubing of the TMI-1 generators)

As is apparent in Table 1 and Table 2, field implementation of these inspection criteria is specific with respect to both tube location and expansion length. The analysis model determined allowable defect sizes (plus influences) as a function of relative radius of the tube bundle for 17" and 22" expansions The analysis model calculated values at specific radial locations; it is conservative to apply results specifically for tubes that are located at a smaller radius as governing for tubes located at a larger radius. This logic represents an additional factor that contributes to the conservatism of the inspection criteria.

As is also apparent in Tables 1 and 2, disposition of defects in the 22" expansions is notably different than for 17" expansions The lower 5" length of the 22" expansion at center and mid-radius locations does not contribute to slip resistance under postulated MSLB conditions due to the tubesheet bowing For this reason the required defect-free expansion lengths ($AKEL_{MIN}$) for the 22" expansions located near the center of the tube bundle are 5" longer than that for 17" expansions located at the same tube bundle radial position. Indications in the lower 5" length of the 22" expansions located near the center of the tube bundle are dispositioned using more stringent free span criteria, since this length of expanded tubing loses contact with the tubesheet as a result of postulated tubesheet bow. Amendment #237 to the TMI-1 Technical Specifications implemented a requirement to implement the freespan tubing acceptance criteria for volumetric ID IGA indications within the lower 5" of the 22" long expansions at the center of the tube bundles Amendment 237 also implemented a requirement that 100% of the 22" long expansions at the center of the tube bundles be examined during each tubing inspection. In summary, the lower 5" of the 22" long expansions are a special subset in which both the freespan inspection acceptance criteria and the kinetic expansion acceptance criteria are applicable. (The freespan acceptance criteria are more stringent than the kinetic expansion criteria.)

3.0 Material Condition Assessment

3.1 Stress Corrosion Cracking Mitigation Resulting From Kinetic Expansion

The impact of kinetic expansion on the TMI-1 OTSG tube material condition can be considered in two separate parts First, there is the effect on pre-expansion defects. Secondly, there is the formation of, and benefits from, post-expansion residual stresses. Kinetic expansion is not a corrosive process; rather it is a mechanical, cold work process that produces plastic strain. It is reasonable to assume that defects that may not have been initially detectable may have been enlarged by the kinetic expansion and, thereby, made more detectable. It is possible, particularly for the axial component of defects because of the induced permanent circumferential strains, that defect dimensions increased due to the expansion, that the distance between defect planes (i.e., crack opening displacement) increased, that grain drop-out increased the defect volume, or that a combination of these changes occurred. As a result of the effects described above, kinetic expansion probably enhanced flaw detection. No defect growth has been observed over the course of recent operating cycles for kinetic expansion defects that have been reviewed with the same ECT technology. The finding of no defect growth is consistent with the same finding for the larger degraded, unexpanded, tube sample population as described in the recent refueling outage ECT results

3.2 Growth Monitoring and Examination Scope

TMI-1 has monitored the growth of eddy current indications within the kinetic expansions for the past several outages (since MRPC inspections were started) and has reported these results to the NRC (References 32, 35, 36). Since the original 1997 submittals regarding the kinetic expansions (i e., References 25 and 26) TMI-1 has provided additional details regarding growth of indications in the TMI-1 steam generators Reference 30 provided information regarding the methods with which TMI-1 has monitored the growth of the ID degradation found in the kinetic expansions, and as well as growth within the unexpanded tubing. Indications have been evaluated for changes in axial extent and circumferential extent over successive outages, and over multiple outages. Analysis of indication growth, and an assessment of that indication growth relative to the repair criteria, is required by the plant as part of operational assessments each outage.

Reference 30 provided information regarding the reliability of ECT techniques used for indication detection and sizing TMI-1 has examined all of the population of inservice kinetic expansions, by examining approximately one third of the population during each of the last three plant refueling outages (Outages 12R, 13R and 1R14). MRPC eddy current examinations of each of the in-service kinetic expansions has now been completed These examinations will serve as "benchmarking" or "baseline" MRPC examinations with which to compare future examination results

TMI-1 will continue to monitor for growth of flaws in its steam generators, including flaws in the unexpanded tubing within the tubesheets and kinetic expansions The plant will continue to perform a significant number of kinetic expansion examinations each refueling outage. A minimum of 20% of the unsleeved kinetic expansions and their transitions that are in service will be examined during each of the TMI-1 refueling outages. In addition, all inservice, unsleeved kinetic expansions and their transitions will be examined at least once over a 3 refueling outage interval. (Specifically, all of the non-plugged, non-sleeved tubes' kinetic expansions and their kinetic expansion transitions shall be inspected with rotating coil eddy current probes over a period of 60 effective full power months or 72 calendar months, whichever is longer. The TMI Unit 1 plant operating cycle length is presently 24 months) This is a conservative scope given that there is currently no evidence of any active degradation within the TMI-1 kinetic expansions. A minimum scope of 20% of the kinetic expansions per refueling outage is ample to examine this expanded tubing to monitor the growth of any existing degradation and for detection of new degradation mechanisms that might occur during future operations.

Approximately one third of the plant's kinetic expansions have been examined during each of the plant's last three refueling outages. These samples were sufficient to detect whether significant growth of existing flaws in the kinetic expansions was occurring, or if any new degradation began to appear within the kinetic expansions. The plant's steam generator program requires that condition monitoring assessments and operational assessments be performed based on the results of the outage examinations The operational assessments must contain an evaluation of the potential for growth during the following operating cycle.

In addition, as a result of TMI's recent steam generator Technical Specification Amendment No 237 (Reference 31), the TMI-1 Technical Specifications prescribe statistical tests to be utilized to evaluate the growth of ID volumetric IGA indications (-the predominant degradation mechanism noted to date in the kinetic expansions) following each steam generator inspection These statistical tests are applied to ID volumetric indications noted in the unexpanded tubing, the kinetic expansion transitions, and the lower 5"of the 22" center bundle region expansions, and the results of these statistical tests are reported to the NRC. These statistical tests, currently prescribed under the plant's Technical Specifications, will provide a quantitative assessment of indication growth in tubing regions where growth is more probable than in the kinetic expansions. Monitoring of possible growth of freespan ID IGA using statistical criteria under the current Technical Specifications will provide a conservative representation of the growth potential for indications within the kinetic expansion. The tubing service stresses in the freespan are greater than those in the kinetic expansions. Higher service stresses in the freespan constitute a more aggressive environment for the potential propagation of stress corrosion cracking (SCC). Circumferential stresses within the kinetic expansion are less than in the freespan due to the participation of the tubesheet ligament in reacting to internal pressure. At operating conditions, increases in both internal pressure and temperature cause an increase in kinetic expansion contact interferences, resulting in higher compressive circumferential stresses. Axial tube loads in the kinetic expansion are diverted into the tubesheet ligaments due to the friction reaction as a result of residual contact pressure from the formation of the joint. Axial stresses in the kinetic expansion are reduced in proportion to the elevation within the repaired joint. In summary, the current TMI-1 Technical Specification requirements for statistical growth analyses for indications in unexpanded tubing and transitions also enable the plant to conservatively assess the potential for growth of kinetic expansion indications.

3.3 Residual Stresses

Kinetic expansion produces residual compression in both the circumferential and axial directions. This can be understood by considering the mechanics of the process. The residual contact pressure from formation is an external pressure on the tube OD due to the interference between the tube and tubesheet. The resulting residual hoop stress in the tube is compressive at a level approaching the yield strength of the tube material. In addition, during the expansion, as contact between the tube and tubesheet increases, the tube is extruded against the friction that is also developing in the contact zone. The friction reaction due to contact pressure causes residual axial compression by resisting extrusion.

Service conditions will not completely remove residual compression of the kinetic expansions in either the circumferential or axial directions. At operating conditions, increases in both internal pressure and temperature cause an increase in contact interference, resulting in higher compressive circumferential stresses Axial tube loads applied during normal operation will not remove residual axial compression completely because contact pressure due to radial interference is not lost. Axial load on the joint is at a maximum during the normal cooldown transient but will not exceed about one-third of the applied axial load during the faulted condition The normal cooldown transient will not remove contact interference even for the limiting 22" expansion at the tubesheet center. Any reduction in axial compression is temporary with full elastic restoration following any (and all) cooldown transient(s).

The kinetic expansion joints, under normal operation, have compressive residual stresses in both axial and circumferential directions. Mitigation of stress corrosion cracking, both for new damage and propagation of existing damage, is accomplished by maintaining these compressive residual stresses within the kinetically expanded regions. Since the analytical model and structural repair criteria assume that all defects are 100% through-wall, and that circumferential defects result in a full relaxation of the tube-to-tubesheet contact pressure over 360° of the tube circumference, there exists substantial allowance for flaw growth. In addition, the MRPC eddy current techniques provide conservative measurements of flaw extents within the kinetic expansions. (See Section 4.0, which follows) With these conservatisms and the other conservatisms of the finite element model, the as-called eddy current indication length and widths are evaluated with respect to the repair criteria. Additional factors or increments to account for flaw growth are not used and are not necessary.

4.0 Basis for Disposition of Defects and NDE Process Variability

The basis for dispositioning defects in the kinetic expansion has been, and continues to be, that even full through-wall damage can be acceptable with respect to both structural integrity and primary-to-secondary leakage, depending on defect location and extent Post-expansion ECT inspections of the kinetic expansion performed in the 1980's identified previously undetected defects. Depth sizing was not possible with the inspection technology that was used at the time (i.e., 8X1 probe) It was concluded (NUREG 1019, Table 3.3-1) that small indications possibly having through-wall extent would not impact the reliability of the joints. More recent analyses, described herein, have also reached this conclusion.

4.1 Examination Techniques and Variability

Kinetic expansion examinations are currently performed with MRPC probes (i.e., Motorized Rotating Pancake Coil). These probes contain a mid-frequency Plus-Point coil and a 0.080" high frequency shielded pancake coil that are used to detect and evaluate indications in the kinetic expansions. These examination techniques are able to characterize the flaws in terms of morphology, surface extent, depth of the flaws, and axial location of the flaws within the expansions.

PWSCC sizing performance of rotating coil examinations in OTSG tubes was evaluated prior to TMI-1's 1997 Outage 12R Machined flaws were introduced into OTSG tubes in order to represent circumferential, axial and volumetric damage. The study concluded that the Plus Point coil examination technique provided the best depth sizing performance and the best flaw extent measurement performance for axially- and circumferentially-oriented flaws. The 0 080" high frequency shielded pancake coil examination technique provided the best extent measurement performance for ID volumetric indications.

Prior to examining a large number of kinetic expansions in the 1997 12R Outage, the contributing sources of expected error during the MRPC examinations were segregated and evaluated separately. The primary source of error was technique error involving differences between the "as-called" values compared with metallurgical "truth". The other contributing factors were analysis variability due to differences between the results of eddy current analysts, and equipment/technique variability due to differences among multiple trials for the same analyst.

In order to establish examination extent and acceptance criteria it was necessary to establish the magnitude of each of these contributing sources of examination error. Using length sizing performance as an example, the relative sizing error was greater than the sum of analysis variability and equipment/technique variability. This result has significance because the average error for both circumferential and axial length sizing is an overcall This means that the sum of all of the error contributing factors remains an overcall for axial and circumferential extent. Since the overall performance was shown to be consistent overcall of flaw lengths, this helps ensure that tubes with unacceptable flaw lengths will be removed from service. Since the examination techniques overcall these extents, the "as-called" circumferential and axial dimensions, without any statistical correction, is used for length sizing

As previously described, only those defects estimated to be greater than 67% through-wall are included in the kinetic expansion accident-induced primary-to-secondary leakage evaluation. (Leakage is highly improbable from shallow defects.) The logic for addressing the expected errors when depth sizing was similar to that for length sizing. In this case, however, an additive correction is used because the typical Plus-Point depth sizing error is an undercall. (ECT estimated the throughwall extent to be less than the actual throughwall depth) The additive correction to the "as-called" depth is large enough to ensure the sum of all factors that contribute to error will result in an overestimate of throughwall depth.

Specifically, the additive correction factor for the mid-frequency Plus-Point probe depth estimate is 32.6% through-wall. Thus, for field implementation, any indication having an "as-called" depth greater than 67% through-wall is considered as potentially contributing to primary-to-secondary leakage, and is included in the leakage assessment calculations

4.2 1999 Analyses and Results of 1997 Tube Pulls

Subsequent to the 1997 outage, additional analyses were performed to evaluate eddy current analysis errors for TMI-1 steam generator tube flaws. The majority of TMI-1 flaws are volumetric ID IGA indications. Axial and circumferential extents of the volumetric ID IGA indications in the freespan are measured using the 0.080" shielded high frequency pancake coil. AmerGen's Reference 30 (RAI Question 1) response provided to the NRC the following information concerning length and width sizing of volumetric ID IGA indications:

"...TMI-1 has evaluated eddy current techniques and expected analyst uncertainties so as to assure that the dispositioning of the ID IGA indications using MRPC probes is conservative. Before 1997's Outage 12R, a study was performed to evaluate the acquisition, analysis, and technique errors expected during the MRPC examinations of the ID IGA indications Volumetric flaws manufactured by EDM were used in the 1997 study. This study was updated before 1999's Outage 13R so as to incorporate the data from the ID IGA flaws in the tube samples pulled during the 1997 outage. A team of 5 production analysts and 1 senior (resolution) analyst was used in the study.

"Acquisition variabilities were obtained by running three separate MRPC exams of the ID volumetric flaws. Comparison of the three separate exams by a single analyst enabled the acquisition errors to be evaluated. Since each flaw was a separate test, a pooled variance was used to combine the results. For the 0.080" HF pancake coil (the coil utilized by TMI-1 to measure the extents of the ID IGA indications), the acquisition pooled standard deviations were 0.0114" for axial length and 0.0084" for circumferential length.

"Analysis variabilities were obtained by comparing the different analysis results of the six different eddy current analysts For the 1999 study, this dataset included 23 EDM flaws and 9 flaws from the 1997 TMI-1 pulled tube, for a total of 32 volumetric flaws. For the 0 080" HF pancake coil (the coil utilized by TMI-1 to measure the extents of the ID IGA indications), the analysis pooled standard deviations were 0.022" for axial length and 0.031" for circumferential length

"Technique variabilities were obtained by comparing the results of the eddy current analyses to the actual metallurgy of the flaws. Again, for the 1999 study, this dataset included the 23 EDM flaws and 9 flaws from the 1997 pulled tube, for a total of 32 volumetric flaws For the 0.080" HF pancake coil (the coil utilized by TMI-1 to measure the extents of the ID IGA indications), the technique standard deviations were 0.039" for axial length and 0.033" for circumferential length. For the 0 080" HF pancake coil, the technique average errors were a 0.124" overestimate of axial extent and 0.127" overestimate of circumferential extent.

"The conclusion of the 1999 error analysis and performance evaluation is that "...the rotating coil techniques have demonstrated that axial and circumferential extents are consistently overestimated Even when analysis and technique / equipment variability are applied at a 95% confidence level, the extents measured by eddy current are larger than the actual extents " The overestimation of axial and circumferential extents is of sufficient magnitude that no correction to the repair limits is necessary to account for eddy current acquisition, analysis, or technique uncertainty. Since the eddy current coils interrogate a volume of metal larger than the volume of the flaws themselves (i.e., "look ahead" and "look behind") the result is a consistent overestimate of flaw extents

"Note that tube pull results from the 1997's Outage 12R demonstrated that the MRPC probe typically overestimates the axial extents of the ID IGA flaws by a factor of approximately three. This occurs due to the "look ahead" and "look behind" phenomena of eddy current coils used in steam generator tube examinations. Additional information on analyst uncertainty is provided in the response to RAI Question No 4."

Similar length sizing studies were performed for axially- and circumferentially-oriented indications prior to the 1997 and 1999 outages using 30 machined notches and 6 laboratory-induced, axially-oriented PWSCC cracks. These measurements were made using the mid-frequency Plus Point coil similar to measurements made in the field. The results of these studies indicated that the Plus Point coil, like the pancake coils, overestimates crack length.

In the kinetic expansion region flaw depth measurements are made using the mid-frequency Plus Point coil. Prior to the 1997 and 1999 outages Plus Point coil depth sizing performance studies were performed in a manner similar to that described above for the length sizing studies. The 1999 study was performed using 68 total flaws that were comprised of 10 machined axial notches, 20 machined circumferential notches, 23 machined ID volumetric IGA like indications, 6 laboratory grown PWSCC indications in OTSG tubing, and 9 TMI pulled tube ID IGA indications. The studies indicated that the measured 95% lower confidence level (LCL) through wall measurement error is expected to be -28.1% through wall. [Note that the additive correction factor for the mid-frequency Plus-Point probe depth estimate was not changed from 32.6% to 28.1% after the 1999 study. Thus, for field implementation, any indication having an "as-called" depth greater than 67% through-wall is considered as potentially contributing to primary-to-secondary leakage, and is included in the leakage assessment calculations.]

It should be noted that the measured eddy current through wall estimate is used for estimation of accident-induced leakage only; the eddy current measured axial and/or circumferential extent is assumed to be 100% through wall for evaluation of structural integrity (resistance to pull-out) as described in previous sections of this report. Based on the eddy current examination results, and in situ pressure tests of freespan indications performed at TMI to date, accident-induced leakage from kinetic expansion indications remaining in service is expected to be very small

In summary, the eddy current techniques used at TMI-1 are based on qualification datasets that included pulled tube samples from TMI-1 and other samples representative of TMI-1's ID degradation Performance studies have demonstrated that eddy current sizing is conservative, and both pulled tubes and in situ pressure testing to date have demonstrated that the techniques used at TMI-1 are able to reliably disposition steam generator tube flaws.

4.3 Conservatism of Measured Depth Criterion

The 67% throughwall threshold for the leakage estimate is a very conservative criterion considering·

- the 33% TW eddy current accuracy (i e , 100% minus 67%) was based on the results of the 1997 eddy current analysis with a 95% single tailed lower confidence level. A team of analysts was used for the study to evaluate error. In addition, a 1999 evaluation determined that 28% accuracy could have been used.

- a number of additional conservatisms are incorporated into the leakage assessment methodology. For example, volumetric indications are hypothesized to form both a circumferential crack and an axial crack, with the entire measured eddy current extent(s) used to calculate expected accident leakage.

- the majority of the indications within the TMI kinetic expansions are ID volumetric IGA indications. In-situ pressure testing of ID volumetric IGA indications at TMI to date has not identified any indications that have demonstrated measurable leakage (i.e., leakage above detectable levels) at simulated normal operating or accident conditions. For example, 69 ID volumetric indications were in situ pressure tested, without leakage, during the plant's most recent 1R14 refueling outage in 2001 (Reference 32).

The results of in situ pressure tests performed during recent refueling outages also provide some additional evidence that the depth estimates of TMI-1 steam generator tube flaws are conservative. For example, during the 1R14 Outage, seven TMI-1 tube indications whose estimated depth by Plus-Point was greater than 80% throughwall were insitu pressure tested. (Reference 32) None of these seven indications leaked at a delta pressure equivalent to three times the delta pressure during normal plant operation (i.e., 3NODP). One of these seven indications, with an estimated depth of 97% throughwall, leaked at a rate of 0.014 gpm, a small leakrate, at a delta pressure of 6450 psi, approximately five times the delta pressure during normal plant operation All seven of these indications had estimated depths greater than 67% throughwall and would have been assumed to leak at MSLB delta pressure, which is less than 3NODP delta pressure, under the kinetic expansion leakage criteria.

4.4 Evaluation of Kinetic Expansions with Indications

If any flaws are detected within a kinetic expansion, the eddy current analysts document the locations, measurements, and types of flaws within the expansions. Evaluation of the flaws with respect to the repair criteria, and leakage estimates, are performed by the plant's engineers.

Note that the expansion transition (i.e., below the ETL+0.00" reference point) is considered freespan for indication disposition purposes. The kinetic expansion transitions are treated as freespan tubing since they are not expanded against the tubesheet bore and do not benefit from any compressive residual stresses such as those present in the expansions. For example, a small circumferentially-oriented indication may be left in service within a 17" long kinetic expansion if sufficient defect-free expansion is present to ensure the structural integrity of the expansion, while any circumferential indication detected in the kinetic expansion transition is removed from service.

4.5 Repair Criteria Application

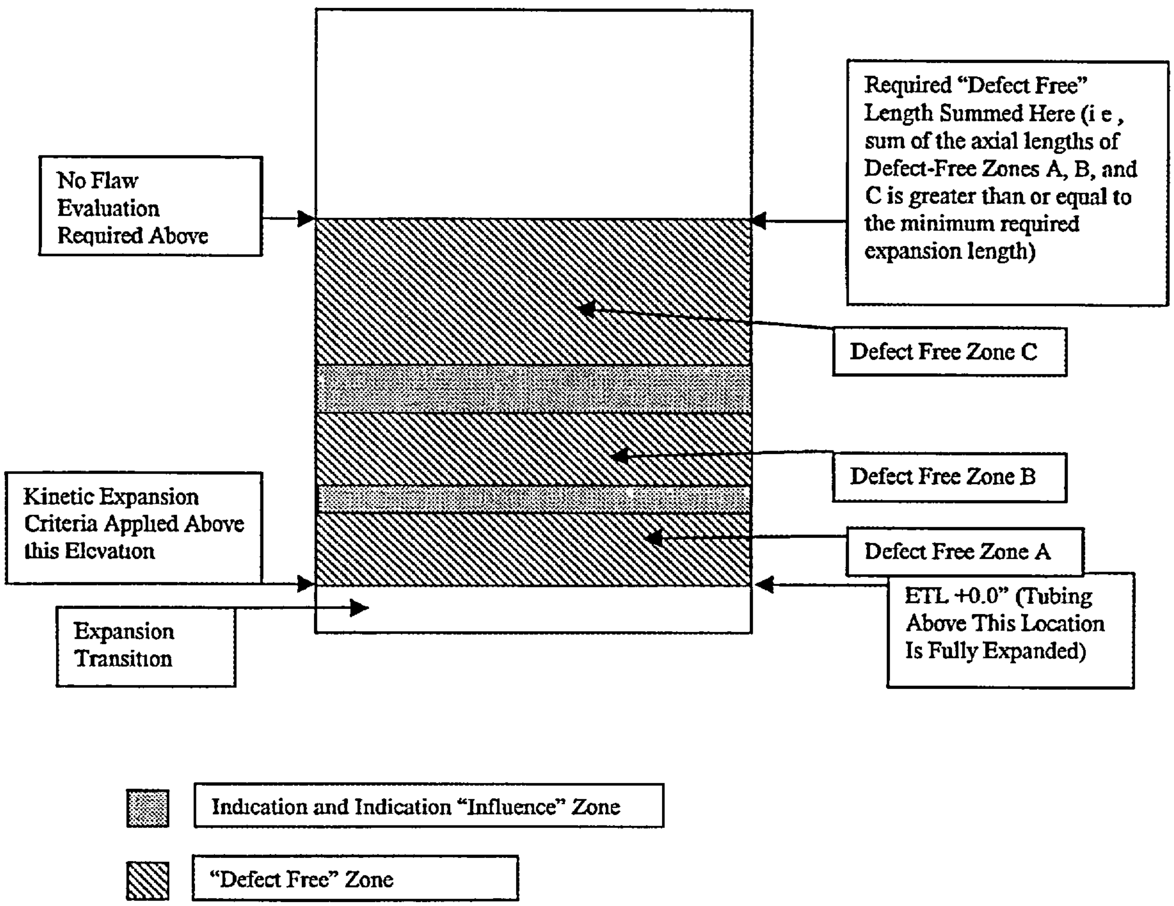
As described above, kinetic expansion evaluations are performed beginning at the ETL + 0.00" location to verify that sufficient defect-free lengths are present. Structural evaluations of the kinetic expansions require that a kinetic expansion be removed from service if insufficient defect-free length is identified over its examined length That is, if a defect (or a combination of defects) is detected that exceeds the allowable circumferential extent acceptance criterion, or an insufficient axial length of defect-free expansion is present, the expansion is removed from service. The inspection of a kinetic expansion may proceed farther (i.e., higher) in the tubesheet if flaws detected during the course of the examination within that expansion are within the conservative structural acceptance criteria. Figure 2, below, provides a visual presentation of the "defect-free" concept for a kinetic expansion with two indications.

If a flaw is detected in a kinetic expansion, the TMI-1 dispositioning criteria conservatively assume that the joint is not usable for structural purposes over the entire axial length of that flaw. For example, if a small volumetric flaw is detected with an eddy current-measured axial extent of 0.15", the entire 0.15" length of the expansion (360 degrees around the surface of the tube) is not credited in the evaluation of the joint structural integrity. In addition, no credit is taken for defect-free tubing along additional axial lengths of the joints adjacent to flaws (known as flaw "influence zones"). Even small circumferentially-oriented flaws, if present, are assigned axial lengths of flaw influence zone so that no credit is given for that axial influence zone length of the entire joint. In summary, sufficient defect-free tubing must be detected to verify the integrity of an expansion during an inspection; no credit is taken for the length of the kinetic expansion where any defect is present, or where any defect might influence joint integrity.

While the kinetic expansion structural dispositioning criteria are very conservative, there is no requirement that the defect-free joint length be "continuous". The kinetic expansions are flaw tolerant. (Burst is precluded due to the presence of the tubesheet; residual compressive stresses are present; bending stresses and vibration are limited; secondary side loose parts are prevented from impacting the tubing.) Small defects do not influence the reliability of the kinetically expanded joints For example, a small volumetric ID IGA pit on the surface of a kinetic expansion will not impact the ability of defect-free tubing, located above or below that pit, to maintain the structural requirements of the joint (e g., no tube parting, no joint pullout). Outside of the flaw influence zones a small ID-initiated axial crack present along the length of a kinetic expansion would not adversely affect the structural integrity of defect-free tubing located above or below that crack. From a structural standpoint, so long as no flaw or combination of flaws is present with a circumferential extent greater than 0.64", the defect-free tubing located above or below the flaw is an integral part of the kinetic expansion joint. (If the 0.64" circumferential extent value is exceeded prior to the required defect-free length being observed, the kinetic expansion is repaired, since the tube, conservatively assuming 100% throughwall degradation, could theoretically be parted under calculated accident-induced loads.) The expansion evaluations only "move higher into the tubesheet" if the examination data is available, and the repair criteria are not exceeded. The technical basis for this continued inspection (i.e., higher in the tubesheet) is provided in the finite element analyses of Reference 24.

FIGURE 2
"Defect Free" Concept

(Inside Surface of a Hypothetical Kinetic Expansion "Flattened" for this Sketch)
---Not to Scale---



5.0 LEAKAGE ASSESSMENT METHODOLOGY

5.1 INTRODUCTION AND BACKGROUND

Primary-to-secondary leakage during an accident must not degrade the ability to provide adequate core cooling capacity nor cause unacceptable or unanalyzed radiological consequences The kinetic expansion inspection criteria provide assurance of joint structural integrity to the ends that joint failure will not occur either by slipping or by tube parting. Each of these failure modes has as a theoretical consequence the introduction of primary-to-secondary leakage

Theoretically, through-wall defects that may be present in the kinetic expansion region may leak when subjected to MSLB conditions, even if these defects are not large enough to create a tube slipping or parting concern The hypothetical MSLB axial loads and differential pressures could cause defects to open and provide a less restrictive leakpath than that provided by the tube-to-tubesheet joint during normal operation

Primary-to-secondary leakage from the expansions is expected to increase during a postulated MSLB. The joint was originally qualified as leak-limiting and not leak-tight. However, in order to address even the possibility of increased primary-to-secondary leakage due to defects in the joint, a number of very conservative assumptions have been made in the leakage assessment methodology.

Defects that are judged to be through-wall, or near through-wall, by the inspection techniques are included in the primary-to-secondary leakage evaluation. While the analysis model for kinetic expansion structural evaluation assumed 100% through-wall, the analysis of accident-induced leakage utilizes through-wall depth information provided by the ECT.

In addition, some potential defects could be located at elevations where contact pressure between the expanded tube and the tubesheet bore remains, albeit reduced, during the accident. The presence of contact pressure considerably reduces leakage. The analysis model results showed that, for tubes that are not affected by tubesheet bowing (i e., peripheral tubes), no part of the minimum required intact expansion loses residual contact pressure during the accident. Tubes that are affected by tubesheet bowing (i.e. tubes near the center of the bundle and mid-radius tubes) will locally lose contact pressure during the MSLB event. As a result, the radial location of a tube within the bundle affects the estimation of leakage from flaws found in its kinetic expansion

"As found" and "as left" leakage estimates for the kinetic expansions are calculated after each inspection. Because no flaw growth has previously been detected, and no growth is expected, it is necessary only to consider defects found in the joint that are dispositioned as acceptable and left in service as potential sources of future primary-to-secondary leakage Defects that are unacceptable are repaired by plugging.

The purpose of this section is to describe the methodology that is used to evaluate the total primary-to-secondary leakage that may occur during a guillotine rupture of a main steamline as a result of assumed through-wall (>67% throughwall) cracks in the kinetic expansion region of the OTSG tubes. In Reference 17 it was demonstrated that the limiting accident scenario which results in the largest tube loads is that which results in a large SG tube-to-shell temperature differential (ΔT). The most restrictive limits were determined to be when the tubes are colder than the steam generator shell. Consequently, in Reference 1, it was concluded that the MSLB accident results in the largest tube to shell ΔT.

In order to establish the total primary-to-secondary leakage that would be acceptable during the MSLB event from assumed through-wall cracks in the kinetic expansion region, a calculation determined the maximum leakage that would meet the offsite dose criteria of 10% of 10CFR100 limits for the 2 hour Exclusion Area Boundary (EAB) and 30 day Low Population Zone (LPZ) (Reference 2). The revised dose consequences for the FSAR MSLB analysis were submitted to the NRC for approval (Reference 3). The results were as follows:

1. Integrated Primary Coolant Leakage @ 2 hrs (gallons @ 579 F) = 3228.
2. Total Integrated Primary Coolant Leakage (gallons @ 579 F) = 9960

The methodology used to estimate leakage from the kinetic expansion indications, and to determine if these leakage limits are met, is discussed in the following sections Section 5.2 provides an overview of the methodology and the subsequent sections provide additional detail.

5.2 OVERVIEW OF METHODOLOGY

The methodology involved the following activities that are depicted in Figure 3·

A Develop the time varying thermal hydraulic (T-H) information from the design basis Main Steamline Break (MSLB) event analysis.

B Determine the OTSG tube tensile and differential pressure loads from the T-H data. The loads vary as a function of time throughout the transient and as a function of radial distance from the center tube to the peripheral tube.

C. Calculate the theoretical crack opening area (COA) separately for postulated circumferential and axial cracks. The COA varies with the applied load, crack orientation, and crack length.

D. Determine the theoretical leakage flow as a function of the crack area Based upon the expansion contact pressure at the flaw location, determine if a leakage reduction factor can be applied to the crack area leakage flow. The total mass released from the crack is obtained by integrating the leakage flow over the first 2 hours and over the entire transient interval.

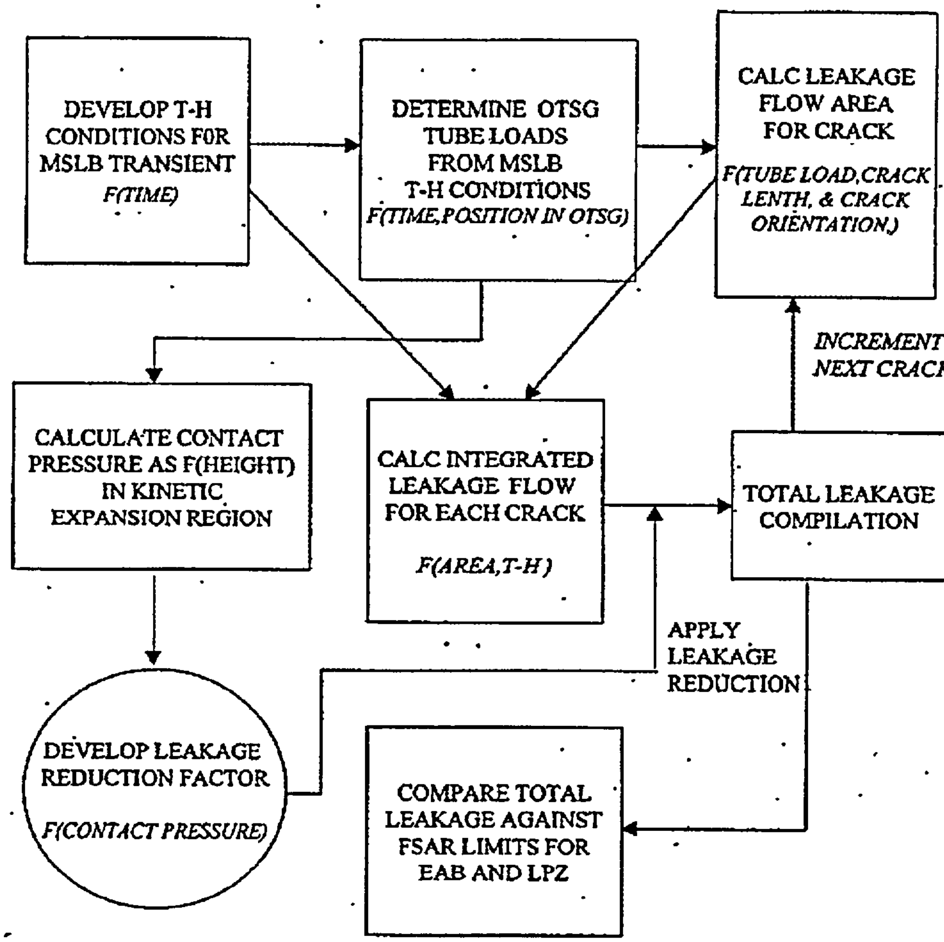
E The integrated leakage flow for each of the identified cracks (based on crack size and radial position within the tube bundle) is summed and the total is compared against the leakage limits specified in the offsite dose calculation (Reference 2) based upon 10% of the 10CFR100 limits.

If the calculated leakage exceeds the limits established in Reference 3, then a decision will be made as to which tube(s) will be repaired (i.e., the leakage contribution from the repaired tube(s) can be eliminated from the total to meet the allowed as-left leakage limits)

Additional details and references regarding each of the activities discussed above are provided in the sections which follow.

FIGURE 3

LEAKAGE EVALUATION METHODOLOGY OVERVIEW



5.3 MAIN STEAM LINE BREAK ANALYSIS

5.3.1 Overview

A conservative plant MSLB analysis was used to generate the transient thermal hydraulic parameters that were needed as input to define the OTSG tube loads, to calculate the leakage from each kinetic expansion crack, and to determine the contact pressure as a function of axial position above the kinetic expansion transition region in the tube sheet for determination of the appropriate leakage reduction factor.

The transient analysis was accomplished in two phases: a short term phase and a long term phase The short term phase duration was 10 minutes (600 sec) and utilized the transient systems analysis code RETRAN-02, Mod 5 (Reference 5). The long term phase thermal hydraulic conditions were developed by applying assumed operator actions, based upon TMI-1 Anticipated Transient Procedures (ATPs), to recover from the event and to calculate the OTSG shell metal cooldown rate in order to develop a technical basis for cooling down to DHR conditions without violating tube-to-shell differential temperature limits. The long-term analysis began at 10 minutes and extended to the end of the transient (approximately 24 hours). Details of these evaluations are provided below.

5.3.2 Short Term Analysis

5.3.2.1 Basis of Duration

As indicated above, this portion of the MSLB thermal hydraulic analysis included the first 10 minutes (600 sec) of the event There were multiple reasons for choosing this duration First, this portion of the transient is characterized by the most complicated and dynamically changing thermal hydraulic attributes. The affected OTSG is blowing down, the Heat Sink Protection System initiates a closure of the Main Feed Water (MFW) control valve and the MFW block valve and also initiates Emergency Feed Water (EFW) on low OTSG level. The RCS is depressurizing and cooling down, the pressurizer is emptying and refilling, an RPS trip occurs, ESAS is initiated, etc. Because of the complexity of this portion of the transient, a relatively sophisticated systems analysis code (RETRAN 02, Mod 5) was used to establish the thermal hydraulic parameters during this period (Reference 5).

Another reason for this duration is that no operator recovery actions were assumed to take place until after 10 minutes had passed. This is a licensing basis for TMI-1.

Following the first 10 minutes, credit for operator actions is permitted.

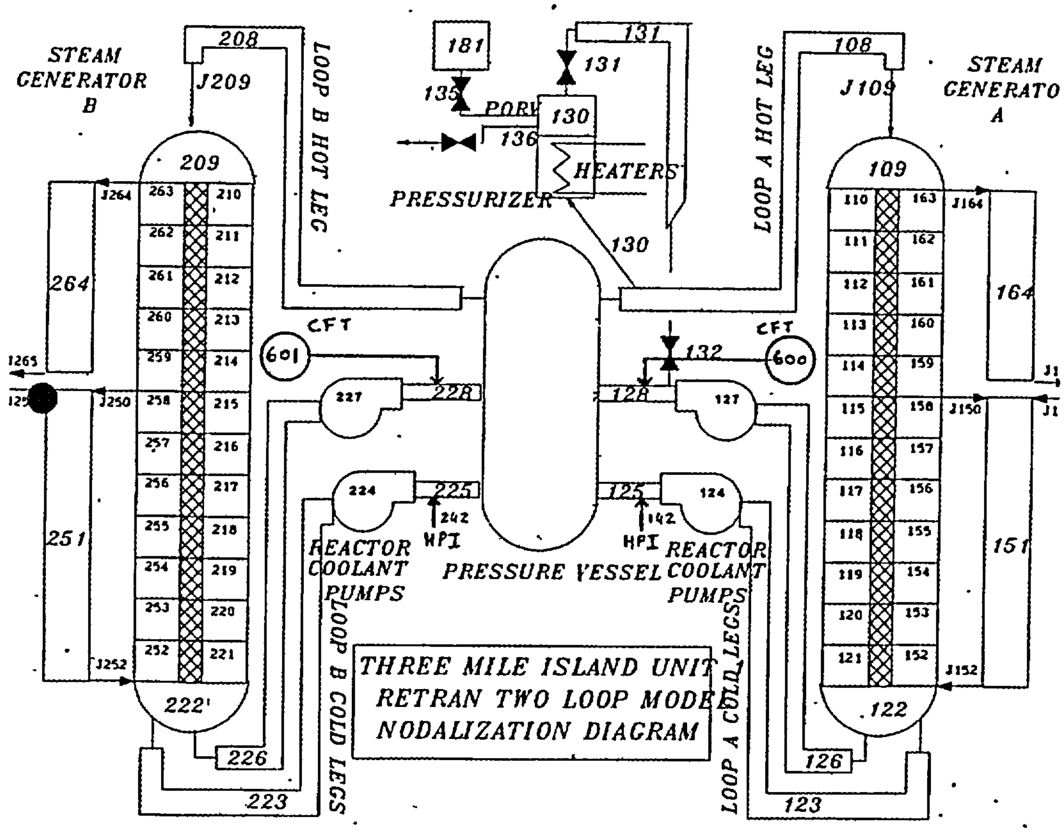
The peak axial, tensile tube loads for this event also occur within the first 10 minutes and the thermal hydraulic conditions at the end of this duration are important since they represent the end of the peak load period and the transition to reduced OTSG tube loads.

In this manner, the first 10 minutes of the MSLB analysis set the stage for the entire leakage determination effort At the end of this period, the system is not characterized by rapid changes in thermal hydraulic conditions and is in transition to the recovery from the event

5.3.2.2 Methodology

The RETRAN-02 MOD005 computer code and a TMI plant model were used to perform this analysis (Reference 4). The TMI RETRAN model has been extensively benchmarked against plant data and previously approved licensing codes. The benchmarks demonstrate the adequacy of the TMI RETRAN model for performing safety analysis. The TMI RETRAN model has also been approved by the NRC for referencing in licensing applications (Reference 5). The TMI Base deck (Reference 6) as shown in Figure 4 was used for this analysis.

FIGURE 4 – Three Mile Island Unit 1 RETRAN Two Loop Model Nodalization Diagram



5.3.2.3 Assumptions

The analysis assumptions and initial conditions as discussed below were chosen to provide a conservative RCS overcooling and pressure history for the MSLB event and the resulting tube loads.

5.3.2 3 1 Initial Conditions

The reactor was assumed to be operatıng at rated power prior to the hypothetical MSLB accident (2568 MWt). The initial pressurizer liquid level was set at 220 temperature-compensated inches, which is the typical hot full power (HFP) pressurizer level. The initial RCS pressure was 2170 psia in the hot leg, which is the normal operating value. The TMI design basis MSLB assumes that offsite power is available and that was the assumption in this analysis. The effect of high RCS loop flow is to minimize the OTSG tube average temperature during the initial phase of the event. Thus, OTSG tube axial loads are maximized

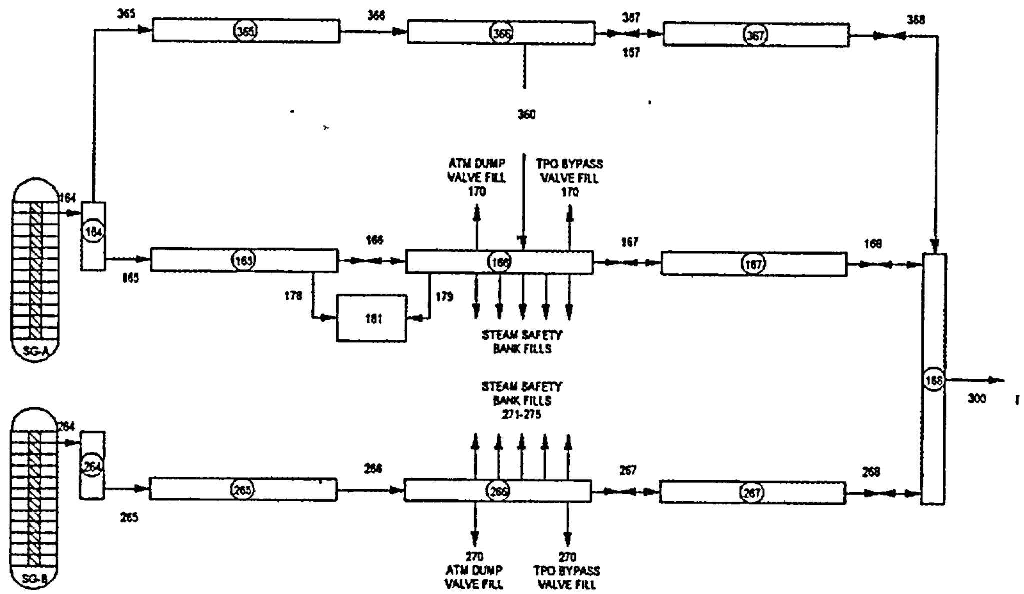
5.3.2.3.2 Break Modeling

The initiating event was assumed to be a double-ended rupture of a 24-inch steam line on one steam generator. This is the largest possible break which results in the maximum cooldown rate. The faulted steam generator steam line was nodalized as shown in Figure 5, so as to model each steamline individually. The flow area of the two break junctions were consistent with the 24-inch steam line piping.

A Moody choking model was used for these break junctions with a contraction coefficient of 1.0 to maximize break flow rate.

The break was assumed to occur in the plant's Intermediate Building upstream of the Main Steam Isolation Valve (MSIV) This is an appropriate break location because it results in a ground level release of coolant activity.

FIGURE 5-Break Nodalization



5.3 2.3.3 Reactor Vessel Mixing

The amount of mixing that was assumed to occur within the reactor vessel was a ratio of the difference in hot leg temperatures to the difference in cold leg temperatures

$$RATIO = \frac{T_{HOT}(\text{unfaulted}) - T_{HOT}(\text{faulted})}{T_{COLD}(\text{unfaulted}) - T_{COLD}(\text{faulted})}$$

A value of RATIO = 0.0 implies perfect mixing while RATIO = 1.0 implies no mixing For the purposes of this analysis, a target value of RATIO = 0.5 was chosen to conservatively bound the analyses at an upper value.

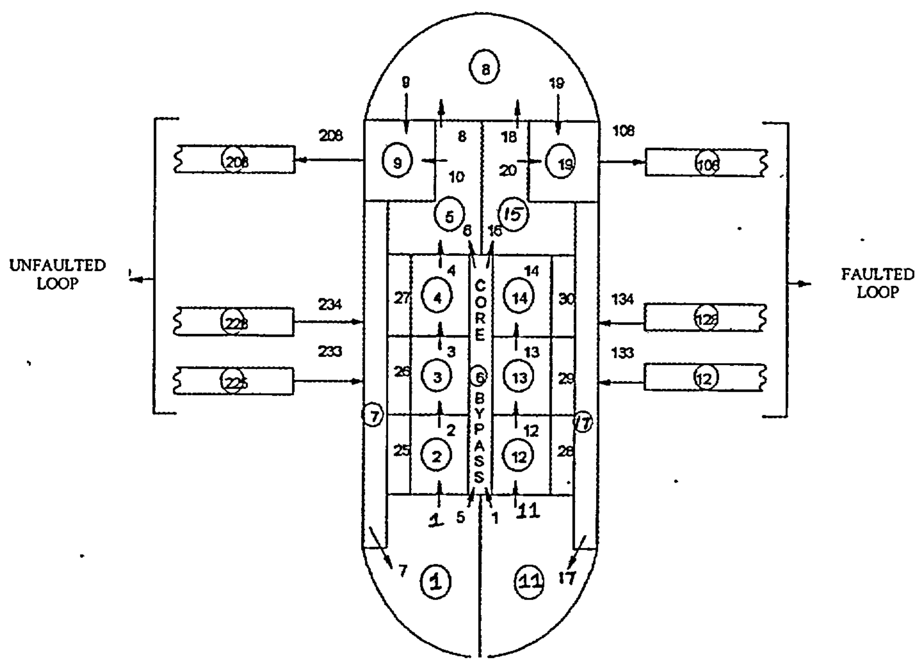
To simulate this mixing in RETRAN, the reactor vessel was modified to include two equal parallel flow paths by splitting the downcomer, the lower plenum, the core, and the upper plenum as shown in Figure 6. For the most part, these parallel flow paths behave independently, with the exception of common connections with the bypass and upper head volumes. These common flow paths keep the loop pressures in balance but contribute little to mixing of loop flows.

5.3.2.3.4 Reactor Kinetics Parameters

To minimize the power increase response to the core temperature decrease, the moderator temperature coefficient (MTC) was set to a value of zero. This was conservative since it will not increase the power prior to trip and results in lower RCS temperatures. Post trip, the MTC determines the extent to which the core energy generation is increased by sub-critical multiplication. An MTC of zero will assure that the post trip reduction in temperature will not lead to increases in power generation above the normal decay heat power. The absence of a return to power after the trip results in a greater cooldown, and therefore a larger axial load on the steam generator tubes.

Decay heat was based on the ANS5.1 1979 decay heat standard. In order to maximize RCS cooldown following reactor trip, a 0.95 multiplier on decay heat was used. The 5% reduction was chosen since it is greater than a 2(sigma) uncertainty for thermal fission of U^{235} under equilibrium operating conditions.

FIGURE 6
RPV Nodalization



5.3 2.3.5 Reactor Trip

With an MTC of zero, the reactor power will not increase with the decrease in moderator temperature, so the reactor will trip on low RC pressure. Since this analysis was primarily interested in steam generator tube temperature, a trip setpoint of 1900 psig plus a 30 psi error was used. This limits the amount of energy the core model generates, resulting in a lower primary system temperature during the event. It should be noted that this setpoint results in an earlier trip, which is conservative for tube temperature calculations. For the steam line break event, the trip setpoint will be reached rapidly due to the dramatic overcooling which would occur.

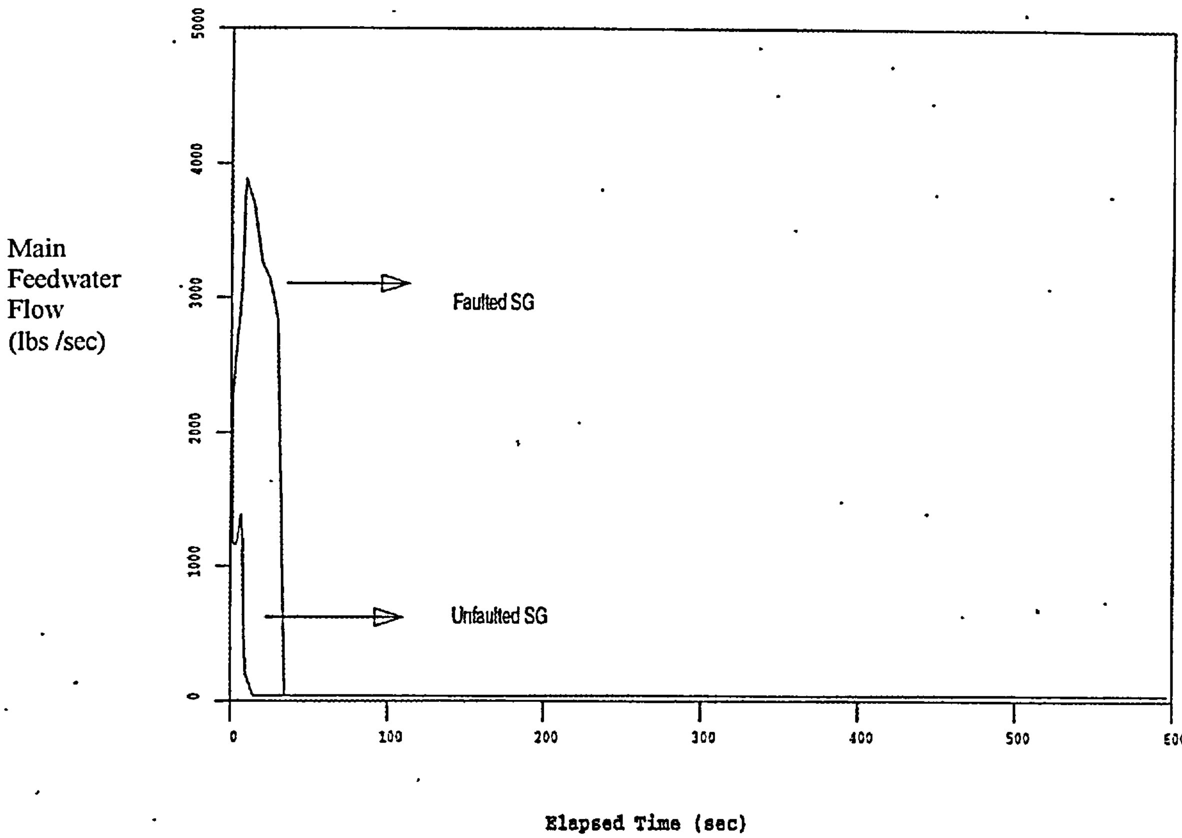
5.3.2.3.6 Initial Steam Generator Mass

The initial steam generator inventory provides a measure of the heat removal capability of the secondary system For a steamline break, a larger initial secondary system inventory in the steam generator associated with the break will lead to a higher integrated heat removal. The larger the heat removal, the lower the resultant reactor coolant temperature. The OTSG design has the maximum inventory at full power conditions. Thus the event should start from full power to maximize the heat removal capability of the steam generator. The steam generator inventory can increase if fouling of the SG tube bundle region occurs The inventory predicted for full power and fouled conditions has been conservatively determined to be approximately 55,000 pounds per SG, and this value was used in the model. In addition, the mass of feedwater between the isolation valves and the affected steam generator, which was calculated to be 35,500 lbm, was also modeled and available to cool the affected steam generator.

5.3.2.3.7 Main Feedwater and Emergency Feedwater Flow

The MSLB accident in this calculation assumed the worst single failure, which is the failure of the feedwater regulating valve to close on the affected generator. This maximizes the overcooling of the event by maximizing the main feedwater

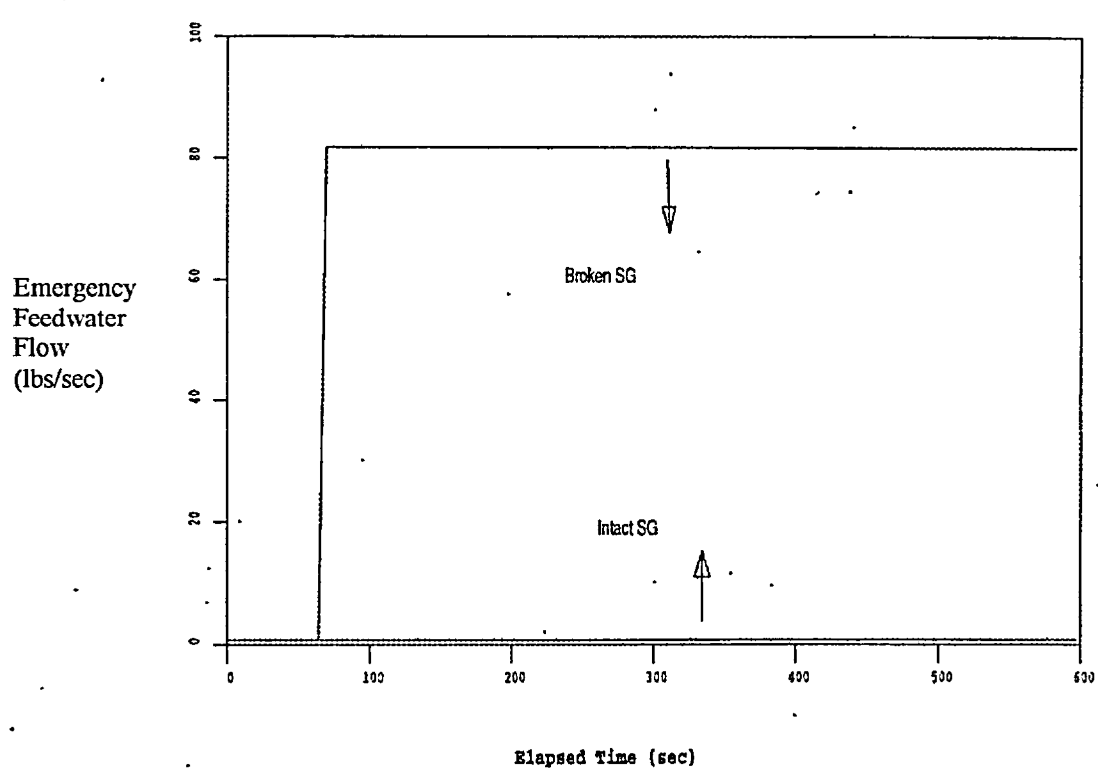
FIGURE 7
Main FeedWater Flow Rates



(MFW) flow to the affected generator as a result of the preferential feeding to the broken, depressurized, side. Feedwater flow to the affected steam generator is shown on Figure 7 above. MFW flow was terminated to the affected steam generator after the MFW block valve closes in about 30 seconds after a low SG pressure of 600 psig is reached.

For this transient, the Emergency Feed Water (EFW) system would be initiated by a low OTSG level signal. The OTSG low level indication signal of 10 inches is measured by the startup range instruments. The setpoint is calculated in the RETRAN model as the collapsed liquid level in the tube region. (Zero inches indicated level is 6 inches above the upper face of lower tube sheet.) EFW controls level at 25 inches indicated. Due to the continued MFW flow to the broken SG until the MFW block valve closes, the OTSG level does not drop below the low level initiation signal until about 67 seconds after the start of the transient.

FIGURE 8
Emergency Feedwater Flow Rates



The start of the motor driven EFW pumps (MDP) is delayed by 5 seconds after the initiation signal and a coastup time of 10 seconds. Subsequent to the EFW initiation signal, the steam admission valve to the turbine driven pump (TDP), MS-V13A, receives an immediate open signal and is fully open in 24 seconds. Turbine testing shows the TDPs are at full speed in 11 seconds after the steam admission valves are full open An additional 8 seconds for flow coastup is typically modeled resulting in TDP flow delivery at 43 seconds.

For this analysis, 2 MDPs and TDP were conservatively assumed to deliver flow instantaneously to the steam generator following an EFW initiation signal (See Figure 8 above)

5.3.2.3.8 High Pressure Injection

The plant's high pressure injection (HPI) system is actuated during the cooldown period following a large area steam line break The system supplies borated water to the RCS to recover the RCS shrink and to provide core cooling if necessary, and to increase the core shutdown margin Boron addition to the reactor coolant, during the controlled cooling to atmospheric pressure, will prevent criticality at lower temperatures. For this analysis, no credit was taken for boron addition resulting from HPI actuation, since the BOL kinetics and best-estimate rod worth will result in keeping the core shutdown. To minimize the primary system temperature, and thus tube temperatures, full HPI was initiated in the model on a signal of 1600 psig plus a 30 psi error at the pressure measurement tap location. This is conservative, since a rapid actuation of HPI will maximize the overcooling.

5 3.2.3.9 Steam Generator Downcomer Modeling

The RCS cooldown was maximized by minimizing the amount of liquid carried over from the steam generator out of the break. To minimize the liquid carryover, the downcomer was modeled with a single bubble rise volume and a large bubble velocity (1E6 ft/sec) which produced less liquid carryover.

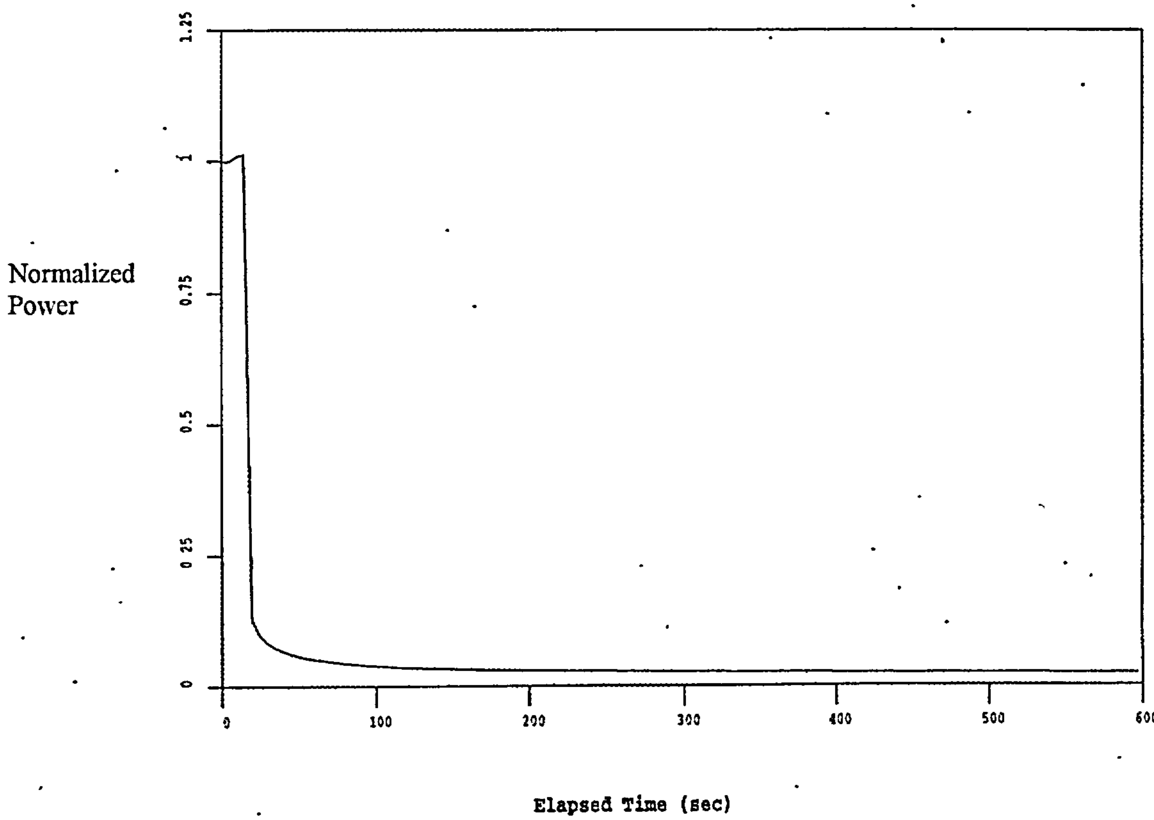
5.3.2.4 Summary of Results

5.3.2.4.1 Power Results

The results of the MSLB analysis for the first 10 minutes (600 sec) are provided in this section. The reactor scram occurs on low reactor pressure in about 10 seconds as shown in Figure 9. This reflects a trip setpoint of 1900 psig plus a 30 psi error.

The reactor power in Figure 9 also indicates that there is no return to power as a result of the absence of a negative moderator temperature feedback. This is a conservative result with respect to the cooldown.

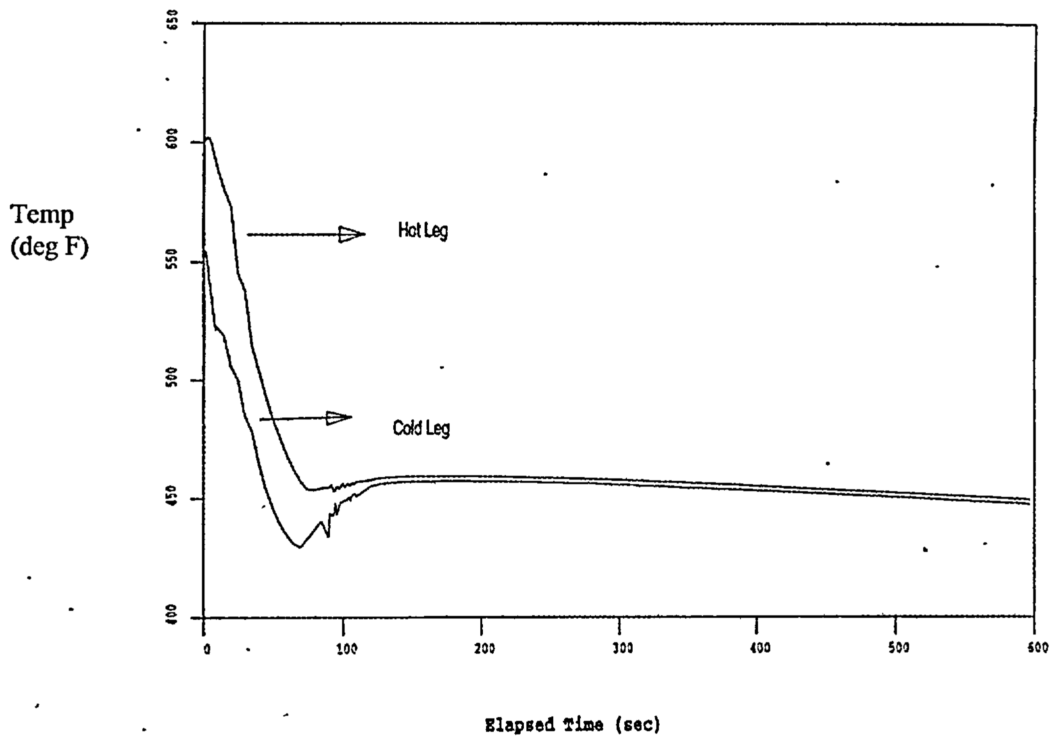
FIGURE 9
Reactor Power



5 3.2.4.2 Loop Temperature Results

The hot and cold leg temperature responses to the MSLB are shown in Figure 10. A rapid overcooling results from the event with the cold leg temperature reaching about 435 degrees F about 70 seconds after the break. After the OTSG blowdown is completed, the primary to secondary heat transfer is reduced and the cold leg and hot leg temperatures are essentially the same The temperature is about 450 degrees F at this point and is maintained for the duration of this portion of the event. The final temperature for this phase of the event reflects the fact that the intact OTSG acts as a heat source as discussed below.

FIGURE 10
RCS Faulted Loop Temperatures



5 3.2.4 3 OTSG Pressure Results

The pressure response results for both the faulted and unfaulted OTSG are shown in Figure 11. The faulted OTSG is fully depressurized in about 100 seconds

The unfaulted OTSG responds initially in a normal post trip manner, increasing to the MSSV setpoint, but is slowly reduced in pressure as a result of reverse heat transfer to the RCS.

5.3 2.4.4 RCS Pressure Results

The RCS pressure results are depicted in Figure 12 and reflect a rapid drop in pressure due to the initial cooldown The decrease in pressure results in a reactor trip, ESAS actuation, and a small influx of Core Flood Tank flow. After the cooldown has stabilized, the RCS repressurizes in response to HPI injection flow refilling the pressurizer. At the end of 10 minutes, the RCS subcooling margin is less than 100 degrees F.

FIGURE 11
Steam Generator Pressure Response

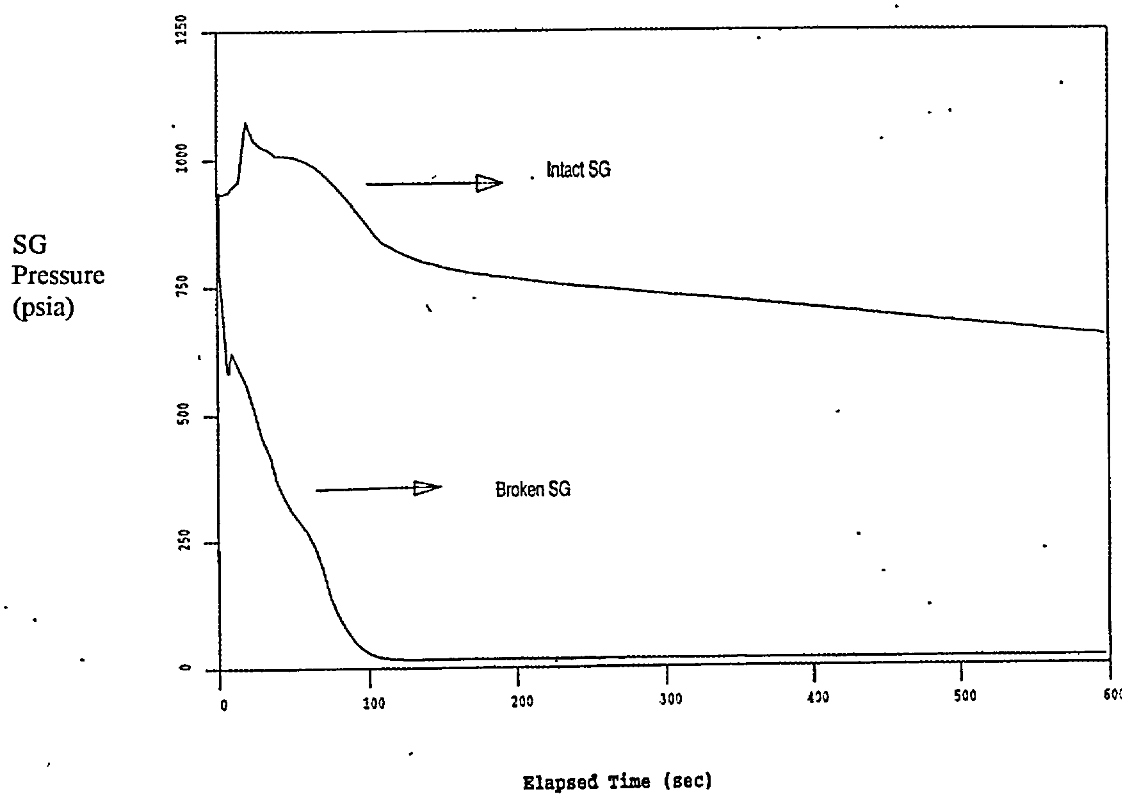
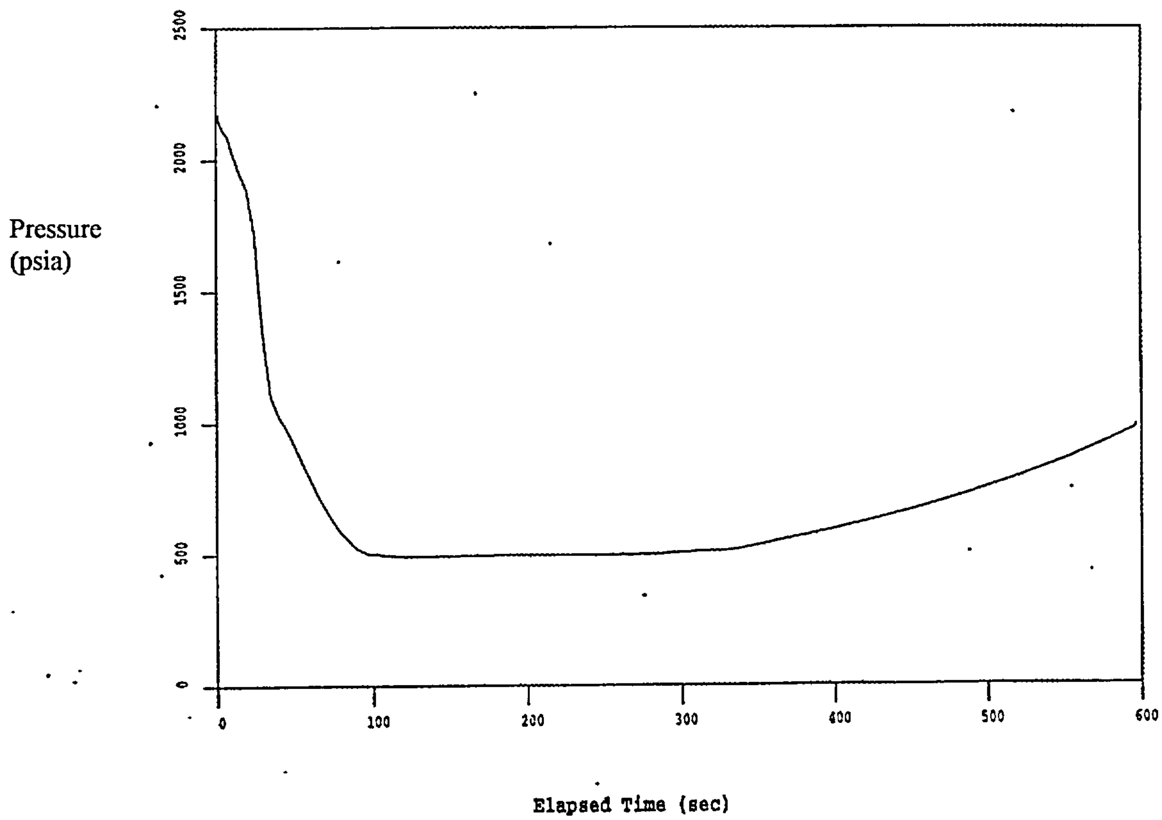


FIGURE 12
Pressurizer Pressure



5.3.3 Long Term Analysis

5.3.3.1 Approach

Following the first ten minutes, it was assumed that operator action would be taken to terminate EFW to the affected OTSG and to begin a controlled cooldown and depressurization to DHR conditions using the unaffected OTSG. The limitations imposed by the various cooldown P-T limits and tube-to-shell differential temperature limits would be observed. The following assumptions reflected this approach.

5.3.3.2 Assumptions

1. The operator will control the NSSS such that the tube-to-shell differential temperature tensile limit of -70°F (tube temp minus shell temp) is observed (Reference 9).

2. RCS temperature will not be allowed to increase to reduce the tube-to-shell differential temperature (Reference 10). Procedure guidance has the operator minimize the RCS reheat following an overcooling event Increasing RCS temperature for this analysis would reduce (i.e., make less negative) the tube-to-shell differential temperature and reduce the tube load. Reduced tube load would lead to reduced tube leakage.

3. RCS pressure will be maintained at a subcooled margin of 75°F. Reference 10 directs the operator to minimize the RCS pressure increase following an overcooling event. The minimum SCM limit is 25°F (Reference 9). An RCS pressure control value of 75°F SCM is reasonable. Higher RCS pressure leads to greater tube leakage

4. As RCS temperature and pressure decrease, additional pressure limitations are established. The operator will maintain RCS pressure in excess of the emergency RCP NPSH limit (Reference 9) A margin of 50 psi is considered to be adequate. A high margin maintains RCS pressure high, increasing tube leakage. However, a large margin to the NPSH curve could prevent initiation of DHR. Therefore, a margin of 50 psi is reasonable. Additionally, the operators will maintain RCS pressure such that the minimum RCP seal differential pressure (275 psid) is maintained (Reference 12). Seal return can be dumped to the sump instead of being sent to the Makeup Tank A margin of 25 psig is maintained to the limit of 275 psid Therefore, a minimum RCS pressure of 300 psig is established.

5. The transient after 600 seconds is quasi-steady-state. Therefore, large time steps could be used in the model. A time step size of 600 seconds was chosen as reasonable.

6. Operator action is assumed to take place at 10 minutes The following actions would be taken by the operator for a MSLB event (Reference 9 and 10):

   a. Terminate EFW to the broken OTSG (MFW is already isolated)

   b. Control/terminate HPI to the RCS to control RCS pressure.

   c. Adjust the TBV on the Unbroken OTSG to prevent RCS temperature from increasing.

5.3.3.3 OTSG Cooldown Analysis

As indicated above, the operator will control the NSSS such that the tube-to-shell differential temperature tensile limit of -70°F is observed. The maximum possible cooldown rate that meets this criterion is established by the rate at which the affected OTSG shell cools down.

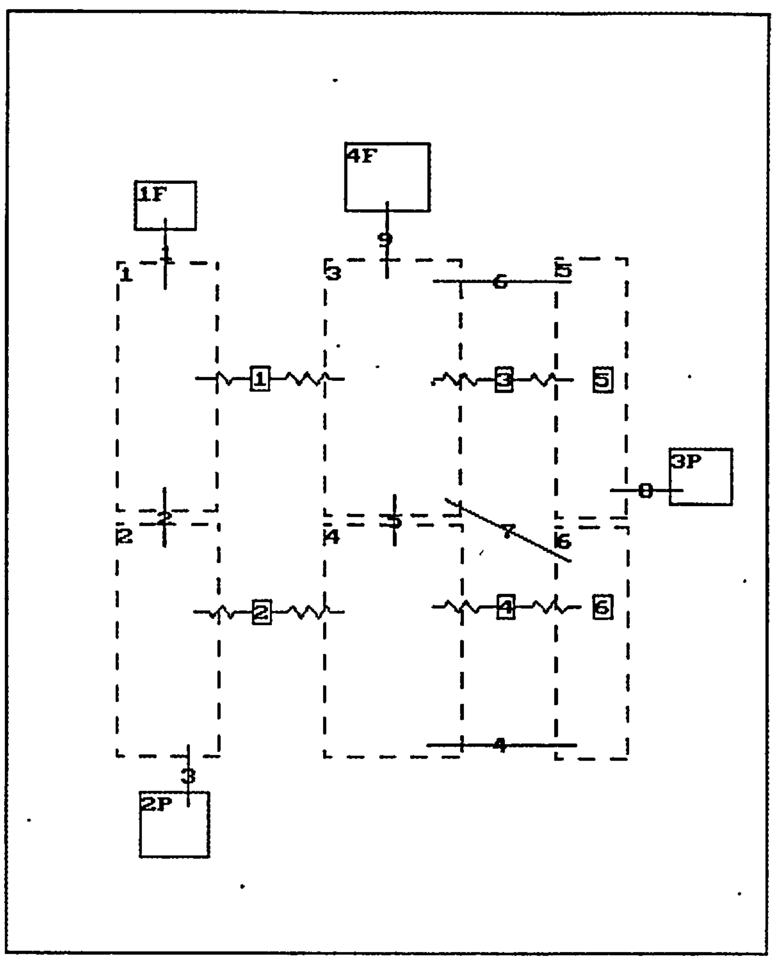
To determine the shell cooldown rate, the GOTHIC computer code, version 5.0e, was used with a six (6) volume model as shown in Figure 13 (Reference 11) Two volumes (volumes 1 and 2) represented the primary (tube) side of the OTSG, two volumes (volumes 3 and 4) represented the secondary (steam side) side of the OTSG shell inside the shroud, and two volumes (volumes 5 and 6) represented the secondary side of the OTSG outside the shroud (i.e., between the shroud and the shell metal). The volumes were divided to correlate with the division of the downcomer region into upper downcomer and lower downcomer regions.

The analysis began at 10 minutes and allowed the RCS to cool down as the shell cooled down to preserve the ~70 deg limit and thus account for the impact of the cooler RCS tube temperature on the cooldown rate of the shell.

The shell cooldown rate results from this analysis are shown in Figure 14 below.

FIGURE 13
GOTHIC Model For Shell Cooldown Analysis

Post-MSLB OTSG Cooldown - Multi-Node SG
Wed Sep 17 09:53:36 1997
GOTHIC Version 5.0(QA)-e - October 1996



5 3.3.4 Results

Figures 14 and 15 below provide the results of the long term analysis. The figures also include data from the first 600 seconds of the analyzed event as well The results reflect the application of the criteria described above. The average shell temperature is a weighted average of the upper and lower shell temperatures at the outside metal surface of the OTSG. The RCS temperature is the average of the hot and cold leg temperatures for the affected OTSG.

FIGURE 14

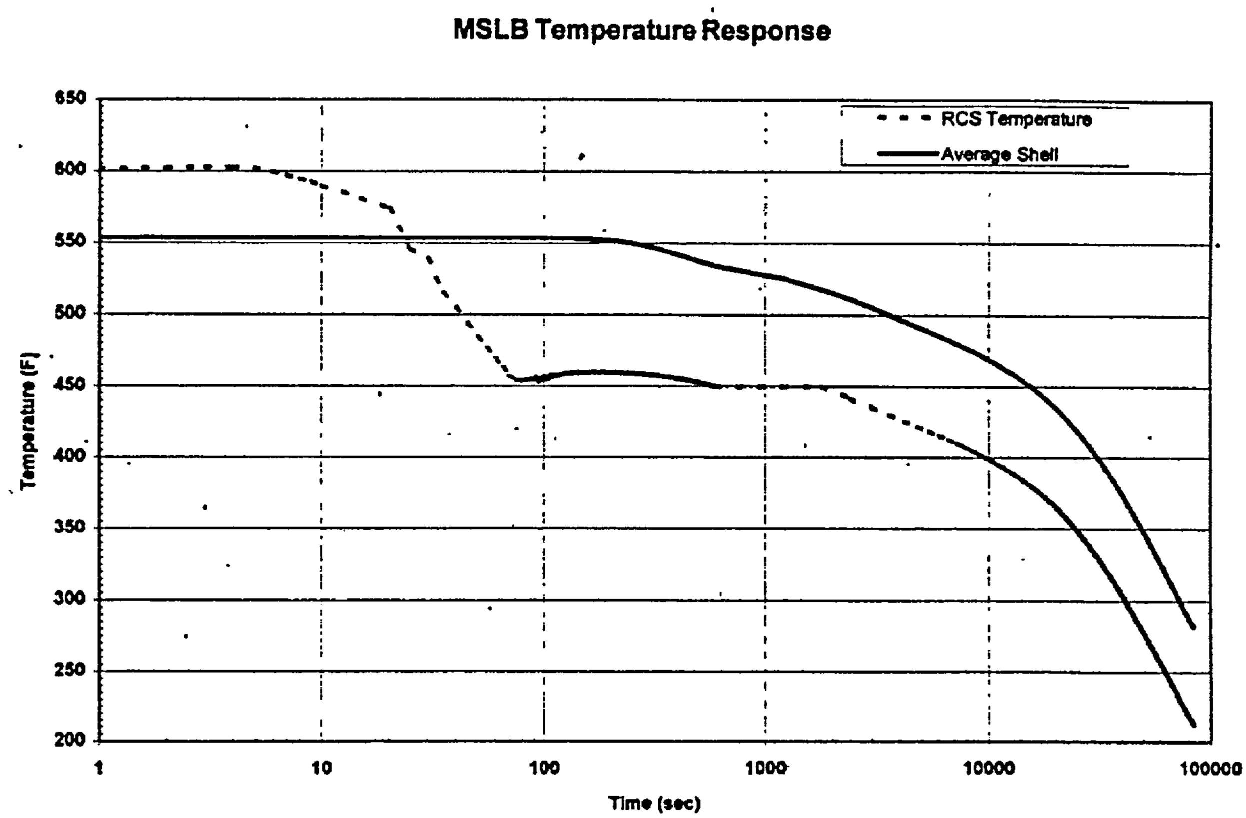
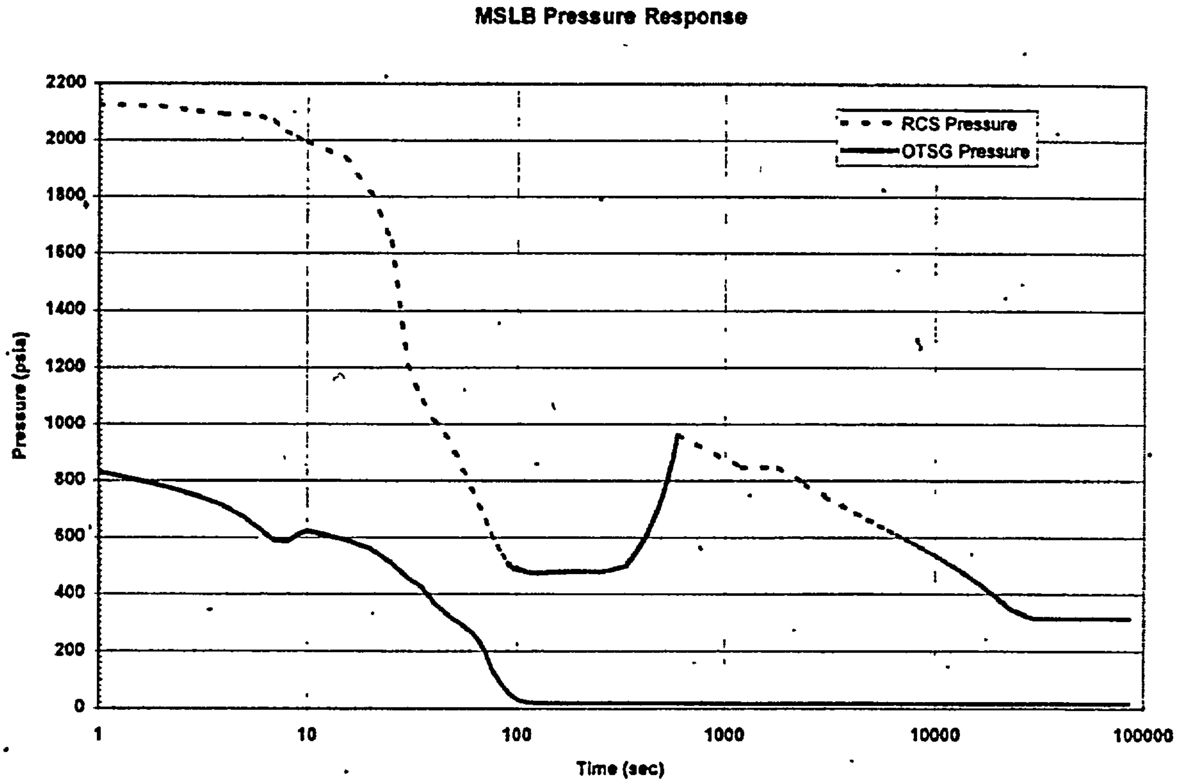


FIGURE 15



5.4 OTSG TUBE LOADS

5.4.1 Introduction

The resulting steam generator tube loads were determined from the T-H parameters provided from the analysis presented in Section 5.3 above. The method of calculating the tube loads evaluated the theoretical tubesheet deflection under a differential pressure and tube axial load and as a function of the different OTSG tube, tubesheet and shell metal temperatures. The resulting pressure and tensile loads were used to determine the leakage area that would develop for a given crack length and orientation as described in Section 5.5 below. Since the thermal hydraulic conditions changed with time, the resulting tube loads also change accordingly. As a consequence of the tubesheet deflection from the center to the periphery, the tube loads varied as a function of the radial distance from the center of the OTSG. In this way, a plot of the tube loads as a function of radial distance from the OTSG center to the OTSG periphery would be different for each set of consistent T-H conditions The discussion below provides an overview of the methodology used by both GPUN and FTI to independently determine the OTSG tube loads using the T-H data in Section 5.3, and a presentation of the results.

5.4.2 Methodology

5.4.2.1 GPUN Methodology

The methodology that was employed by GPUN for the determination of the tube loads is described in Reference 16 and comprised the following steps:

- Establish the tubesheet behavior as a function of applied load and material properties as a function of temperature

- Establish the tube loading (pre-load) in the OTSG as a function of the measured gap between the separated sections of a failed tube at the temperature at the time of measurement The calculation will be based on the assumption that very few tubes have parted so that the loading on the balance of the intact tubes is unchanged

- Separate the three major OTSG components (tubes, shell, and tubesheet) to free components (bodies), remove all loads acting on them and find their unloaded geometry.

- Establish the physical variables that will result in deformation of the free bodies and calculate these deformations, including an accounting for the Poisson effect on the tubes and on the shell.

- Re-combine the deformed free components by pulling the tubes until they meet the final tubesheet location. The final tubesheet location must simultaneously satisfy both of the following conditions:

  - The tubesheet periphery must be at the same location as the shell.

  - The tensile load from all of the tubes must be equal to the shell compressive load

5 4.2.2 Framatome Technologies, Inc. (FTI) Methodology

An ANSYS finite element model of the OTSG was used to determine the tube load contribution for various system operating parameters The ANSYS model was basically identical to the NASTRAN model used in the 'OTSG Tube Topical Report' (Reference 17) The NASTRAN model was converted to ANSYS due to some extra features ANSYS possessed at the time.

The model was an axisymmetric thermal and structural model of the OTSG. The model included the steam generator shell sections, upper and lower heads, upper and lower tubesheets, support skirt, and twelve beams representing twelve effective tube regions The tubesheet model accounted for the material properties which were adjusted to account for the tubesheet temperature and the effects of the perforated plate.

Several different load cases (parameter study) were executed to establish the variation in tube loads due to change in primary pressure, secondary pressure, tube-to-shell delta T (both tubes hotter and cooler than the shell), and average tube temperature. The end result was a series of equations as a function of average temperature and tubesheet radius, that provided the load in the tubes for each of the pertinent system parameters.

Using the postulated MSLB system transient parameters discussed in Section 5.3 above, the total tube loads for the transient, as a function of transient time and tubesheet radius, were determined

5.4.3 Results

5.4.3.1 GPUN OTSG Tube Loads

The GPUN analysis results are provided in Figure 16. This figure shows the OTSG tube loads for three radial positions in the OTSG (Center, Average, and Periphery) as a function of time from the start of the MSLB transient. The peak axial tube load of 1310 lbs occurs 60 seconds into the transient at the periphery of the OTSG. The smallest loads occur at the center of the OTSG tube bundle as was discussed earlier.

5.4.3.2 FTI OTSG Tube Loads

The FTI results (Reference 22) are provided in Figure 17. As can be seen, they were very similar to the GPUN load results. The peak axial tube load was 1135 lbs at 60 seconds and also occurs at the OTSG periphery, with the smallest loads at the center as well.

A comparison of the GPUN and FTI results is provided in Section 5.4.4 below with an explanation for the loads that were used to perform the subsequent tube-to-tubesheet interface pressure and the leakrate analyses (which are described in Sections 5.5 and 5.6).

FIGURE 16

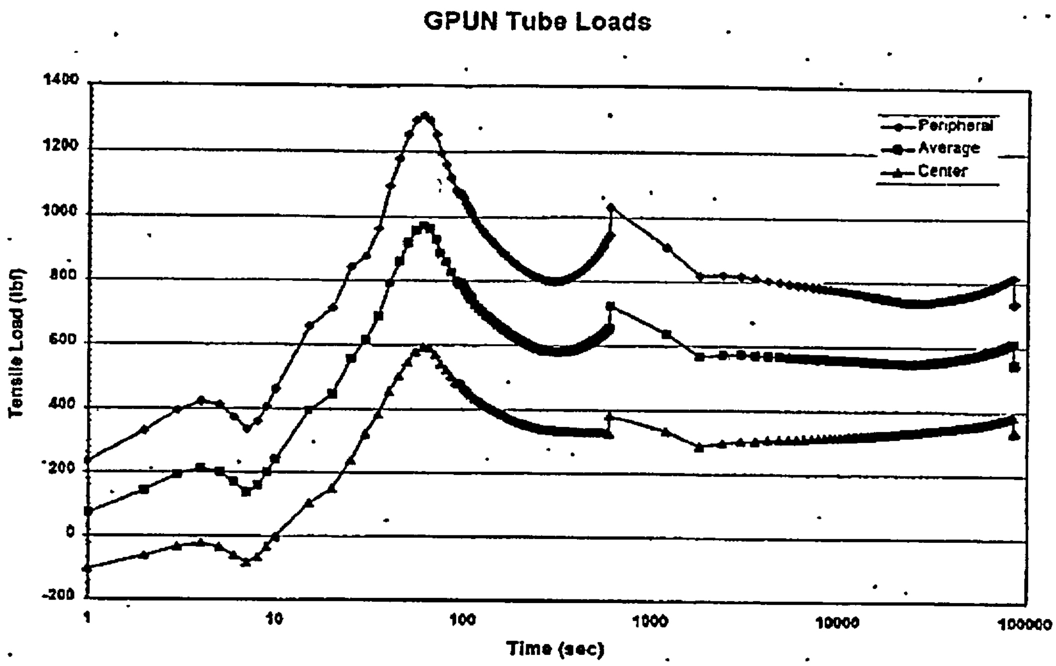
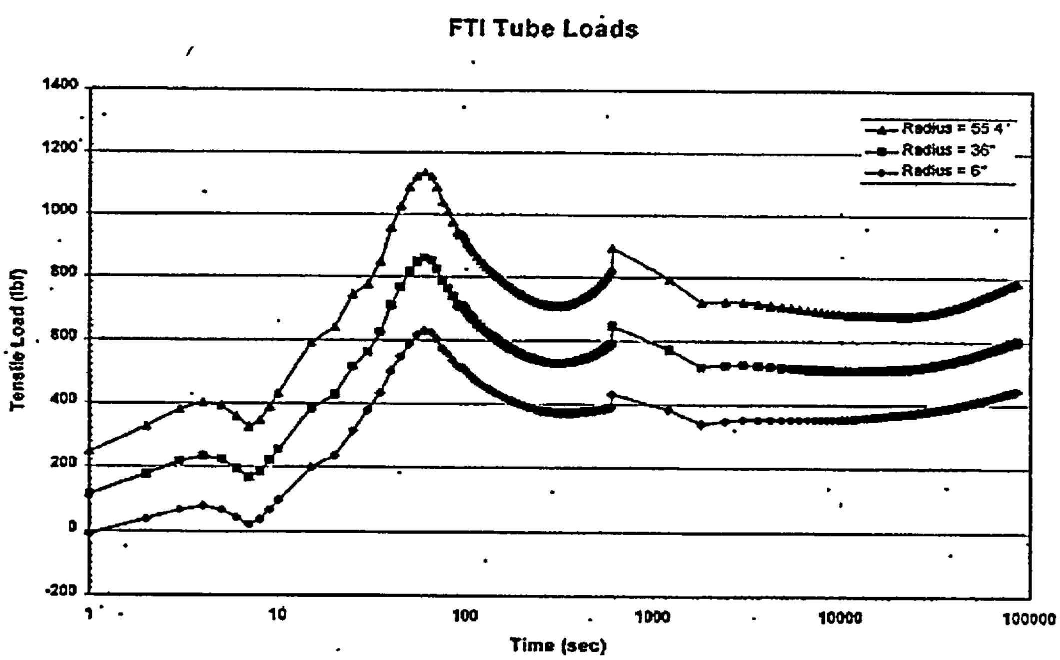


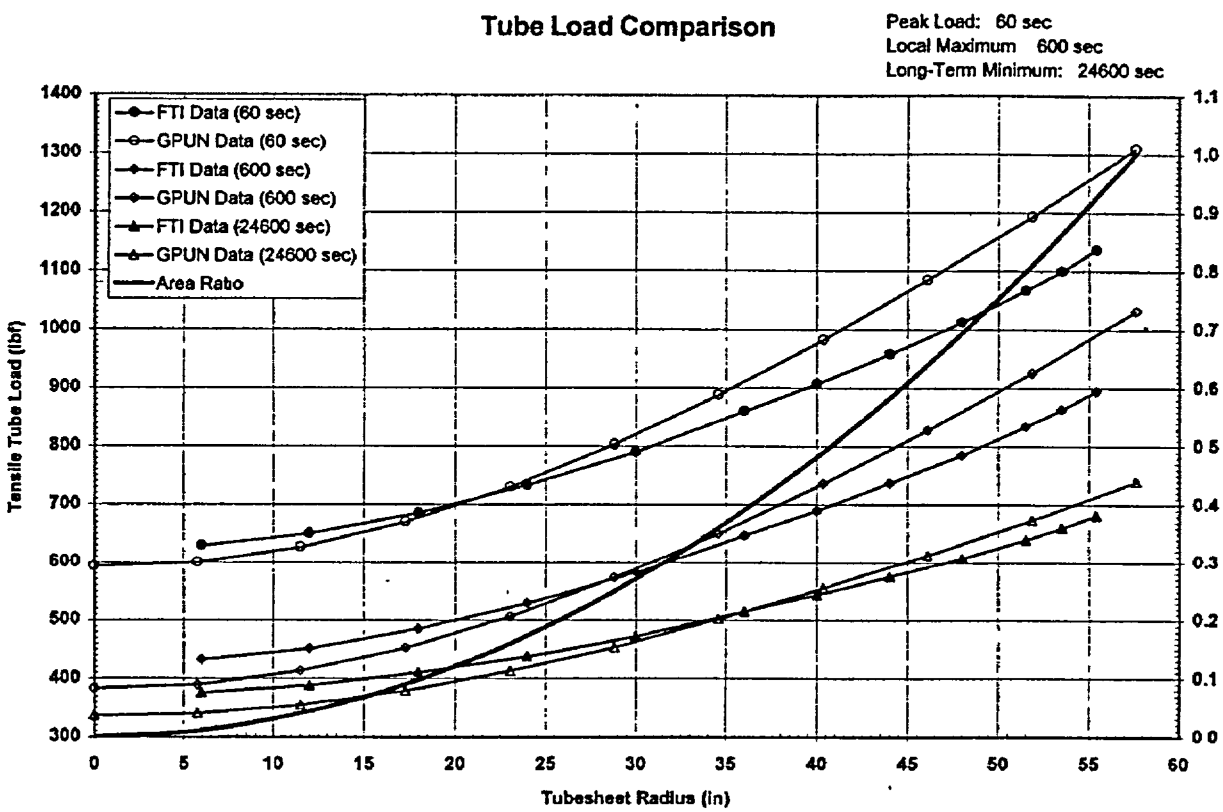
FIGURE 17



5.4.4 Analysis of Loads

Figure 18 provides a comparison of the FTI and GPUN OTSG tube load results. Results are presented for three points in time as a function of radial distance from the OTSG center to the periphery. While the results were very close, it can be seen that the GPUN results tended to be more conservative than the FTI results as radial location (R) increases Similarly, for smaller R, the FTI results were slightly more conservative. The plot of area ratio vs. radial position (right side ordinate axis is the area ratio) shows that there are substantially more tubes at the higher R values than at the lower R values. It was judged that the GPUN results would be more conservative since they would result in higher loads on a greater number of tubes. As a result, for this study, the GPUN-calculated loads were used to perform the subsequent crack area and crack leakage analyses described below.

FIGURE 18



The two sets of independent analyses were confirmatory and demonstrated that the calculated OTSG tube loads are reasonable.

5.5 CRACK AREA DETERMINATION

5.5.1 Introduction

The crack opening area (COA) determination was based upon the methodology provided in Reference 13 and established a method for calculating the crack opening area for through-wall cracks in tubes Primary-to-secondary leakage was calculated using two potential crack orientations in combination with a specific applied load (Reference 14). These were

1 Circumferential Through-Wall Crack in Tension (Note: The contribution of primary pressure is included in the applied tension load)

2. Axial Through-Wall Crack Subjected to Internal Pressure

Using these methods, the user could calculate the crack opening area (COA) for a crack given the specified conditions and use that area to determine the tube leakage (See Section 5.6).

There are conditions particular to the capture of the tube within the kinetic expansion region that separates the COA within the kinetic expansion from the COA for a defect in the free span (Therefore, the subject leakrates calculated for flaws in the kinetic expansion are not usable for flaws in the free span.)

It is arguable whether any COA occurs at all within a kinetic expansion because the tube will not slip or rotate within the expansion Within any expansion region, the tubesheet, due to its proximity alone, guides the tube and prevents rotation at the elevation of a defect that could result in increasing COA In addition, remaining contact pressure on the tube OD surface further provides a friction reaction that prevents bending of the tube that could result in increasing COA.

Therefore, for the purpose of leakage assessment from flaws in the kinetic expansions, COA depends on applied axial tension only because there is no rotation at the elevation of a defect due to remotely applied tension. COA is assumed to develop because of asymmetry local to the section as the symmetrically distributed load comes into equilibrium with the asymmetrical section containing the defect.

NUREG/CR-3464 (Reference 13) provides the solution for COA for circumferential defects in OTSG tubes under applied axial tension The COA for axial defects is also provided. This reference has been widely used in the nuclear industry and, in particular, was the source for COA evaluation for the leak-before-break analysis of RCS piping in B&W plants (Reference 18)

5.5.2 Methodology (Kinetic expansion region)

Reference 13 provided the equations necessary to calculate the crack opening area for circumferential through-wall cracks in tension and axial through-wall cracks subjected to internal pressure The methodology was implemented in Reference 14 and is summarized herein.

5.5 2 1 Circumferential Through-Wall Crack in Tension

The crack opening area as a function of the axial, tensile, tube load was calculated based on the applied axial stress (σ_t), Young's Modulus (E) for the tube material, and a non-dimensional function ($I_t(\theta)$) formulated from the stress intensity factors.

$$A_t = \frac{\sigma_t}{E}\left(\pi R^2\right)I_t(\theta)$$

The applied stress was calculated given the axial tensile load (P) and the mean tube radius (R) with the tube wall thickness (t), or the inner and outer tube radius (R_i and R_o, respectively):

$$\sigma_t = \frac{P}{2\pi Rt} = \frac{P}{\pi\left(R_o^{\ 2} - R_i^{\ 2}\right)}$$

5.5.2.2 Axial Through-Wall Crack Subjected to Internal Pressure

The crack opening area for an axial through-wall crack with internal pressure was calculated based on the membrane stress (σ), Young's Modulus (E) for the tube material, mean tube radius (R), tube wall thickness (t), and a non-dimensional function ($G(\lambda)$) formulated from the stress intensity factors:

$$A = \frac{\sigma}{E}(2\pi Rt)G(\lambda)$$

The applied stress was calculated given the differential pressure (p), mean tube radius (R), and tube wall thickness (t):

$$\sigma = \frac{pR}{t}$$

This methodology was used to calculate the crack opening area for through-wall cracks of tubes with an outer radius to wall thickness ratio (R/t) of less than or equal to 10.0 with no bending moment applied The crack opening areas for R/t ratios of less than 10.0 are conservatively large.

5.6 CRACK AREA LEAKAGE ANALYSIS

5.6.1 Overview

The leakage flow for a given crack area (from Section 5.5) was determined by the PICEP (Pipe Crack Evaluation Program) computer code developed by EPRI (Reference 15) A brief description of the code is provided in this section.

The crack area as a function of time for a given crack length and crack orientation was provided from the analysis described in Section 5.5 above. The T-H parameters were provided in Section 5.3 above. The PICEP code utilizes a crack area, the RCS pressure, RCS temperature, and OTSG pressure at a single point in time and calculates a leak rate through the crack for that specific time In order to develop a leak rate as a function of time, the code has to be run numerous times throughout the MSLB transient duration The PICEP analysis was run at the MSLB transient model data intervals The result was a leak rate as a function of time, which was then integrated to provide a total leakage volume for a given crack. This process was repeated for each type of crack indication at different radial locations within the tube bundle. (See Section 5.7.)

The contact pressure between the expanded tube and the tubesheet causes a significant reduction in leakage. This was determined empirically and the evaluation for this 'leakage reduction factor' (LRF) is provided below. A discussion of the method used to calculate the contact pressure is also provided in this section

5.6.2 Code Description

The PICEP program (Reference 15) was used to calculate the crack opening area, the critical crack length and the flow rate through various sizes and types of cracks in kinetic expansions Options are available to calculate the leakage with a crack area that is supplied by the user. For subcooled or saturated liquid discharge, the critical flow equations are based on the Henry/Fauske homogeneous non-equilibrium critical flow model with modifications to account for fluid friction due to surface roughness, crack turns, and non-equilibrium 'flashing' mass transfer between liquid and vapor phases. The flow was assumed to be isenthalpic and homogeneous with non-equilibrium effects introduced through a parameter, N, which is a function of equilibrium quality and flow path length-to-diameter ratio, L/D.

The PICEP program was used to estimate calculate the theoretical leakage from the axial, circumferential, and volumetric indications in the TMI-1 kinetic expansions. (As described above, volumetric indications are conservatively assumed to result in both a circumferential crack and an axial crack.) The PICEP program predicts the theoretical flow through straight cracks The volumetric morphology of the ID IGA flaws, the predominant flaws within the kinetic expansions, is dissimilar to the morphology of straight cracks. However, given the constraint of the tubesheet, it is very conservative to predict leakage based on the assumption that each volumetric flaw will result in one circumferential, throughwall, straight crack and one axial, throughwall, straight crack.

Numerous inputs were required for the PICEP calculations to estimate the leakage from the kinetic expansion flaws:

- Tensile loads on the tube were set to zero for the axial cracks (since tensile loads tend to tighten these cracks and reduce leakage).

- Surface roughness was set to 0.0002 inches, a value of roughness typical for corrosion-induced cracks.

- No credit was taken for any tortuosity of the crack channel (The number of 45 degree turns was set to zero for the computer code runs)

- Minimum tube wall thickness of 0 034" was assumed.

Validation/benchmarking of the PICEP program was based on a large number of flaws and is described in Appendix C of EPRI NP-3596-SR (Reference 15). PICEP crack flow results were assessed using several sets of leak data including data from EPRI (Battelle Columbus and Wyle Laboratory), NRC (UC Berkeley), Canada (AECL), Italy, and Japan. The types of cracks used for this validation work were varied. For example, PICEP results were compared with flow data from cracks formed by parallel plates, pipes with circumferential cracks, and rectangular slits. Among the test results with which PICEP was compared were those results described in NUREG/CR-3475, "Critical Discharge of Initially Subcooled Water Thru Slits". (The PICEP results showed good agreement with the NUREG's results.) Additional work to benchmark the PICEP code is described in EPRI NP-6897-L, "Steam Generator Tube Leakage Experiments and PICEP Correlations" (Reference 33). In that study the PICEP results were benchmarked against numerous steam generator tube laboratory leak tests (48 leak tests were conducted on I-600 steam generator tube specimens with laboratory-generated flaws)

5.6.3 Leakage Reduction Factor

The leak rates calculated per the above sections provide the expected leakage for a crack in an expanded tube; they take no credit for the presence of only a very tortuous path for leakage between a kinetically-expanded tube wall and the tubesheet bore into which the kinetic expansion was installed. Leakage from flaws located in the expansion will be severely restricted due to the presence of the tubesheet. In order to conservatively quantify a leakage reduction factor to estimate this effect, laboratory testing was undertaken to quantify expected leak reductions. The primary-to-secondary leak rate test results report (Reference 20) provided the basis for identifying a minimum leakage reduction factor (LRF) due to contact pressure between the expanded tube and tubesheet, as well as a justification for neglecting any contribution to leakage from potential defects located further into the expansion than the minimum required inspection distance to assure structural integrity.

Primary-to-secondary leakrate tests were conducted using a bolted split clamp assembly to simulate the presence of the tubesheet adjacent to a tube specimen. Increased tube to clamp contact pressure was achieved by applying increasing torque to the bolts in the assembly. Additional experimental components provided the capabilities to achieve a very wide range of primary and secondary temperatures and pressures, as well as to develop axial tube loads Each OTSG tube specimen contained a small, through-wall, Electro-Discharge Machine (EDM) circumferential notch (EDM notches are less tortuous and smoother walled than typical steam generator tubing cracks; thus the use of EDM notches for leak testing is conservative) By sliding the tube specimen within the clamp, primary-to-secondary leakage could be measured with the notch within the clamp, or with the notch outside the clamp (representing the free-span condition).

The general trend of results showed an expected, dramatic reduction in leakage for a minimum applied contact pressure equal to 500 psi and a minimum leak path length equal to 0 25 inches There was little or no benefit derived from increasing the contact pressure above 500 psi to as much as 3000 psi. It was necessary to remove the influence of tube internal pressure from the test results and isolate only the effect of increasing contact pressure in the derivation of the leakage reduction factor (LRF). This was accomplished by using as a basis for comparison the zero applied contact pressure results, which are representative of the effect of tube internal pressure alone. With this as a basis, the effect of applied contact pressure alone was determined using results obtained for increasing applied contact pressure since the same tube internal pressure was used throughout the tests. It was also necessary to remove the effect of "thermal tightening" from the test results. (The thermal expansion of a heated tube against a colder block representing a tubesheet could have resulted in increased tube-to-block contact pressure.) This was accomplished by testing at cold conditions.

The leakrate for a contact pressure equal to 500 psi was about 1/36th of that for zero contact pressure. Using ASME Code guidance for faulted conditions as a basis for establishing a safety factor, only 70% of maximum capability should be used. Therefore the LRF used for the kinetic expansion leakage estimates is 1/25th or 4E-2. The LRF of 1/25 is associated with a reference EDM notch location 0.25 inches from the edge of the clamp, or, effectively, a 0.25 inch leak path length.

The leakrate test results also suggested that less remaining contact pressure than that used in the test will be equally effective in reducing leakage since there is no benefit from increasing contact pressure to reduce leakage. Leakage reduction is not proportional to the magnitude of remaining contact pressure but is achieved by establishing and maintaining minimal contact pressure, independent of magnitude The leakrate test results indicated that there was almost zero correlation between leakage from tube flaws and changes in joint contact pressure at those flaws. Testing was performed at contact pressures of 500, 1500 and 3000 psi, and leak rates at each of these contact pressures were extremely low in comparison to the no contact pressure case The results suggested that leakage would be reduced at any time where positive contact pressure existed between the tubesheet bore surface and the tube outside diameter surface (i e., conditions where the tube remained in contact with the tubesheet). Intuitively, these results were logical because the presence of tube-to-tubesheet contact should significantly reduce the leakage in comparison to the case where no such contact is present.

Two hundred and fifty (250) psi was used as the threshold contact pressure at which to consider reduced leakage from the joints based upon the following:

--Two hundred and fifty (250) psi is a significant remaining contact pressure for the joint with respect to the zero contact pressure condition (Since a positive contact pressure still exists, the expanded tube is still in close contact with, and pressed against, the tubesheet bore. Thus, any annular space between the expanded tube and the tubesheet bore that might create a leakage path should be very small.)

--Testing with the leaktest apparatus was very conservative because the test apparatus was not "pre-conditioned" by the kinetic expansion pressure to achieve mating surface-to-surface contact between the tube and mockup test block. In the TMI-1 steam generators, the inservice tubing was kinetically-expanded (with an explosive charge) so that the tubing was plastically flattened against the inside surface of the tubesheet bore. Contact pressure greater than yield strength was achieved in the kinetically repaired joint In-service pressures, which are much lower, are actually applied to these surfaces that have been plastically compressed or "flattened". No such effort to plastically expand the tubing against the tubesheet block was attempted for the laboratory leakrate tests to evaluate the LRF. (The compressed surfaces of the kinetic expansions will remain compressed as the applied contact pressure is reduced--in the same manner that bolted, flanged joints remain leaktight until the bolt preload is exceeded by the applied load) The demonstrated leak reduction capability of the test apparatus should be considerably less than the leak reduction capability of the kinetically repaired joint since the latter has the benefit of plastically compressed surfaces.

-In addition, the results of the leakrate tests were conservatively applied to derive the leakage estimates for flaws in the tube-to-tubesheet joint For example, peak axial tensile tube load was applied over the full duration of the laboratory leakrate tests [The axial tube load causes Poisson contraction of the tube within the joint, which tends to decrease the joint contact pressure] The leakrate test results were used to help estimate leakage from flaws over a postulated MSLB event of about 24 hrs duration, while the calculated peak axial loads act upon the joint for approximately one minute. (Peak calculated tube load of 1310 lbs. is reached at t= 60 seconds; calculated loads are less than 1000 lbs. after t=115 seconds.) Thus, in implementing the leakage estimate a large amount of Poisson contraction was assumed over the entire course of the event, while this maximum amount should be present for a only relatively short time during an actual event.

-An additional conservatism is that the 250 psi contact pressure was used only to derive a "minimum location" at which the Leakage Reduction Factor could be applied to project a leakage volume. The leak tests were conducted on flaws that were only 0.25" and 0.325" from the edge of a mockup tubesheet block (i.e., from the "freespan" condition). No credit was taken for additional leakage reduction that might have occurred for flaws that were a larger distance from the edge of the block. In implementing the leakage estimates for the as-found flaws during inspections this results in cases where flaws may have 2 or 3 inches of expanded tubing between the flaw and the transition, but the leakage estimate is the same that would be estimated if the flaw only had 0 25" of expanded tubing between the flaw and the transition

In summary, the leakrate projection performed for flaws present in the kinetic expansions is conservative with the 250 psi contact pressure threshold. Therefore, the criteria for determining whether the LRF may be applied are that the defect must be located at an elevation at which structural analysis results identify a remaining contact pressure at least equal to 250 psi and a leak path length of at least 0.25 inches from the expansion transition. (The analysis results must indicate that both the location of the defect and the entire length of the 0 25" minimum leak path have a contact pressure of at least 250 psi) Table 3 provides a listing of these locations where the LRF may be applied to estimate leakage from a given kinetic expansion indication Table 3 also illustrates those locations where the LRF may not be applied, defects that are not located sufficiently far within the kinetic expansion are evaluated without a LRF.

5.6.4 Contact Pressure Determination

The application of both the leak reduction factor (LRF) discussed above and the crack opening area (COA) solution (Section 5.5) requires an assessment of remaining contact pressure within the kinetic expansion at the location of a flaw. It was necessary that contact pressure be established and maintained so that both LRF and COA were correctly applied to estimate flaw leakage.

For the 17 inch kinetic expansions, for purposes of leakage assessment, analysis results (Reference 19) showed that the minimum contact pressure of 250 psi is established and maintained at all times throughout the expansion regardless of location within the tube bundle. Because of these conditions, use of the LRF is appropriate without exception so long as a leak path length of 0 25" is available.

For the 22 inch kinetic expansions, the analysis results (Reference 19) also showed that minimal contact pressure is established and maintained at all times beginning at the center of the unit at an elevation above the transition equal to 0.86 inches. The tubesheet radial location at which minimal contact pressure is established at the transition begins at 0.2R and the radial location at which 250 psi contact pressure is maintained at the transition begins at 0.36R. The application of the leakage model using the COA solution is appropriate everywhere except for the 22 inch expansion between 0.0R and 0.2R for defect location up to 0.86 inches from the expansion transition.

These implementation criteria for use of the LRF are captured in Table 3, which is used for the leakage assessment determination By using Table 3, a determination can be made whether an LRF can or cannot be used to modify the leakage calculation for a given flaw indication. Leakage assessment of each flaw indication is accomplished given the length of the tube expansion, the radial position of the tube, and the elevation of the flaw indication with respect to the transition location

5.6.5 Leakage from Defects Above the Required Kinetic Expansion Length

Any leakage contribution due to possible defects located further into the expansion than the minimum inspection distance was considered negligible. Established calculation methods for leakage through cracks show that leakage is inversely proportional to the length of the leak path. The experimental results discussed above show a 20% leakage reduction for an additional leak path length of 0.125 inches without applied contact pressure. The minimum inspection length is 2.1 inches above the transition for peripheral tubes There is both a theoretical and experimental basis for assuming that the flow resistance due to 1.975 inches of additional leak path length with applied contact pressure would effectively prevent additional leakage

Estimated leakage from flaws that are located above the $AKEL_{MIN}$ expansion lengths will be very small in comparison with flaws that are located nearer to the expansion transitions In classical equations for laminar flow through a small annular orifice formed by concentric members with circular cross sections - a highly idealized representation of the kinetic expansions in which the tubing was expanded against a drilled tubesheet bore with explosive force - flow is inversely proportional to length of the orifice (Reference 34) Thus, if it was conservatively assumed that a kinetic expansion flaw's leakpath were a concentric annulus, expected leakage from a hypothetical flaw 3.0" into the expansion would be 10% of the expected leakage from an identical flaw located 0.3" into the expansion

Laboratory leak testing that was performed for the kinetic expansion work demonstrated that even a small length (e.g. 0 25") of expansion, even with no contact pressure, will significantly decrease leakage over the "freespan" condition. (This is consistent with established calculational methods for leakage through cracks where leakage is inversely proportional to the length of the leak path, as described above. This is also consistent with leakage evaluations for other types of expanded tube-to-tubesheet joints where leakage resistance is increased with increased length of the joint.) The laboratory leak testing performed for the TMI-1 kinetic expansions also showed a 20% decrease in flaw leak rate with an additional 0 125" length of leak path—even with no applied contact pressure on the leaking flaws within a loose tubesheet mockup block.

The following discussion is also provided for perspective as to the small amount of leakage that might be expected from flaws located above the minimum expansion lengths in comparison to those flaws located near the kinetic expansion. For example, a flaw that is located 0.2" into the expansion (i.e., at ETL + 0.2") is conservatively treated as a "freespan" flaw, and this flaw has a relatively significant leakrate. If this same flaw were located further into the expansion, for example at 1 inch into the expansion at ETL+1.0", its assigned leakrate is reduced (from that expected at the ETL + 0.2" location) by the Leakage Reduction Factor (LRF) of 1/25th If this same flaw were located above the "minimum inspection distance", there would be a minimum of 2.1" of defect free kinetic expansion between the flaw and the expansion transition (since the shortest minimum inspection distance is 2.1"). Considering that the kinetic expansion leakage tests showed that even a small length (0 25") of expansion will restrict leakage by more than a factor of 25 with minimal joint contact pressure, 2.1" of defect-free expansion (with installed contact pressures from the expansion process's plastic deformation of the tubing) should prevent additional leakage. Given the above, the estimated leakage from flaws above the minimum inspected lengths of the kinetic expansions should be very small in comparison to the projected leakrates calculated for flaws nearer to the kinetic expansion transitions. Defects that are located near (i.e , within 0.25" of) the expansion transition, and therefore whose leakage is not reduced by the Leakage Reduction Factor of 1/25, are the dominant contributors to the results of the leakage estimates

5.7 TOTAL LEAKAGE EVALUATION

5.7.1 Overview

This section describes the approach taken to determine the total leakage for the purposes of comparison against the leakage limits. A calculation methodology was developed that integrates the OTSG tube loads with the thermal hydraulic data and analysis needed for leakage through the cracks and combines the results into leakage assessment tables. These calculated leakages are based on implementing the methodology discussed in Sections 5.3 through 5.6 above. Also discussed in this section are the ways in which the unaffected OTSG will be treated since the tube loads are quite different (i.e., smaller) and the steamline is intact.

5.7.2 Leakage Results

A calculation which applied the methodology discussed in earlier sections of this report to calculate the leakrate through a crack in a tube in the tubesheet region of an OTSG was implemented (Reference 21). The crack opening area was calculated based on the tube tensile load or the differential pressure depending on the orientation of the crack. The mass flux was calculated using the PICEP computer program given the crack geometry and the fluid properties as discussed in Section 5.6. The mass flux was converted to a volumetric leakrate based on a reference density (579 degrees F and 2200 psi) and the crack opening area. (This reference density corresponds to the same value as was used in determining the FSAR leakage limits.) The leakage is integrated over a period of 2 hours and for the duration of the MSLB transient. The results of this calculation can be provided by 'binning' of integrated leakage from cracks in the range of sizes for circumferential and axial leakage. The circumferential crack size bins for a given radial position in the OTSG are the same, but the integrated leakage for a given crack size is different as a function of radial position This is necessary for circumferential crack leakage-- but is not necessary for axial crack leakage which is not sensitive to radial position, only differential pressure.

The circumferential crack integrated leakage results, presented as leakage tables according to crack size for 5 concentric, radial "zones" (from the center of the tube bundle to the periphery), are provided in Table 4. For axial cracks, the leakage is provided as crack size bins in Table 4. The bins for all of the circumferential crack tables range from 0.05 inch crack size (.05 inch leakage is used for all cracks from 0.02 to 0.05 inches) through 0.65 inches. Table 4 also provides the leakage calculation results for axial indications up to 1 inch in length In the field all circumferential and axial extents are 'rounded up' to the next 0.05 inch increment. [Note that the circumferential crack integrated leakage 5 bins are slightly different than the 11 bins of the original version of this document. Reference 26 originally placed the results into 11 bins. One of those 11 bins was eliminated since it was for the very center of the steam generator (radius = 0") and there are no tubes at the center of the generators. The remaining 10 bins were combined into 5 bins]

The leak volumes given in Table 4 do not include the application of the Leakage Reduction Factor (LRF). This factor of 1/25 is to be applied on a case-by-case basis as per the guidelines discussed in Section 5.6 4 and illustrated in Table 3 (i.e., a minimum contact pressure and minimum leak path length are required).

As previously described, if an indication is determined to be volumetric, it is treated as two cracks. Each volumetric indication is treated independently as if there were one axial and one circumferential crack of lengths equal to the volumetric flaw's axial and circumferential extent, respectively. It is very conservative to estimate the theoretical leakage from volumetric flaws in the kinetically expanded tubing by considering them as a combination of a 100% throughwall circumferential crack of length equal to the as-called circumferential extent of the volumetric flaw and a 100% throughwall axial crack of length equal to the as-called axial extent of the volumetric flaw. This treatment of the volumetric flaws is conservative for a number of reasons including:

- the fact that the tubing is expanded into the tubesheet and is unlikely to crack axially. (Expansion and deformation of the tube in the hoop direction are prevented by the constraint of the tubesheet.)

- pulled tube examination results from TMI-1 have demonstrated that the MRPC examinations tend to overestimate the extents of the ID volumetric IGA flaws (as a result of the "look-ahead/look behind" effect and the proximity of the ID flaws to the surface-riding coils),

- bending of the tubing is prevented by the presence of the tubesheet. (Crack formation is less likely since movement/displacement of the tubing is severely restricted).

- the presence of the tubesheet prevents formation of a volumetric "hole"; thus only a tortuous flow path through an intergranular flaw surface (similar to a crack) would be expected

5.7.3 Affected OTSG Versus Unaffected OTSG

Since both the affected OTSG and the unaffected OTSG will experience tube loads, leakage is possible from both generators. Since either of the two OTSGs might be the affected one, it is necessary to assume that the OTSG with the greatest volume of estimated leakage is the affected generator.

The leakage from each of the indications has to be summed, and the total leakage for the OTSG can then be compared against the total leakage limits of 3228 and 9960 gallons (at 579 degrees F, 2200 psia) for the 2 hour EAB and 30 day LPZ, respectively, discussed in Section 5.1. Since OTSG tube loads were not specifically determined for the unaffected OTSG, it is necessary (and conservative) to treat the unaffected generator as if it had the same loads as the affected generator. Thus, the same process used for the affected OTSG will be used for the unaffected OTSG. The leakage calculations assume that either steam generator could leak (as if it were the affected generator during an MSLB) and determine the leakage based on the sum of the cracks in that generator without taking credit for the intact steamline of an unaffected generator.

The estimated leakage from kinetic expansions is calculated for each of the steam generators based on outage inspection results. Since either of the TMI-1 steam generators could have been the affected OTSG during a hypothetical MSLB that occurred in the operating cycle prior to the inspection, it is necessary that each of the OTSGs has an "as-found" estimated leakage less than the above leakage limits. Since either of the TMI-1 steam generators could be the affected OTSG during a hypothetical MSLB that occurs during the operating cycle following the inspection and required tube repairs, it is necessary that each of the OTSGs has an "as-left" estimated leakage less than the above leakage limits. (Note that estimated leakage from flaws in the steam generator tubing located in areas other than the kinetic expansions, possible leakage from other tubing repairs, and possible primary-to-secondary leakage during the operating cycle must also be considered in this evaluation of possible leakage versus the steam generator performance criteria limits.)

5.8 LEAKAGE ASSESSMENT METHODOLOGY SUMMARY

The leakage assessment methodology allows for a determination of the leakage that may occur during a Main Steam Line Break (MSLB) event from conservatively assumed through-wall cracks in the kinetic expansions in the upper tubesheets. Eddy current indications with throughwall estimates greater than 67% are assumed to be 100% through-wall cracks that will leak during the MSLB.

The amount of leakage is determined by calculating the leakage area resulting from the MSLB-induced tube loads (differential pressure only for axial cracks), and then calculating the subsequent leakage flow rate and total event integrated leakage for each applicable indication based upon the thermal hydraulic conditions associated with the MSLB event. The estimated leakage for all cracks is compared against 2 hour and event duration leakage limits. These leakage limits for the TMI-1 steam generators ensure that exclusion area boundary and 30 day low population zone doses do not exceed a small fraction of 10 CFR 100 requirements if the MSLB event were presumed to occur.

The implementation of this leakage assessment methodology using OTSG eddy current data provides reasonable assurance that the leakage that could occur during a design basis MSLB from indicated cracks in the kinetic expansion region may be conservatively determined

6.0 INSPECTION CRITERIA AND LEAKAGE ASSESSMENT SUMMARY

The kinetic expansions were installed in the upper tubesheet region of more than 30,000 TMI-1 steam generator tubes in the early 1980's. Finite element analysis modeling has demonstrated that the kinetic expansions are relatively flaw tolerant. These expansions are protected from a number of types of stresses, vibrations, bending, and secondary-side loose parts by the presence of 24" thick tubesheets.

Eddy current inspections of the TMI-1 kinetic expansions are required by the plant's steam generator program This document provides inspection acceptance criteria and a leakage assessment methodology that conservatively disposition kinetic expansion inspection results. Kinetic expansions that contain flaws that might be adversely influenced by MSLB-induced stresses are removed from service under the subject conservative criteria. This document also requires a conservative evaluation of the estimated leakage that might occur from flaws detected within the kinetic expansions

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TABLE 1

INSPECTION ACCEPTANCE CRITERIA FOR OTSG KINETIC
EXPANSION REGION
(REQUIRED EXPANSION LENGTH)

Kinetic Expansion Length	**Radius From Center of Tube Bundle**	**Minimum Defect-Free Kinetic Expansion Length Required $AKEL_{MIN}$**
17”	0.00” – 20.00”	3.4”
	20.01” – 42.00”	3 2”
	42 01” – 46 00”	3 0”
	46 01” – 50.00”	2.7”
	50.01” – 55.00”	2.4”
	> 55.00”	2.1”
22”	0 00” – 20.00”	8.4”
	20.01” – 42.00”	8.2”
	42.01” – 47.00”	8.0”
	47.01” – 50.70”	5.2”
	50.71” – 54.30”	4.2”
	>54.30”	3.2”

TABLE 2

INSPECTION ACCEPTANCE CRITERIA FOR OTSG KINETIC-EXPANSION REGION (FLAW DISPOSITIONING CRITERIA)

Defect Type (Note 1)	Requirement(s)
Axial	The $AKEL_{MIN}$ length (Table 1) of defect-free tubing must be present. For multiple defects, ¼-inch shall be added to the length of each defect, except the first defect. Also, for each circumferential defect, a defect length of ¼-inch shall be added Example Three axial defects are found, with one defect 1-inch long and two defects each ½-inch long. In addition, two circumferential defects are found The effective length of the ½-inch defects is: ½ inch + ¼ inch = ¾ inch The combined length of the three axial defects is: 1-inch + ¾-inch + ¾-inch = 2 ½-inch. The effective axial influence of the two circumferential defects is: ¼-inch + ¼-inch = ½-inch The total length of axial influence is 2 ½-inches + ½-inch = 3inches.
Circumferential	The $AKEL_{MIN}$ length (Table 1) of defect-free tubing must be present For single defects, no defect may be longer than 130 degrees or 0 64 inches. For multiple defects· • If separated axially by less than 1-inch, their length shall be combined, and the total shall be less than 0.64-inch • If separated axially be more than 1-inch, the individual defects shall each be less than 0.64-inch in extent.

NOTES·

1. For volumetric defects, the criteria for axial defects shall be used for the axial length of any volumetric defect, and the criteria for circumferential defects used for the circumferential length of any volumetric defect.

TABLE 3
LEAKAGE ASSESSMENT DETERMINATION

TUBE RADIAL POSITION	LENGTH OF KINETIC EXPANSON AND LOCATION OF DEFECT	LEAKAGE ASSESSMENT METHOD
	17 inch KE	
All locations	ETL + 0.01" TO ETL + 0 25"	USE LEAKAGE TABLE 4
	ETL + 0.25" TO ETL + REQUIRED*	USE LEAKAGE TABLE 4 AND LRF
	ABOVE REQUIRED*	NO LEAKAGE IS ASSUMED
	22 inch KE	
0" to 12.00" (0R TO 0.2R)	ETL+ 0.01" TO ETL + 0 86"	ANALYSIS OR IN-SITU PRESSURE TESTING REQUIRED
	ETL + 0.86" TO ETL + 5.25"	USE LEAKAGE TABLE 4
	ETL + 5.25" TO ETL + REQUIRED*	USE LEAKAGE TABLE 4 AND LRF
	ABOVE REQUIRED*	NO LEAKAGE IS ASSUMED
12 01" to 22.00" (0.2R TO 0 36R)	ETL TO ETL +5.0"	USE LEAKAGE TABLE 4
	ETL + 5.0" TO ETL + REQUIRED*	USE LEAKAGE TABLE 4 AND LRF
	ABOVE REQUIRED*	NO LEAKAGE IS ASSUMED
22.01" or greater (0.36R TO 1.0R)	ETL TO ETL +0.25"	USE LEAKAGE TABLE 4
	ETL +0.25" TO ETL + REQUIRED*	USE LEAKAGE TABLE 4 AND LRF
	ABOVE REQUIRED*	NO LEAKAGE IS ASSUMED

* Required length of expansion for structural integrity (See Table 1)

Table 4
Leakage Assessment Evaluation Data

CIRCUMFERENTIAL INDICATIONS:

Theoretical MSLB Leakage Based on Circumferential Extent

Tubesheet Radius Location of Tube (inches)	Circ. Extent (Inches)	2 Hour Leakage (gal)	Duration Leakage (gal)
0.0 – 11.525	0 - 0.01	0	0
	0.02 - 0.05	0	0.05
	0.06 - 0.10	0.03	0.28
	0.11 - 0.15	0.08	0.85
	0.16 - 0.20	0.18	1.93
	0.21 - 0.25	0.35	3.77
	0.26 - 0.30	0.61	6.66
	0.31 - 0.35	1.01	11
	0.36 - 0.40	1.61	18.21
	0.41 - 0.45	2.63	29.93
	0.46 - 0.50	4.1	47.04
	0.51 - 0.55	6.21	71.34
	0.56 - 0.60	9.14	105.1
	0.61 - 0.65	13.17	151.16
11.526 - 23.05	0 - 0.01	0	0
	0.02 - 0.05	0.01	0.06
	0.06 - 0.10	0.04	0.35
	0.11 - 0.15	0.11	1.07
	0.16 - 0.20	0.24	2.42
	0.21 - 0.25	0.46	4.7
	0.26 - 0.30	0.81	8.3
	0.31 - 0.35	1.34	13.98
	0.36 - 0.40	2.28	24.02
	0.41 - 0 45	3.66	38.99
	0.46 - 0.50	5.64	60.54
	0.51 - 0.55	8.42	90.73
	0.56 - 0.60	12.25	132.12
	0.61 - 0.65	17.43	187.93

Table 4 (Cont'd)

CIRCUMFERENTIAL INDICATIONS:

Tubesheet Radius Location of Tube (inches)	Circ. Extent (Inches)	2 Hour Leakage (gal)	Duration Leakage (gal)
23.051 - 34.575	0 - 0.01	0	0
	0.02 - 0.05	0.01	0.08
	0.06 - 0.10	0.05	0.47
	0.11 - 0.15	0.15	1.42
	0.16 - 0.20	0.34	3.22
	0.21 - 0.25	0.65	6.25
	0.26 - 0.30	1.15	11.08
	0.31 - 0.35	2.05	20.02
	0.36 - 0.40	3.41	33 81
	0.41 - 0.45	5.4	53.99
	0.46 - 0.50	8.19	82.54
	0.51 - 0.55	12.04	121.84
	0.56 - 0.60	17.25	174.88
	0.61 - 0.65	24.18	245.4
34.576 - 46.1	0 - 0.01	0	0
	0.02 - 0.05	0.01	0.11
	0.06 - 0.10	0.07	0.63
	0.11 - 0.15	0.21	1.9
	0.16 - 0.20	0.47	4.3
	0.21 - 0.25	0.92	8.35
	0.26 - 0.30	.1.74	15.93
	0.31 - 0.35	3.05	28.43
	0.36 - 0.40	4.99	47.19
	0 41 - 0.45	7.76	74.12
	0.46 - 0.50	11.6	111.51
	0.51 - 0.55	16.79	162.14
	0.56 - 0.60	23.69	229.5
	0 61 - 0.65	32.78	318.02
46.101 - 57.625	0 - 0.01	0	0
	0.02 - 0.05	0.02	0.14
	0.06 - 0 10	0.1	0.84
	0.11 - 0.15	0.29	2.5
	0.16 - 0.20	0.64	5.65
	0.21 - 0.25	1.32	11.51
	0.26 - 0.30	2.5	22.24
	0.31 - 0.35	4.31	38.98
	0.36 - 0.40	6.94	63.64
	0.41 - 0.45	10.64	98.41
	0.46 - 0.50	15.67	145.89
	0.51 - 0.55	22.37	209.32
	0.56 - 0.60	31.18	292.75
	0.61 - 0.65	42.65	401.91

Table 4 (Cont'd)

AXIAL INDICATIONS:

Theoretical MSLB Leakage Based On Axial Extent

Axial Extent (Inches)	2 Hour Leakage (gal)	Duration Leakage (gal)
0 - 0.01	0	0
0.02 - 0.05	0.01	0.02
0.06 - 0.10	0.04	0.13
0.11 - 0.15	0.12	0.45
0.16 - 0.20	0.31	1.19
0.21 - 0.25	0.7	2.73
0.26 - 0.30	1.53	5.72
0.31 - 0.35	3.14	11.21
0.36 - 0.40	5.81	20.49
0.41 - 0.45	9.87	36.51
0.46 - 0.50	15.64	61.2
0.51 - 0.55	23.45	96.42
0.56 - 0.60	33.61	144.31
0.61 - 0.65	46.45	206.92
0.66 - 0.70	62.33	286.28
0.71 - 0.75	81.64	384.43
0.76 - 0.80	104.81	503.54
0.81 - 0.85	132.33	646.46
0.86 - 0.90	164.68	815.41
0.91 - 1.00	245.97	1238.97

Table of Acronyms

AECL	Atomic Energy of Canada, Ltd
AKEL	Axial Kinetic Expansion Length
ASME	American Society of Mechanical Engineers
ATP	Abnormal Transient Procedure
BOL	Beginning of [Core] Life
CFR	Code of Federal Regulations
COA	Crack Opening Area
DHR	Decay Heat Removal
EAB	Exclusion Area Boundary
ECT	Eddy Current Test
EDM	Electro-Discharge Machine
EFW	Emergency Feed Water
EPRI	Electric Power Research Institute
ESAS	Engineered Safeguards Actuation System
ETL	Expansion Transition Location
F	Fahrenheit
FSAR	Final Safety Analysis Report
FTI	Framatome Technologies, Inc.
GPU	General Public Utilities
GPUN	GPU Nuclear Corp
HF	High Frequency
HFP	Hot Full Power
HPI	High Pressure Injection
ID	Inside Diameter
IGA	InterGranular Attack
LCL	Lower Confidence Limit
LPZ	Low Population Zone
LRF	Leakage Reduction Factor
MDP	Motor Driven Pump
MFW	Main Feed Water
MRPC	Motorized Rotating Pancake Probe
MSIV	Main Steam Isolation Valve
MSLB	Main Steam Line Break
MSSV	Main Steam Safety Valve
MTC	Moderator Temperature Coefficient
NDD	No Detectable Degradattion
NDE	Non-Destructive Examination
NODP	Normal Operating Delta Pressure
NPSH	Net Positive Suction Head
NRC	Nuclear Regulatory Commission
NSSS	Nuclear Steam Supply System
OD	Outside Diameter
OTSG	Once-Through Steam Generator
PICEP	Pipe Crack Evaluation Program
P-T	Pressure-Temperature
PWSCC	Primary Water Stress Corrosion Cracking
R	Radius
RAI	Request for Additional Information

RCP	Reactor Coolant Pump
RCS	Reactor Coolant System
RPS	Reactor Protection System
RPV	Reactor Pressure Vessel
SCC	Stress Corrosion Cracking
SCM	Sub-Cooling Margin
SG	Steam Generator
TBV	Turbine Bypass Valve
TDP	Turbine Driven Pump
T-H	Thermal-Hydraulic
TMI	Three Mile Island
TMI-1	Three Mile Island, Unit 1
UFSAR	Updated Final Safety Analysis Report

ATTACHMENT B

RESPONSES TO PRIOR NRC ISSUE / QUESTIONS

RESPONSES TO PRIOR NRC ISSUES/QUESTIONS

The following are responses to NRC issues or questions regarding previous submittals on TMI-1's kinetic expansion acceptance criteria. These issues are those identified in the NRC's letter of August 24, 2001. (Reference 1). (Note that, where possible, we have provided the NRC's wording in italics. Note also that the numbering of the questions below does not correspond with any numbering in Reference 1.)

Question 1

Reference 1 states, "*Explain whether LBB was credited at TMI-1 when the design of the kinetic expansion was developed. If so, this is inappropriate. Explain why the joints are acceptable for operation given the possibility of an LBLOCA in the candy cane region of the main coolant loop.*"

Response

Leak-Before-Break (LBB) was not credited at TMI-1 for the 1980's design of the kinetic expansions. The design of the kinetic expansion included an assessment of the strength of the joints during a postulated hot leg LOCA. GPU Nuclear Technical Data Report 007 (GPUN-TDR-007; Reference 5) included a review of the kinetic expansion joint during postulated LOCA conditions. For example, the following is stated on Page 2-26 of that report regarding the effect of a postulated hot leg LOCA on the kinetically-expanded joints:

> "...Because of the higher coefficient of thermal expansion of the Inconel tube, interference increases with temperature. The only case that would cause decreased interference is a large, rapid decrease in primary coolant temperature, which would cause the tube to cool faster than the tubesheet. This does not occur during any normal or upset condition transient. In fact, it occurs only during a hot leg LOCA, and analyses have determined its effect on joint interference and strength. The conclusion is that the delta T does not reduce the interference of the joint to an unacceptable level at any time..."

GPU Nuclear Technical Data Report (TDR) 007 was submitted to the NRC and was Reference #6 of the NRC's NUREG 1019 (Reference 2), the safety evaluation for the kinetically-expanded tubing joints. (Refer to responses to questions #2-4 below for additional information regarding the kinetic expansions during postulated LOCAs.)

Question 2

Reference 1 states, "*Recently, the B&W Owners Group submitted a risk-informed analysis to the NRC which included a topical report BAW-2374, "Risk Informed Assessment of Once-Through Steam Generator Tube Thermal Loads due to Breaks in Reactor Coolant System Upper Hot Leg Large Bore Piping," dated March 2001, supporting, in part, the LBLOCA aspect of the licensing basis for steam generator tube loading in B&W plants. Is TMI-1 covered by this topical report, especially for the kinetic expansion joints? Is the licensee planning to submit a risk-informed amendment request to revise TMI-1's licensing basis, referencing this topical report?*"

Response

Note that, as described in the preceding response to question #1, hypothetical hot leg LBLOCA loads were addressed during the original 1980's design review of the TMI-1 kinetic expansion joints. TMI-1 is a member of the B&W Owners Group and the TMI-1 plant's steam generators, including kinetic expansions, are covered under topical report BAW-2374.

TMI-1 desires that the hot leg LBLOCA issue be addressed under the BAW-2374 submittal since, as described in Section 2.0 of BAW-2374, there are many aspects of the TMI-1 Once-Through Steam Generators (e.g. tube repair products, replacement steam generator design) affected by the LBLOCA issue.

AmerGen is not currently planning to make an additional submittal referencing Topical Report BAW-2374. However, it may be necessary for AmerGen to make an additional submittal, pending the NRC's review of that report.

Question 3

Reference 1 states: "*Describe the analyses that have been performed to demonstrate that the kinetic expansion joints and the potential defects identified and left in service in this region are acceptable for the range of design basis accidents (including LOCA and MSLB).*"

Response

There were a large number of analyses and tests performed to demonstrate that the kinetic expansion joints are acceptable. NUREG-1019 (Reference 2), Section 3.4 contains a summary of the analyses and tests conducted for the original qualification of the joints. These tests included axial load testing, thermal and pressure cyclic loading tests, analyses of tube operational and vibrational characteristics, residual stress analyses, leak tests, mechanical integrity tests, and fatigue tests.

Since the installation of the kinetic expansion additional analyses have been performed to qualify the joints for an extended period of time. (The original analysis for the fatigue life-cycle of the joints was for a duration of 5 years.) Additional analyses were performed to verify that the joints had an expected fatigue life that would allow the joints to be used through 2014, the current license expiration date for the TMI-1 plant. Additional analyses were also performed to evaluate the flaw tolerance of the kinetic expansion joints. (The joints are relatively flaw-tolerant since they are captured within the tubesheets.) These analyses were forwarded to the NRC in References 9 and 12, and were the basis of the kinetic expansions' MRPC examination acceptance criteria used during the plant's 1997 (12R), 1999 (13R), and 2001 (1R14) refueling outages (References 6,7,8).

Question 4

Reference 1 inquires, "*Notwithstanding the above discussion, has the potential for thermal loads during the bounding LBLOCA been considered when evaluating the potential defects identified and left in-service in this region?*"

Response

LBLOCA loads, as described above, were considered during the original design analyses of the kinetic expansions. However, the most recently calculated LBLOCA thermal loads have not been used to evaluate structural integrity of the kinetic expansions. Technical justification for not considering the most recent LBLOCA thermal loads is provided in BAW 2374, Revision 1, "Risk-Informed Assessment of Once-Through Steam Generator Tube Thermal Loads Due to Breaks in Reactor Coolant System Upper Hot leg Large-Bore Piping."

Question 5

Reference 1 cites the following as an inconsistency : "*...The licensee initially states that the kinetic expansion inspection criteria identify the minimum required "defect-free" kinetically expanded tube that must be present within the inspected distance for axial flaws. However, Table 3-5 in MPR-1820, Revision 1, which contains a comprehensive summary of the inspection acceptance criteria, identifies the inspection acceptance criteria for the OTSG kinetic expansion region in terms of "allowable defect length." These two criteria are utilized in discussions throughout the documents. During discussions with the NRC staff, the licensee has stated that the criteria do not conflict and are simply two different ways of expressing the same concept. The licensee also indicated that the "defect-free" concept is that which is used in the field. The NRC staff believes that without adequate explanation, this issue leads to confusion. In addition, when this issue is combined with the other inconsistencies identified below, the intended inspection and acceptance criteria are even less clear.*"

Response

Table 3-5 in MPR-1820, Revision 1, (an Attachment to Reference 11) provides results of analyses that were based on finite element modeling of a 5.5" kinetic expansion length plus a 0.5" expansion transition. [Note 4 of that table states, "These criteria are only applicable for the fully-expanded region from 0.5" to 6" above the bottom of the kinetic-expansion joint." The length of the kinetic expansion transitions at the bottom of the kinetic expansions is approximately 0.5".] Table 3-5 provides "allowable defect lengths" within the 5.5" fully expanded length. For example, for a given tube location Table 3-5 may report that the allowable defect length is 4.4". Another way to state this is that a minimum of (5.5" minus 4.4", or) 1.1" of the kinetic expansion must be "defect free". In summary, the "required defect-free" lengths of the kinetic expansions, based on the finite element analysis, is the 5.5" modeled length of the kinetic expansions minus the calculated "allowable defect length".

Note that the expansion transition (i.e., the first 0.5") is considered freespan for indication disposition purposes. The original design included the expansion transition in the 6" defect-free zone measurement. The expansion transition is now considered equivalent to freespan tubing for the purposes of inspection.

Note also that TMI Unit 1 uses lengths more conservative than those calculated in the MPR-1820 report's analysis model in order to account for examination uncertainties. (These lengths are given in Table 1 in Response #6 of this submittal.)

TMI Unit 1 has found that the "defect-free" concept is more useful for field application than the allowable defect length. For example, suppose a kinetic expansion has a required defect-free length of 3.4". An eddy current analyst reviews the data from that kinetic expansion and if no flaws are detected over the lower 3.4" length of that kinetic expansion then there is sufficient defect-free expansion length to conclude that the expansion's integrity is intact.

If any flaws are detected within a kinetic expansion, the eddy current analysts document the locations, measurements, and types of flaws within the expansions. Evaluation of the flaws with respect to the repair criteria, and leakage estimates, are performed by the plant's engineers.

Question 6

Reference 1 states, "*The licensee states that the structural criteria are based on 6 inches of the kinetic expansion. This would imply that inspection data is routinely collected and assessed on 6 inches of the kinetic expansion. However, the licensee has verbally stated that the actual field practice is to only inspect/assess the minimum distance necessary to identify adequate "defect-free" tubing. This is not clearly documented.*"

Response

The original 1980's installation of the kinetic expansions was based on a 6" length (e.g. 6" of defect-free material based on a bobbin coil probe examination was required *before* a kinetic expansion was installed), therefore much of the written material has referred to the kinetic expansions as 6" long. In actual practice the in-service tubes were fully expanded to kinetic expansion lengths of either 17" or 22" depth in the upper tubesheets.

As described in the response to question 5, above, the finite element analysis that was used to evaluate the flaw tolerance of the kinetic expansions was a 6" long model (consisting of 5.5" of fully expanded tubing and a 0.5" transition.)

As described above, TMI-1 uses required kinetic expansion lengths that are conservative and are longer than those defined by the analysis model. TMI inspects and dispositions only these required expansion lengths. (Refer to Table 1, below.) A TMI-1 eddy current analyst reviews the tube's MRPC signal to locate the top of the kinetic expansion transition (i.e., that point where the tube is fully kinetically expanded against the tubesheet bore). This point is designated by the eddy current analyst as ETL+0.00". (ETL = Expansion Transition Location) The analyst reviews the eddy current signals from the fully-expanded section; if no flaws are detected over the minimum required defect free length then the tube is dispositioned as "NDD" (i.e., No Detectable Degradation). If a flaw is detected, it is characterized, located with respect to the ETL+0.00" reference point, and additional kinetic expansion length is reviewed by the analyst to detect/characterize any other flaws that might be present. If the additional analyzed length contains flaws such that sufficient defect free tubing is not identified, the tube is repaired. If the additional kinetic expansion length is analyzed and sufficient defect free tubing length is identified, the expansion then may be left in service (provided it meets all other criteria to remain in service).

TABLE 1
Minimum Axial Kinetic Expansion Length Values

Kinetic Expansion Length	Radius From Center of Tube Bundle	$AKEL_{min}$ (inches)
17"	0.00" – 20.00"	3.40"
	20.01" – 42.00"	3.20"
	42.01" – 46 00"	3.00"
	46.01" – 50 00"	2 70"
	50.01" – 55.00"	2.40"
	>55.00"	2.10"
22"	0.00" – 20 00"	8 40"
	20 01" – 42.00"	8 20"
	42 01" – 47.00"	8.00"
	47.01" – 50.70"	5.20"
	50 71" – 54.30"	4.20"
	>54.30"	3.20"

In summary, the inspections determine whether the conservatively calculated minimum kinetic expansion length is present and "defect free". If this length is present and defect free, then no further eddy current analysis is performed. No further eddy current analysis is needed once the required kinetic expansion length has been established by acceptable inspection results.

It should be noted that the above discussion pertains to the evaluation of the kinetic expansions (i.e., fully expanded tubing). During the examinations the kinetic expansion transitions are also examined with the MRPC probes, evaluated for the presence of flaw indications, evaluated as freespan tubing, and repaired if required.

Figure 1, which follows, provides an illustration of a typical kinetic expansion.

17" KINETIC EXPANSION (TYPICAL)

(NOT TO SCALE)

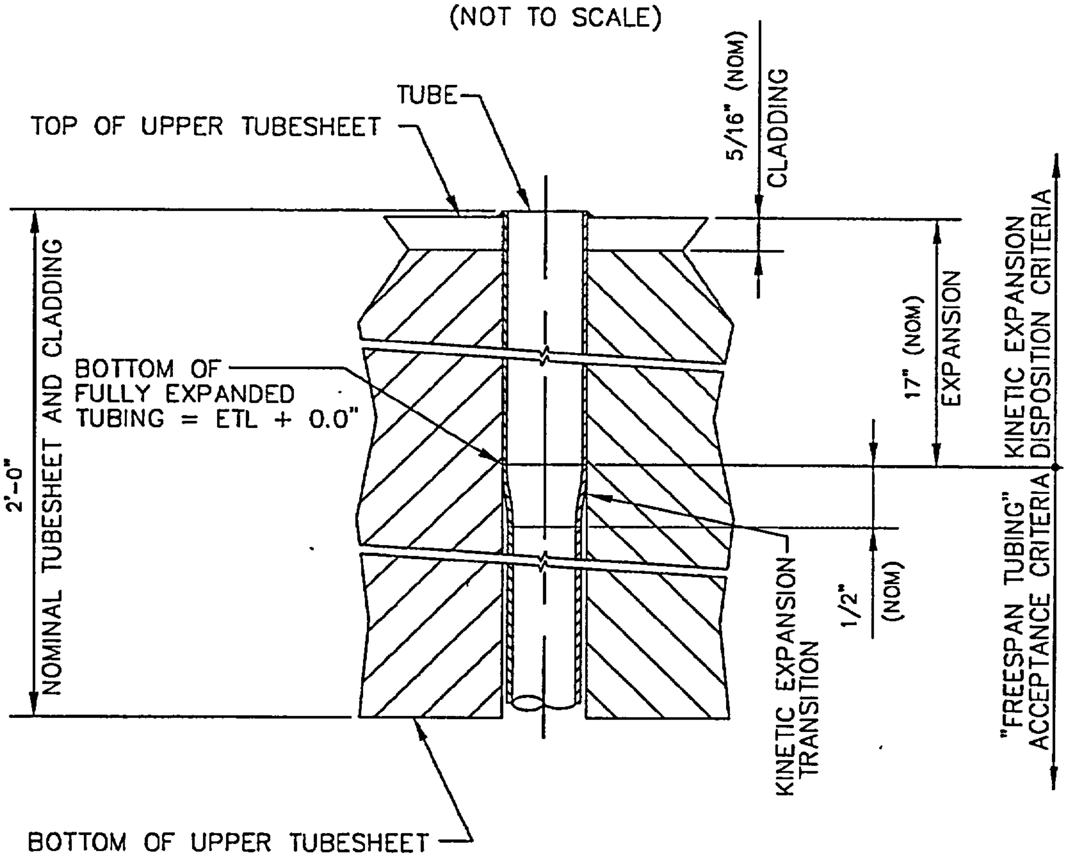


FIGURE 1

Question 7

Reference 1 states: *"Footnote (4) to Table 3-5, in MPR-1820, Revision 1, states that the inspection acceptance criteria are only applicable for the fully-expanded region from 0.5 inch to 6 inches above the bottom of the kinetic expansion joint. The staff identified two issues with this statement:*

The table identifies allowable defect length. Is the allowable defect length within the 6-inch distance or within the 5.5-inch distance. For example, the allowable defect length for an axial flaw in a tube in the periphery is 4.4 inches. Therefore, when applied in the field, is the "defect free" length 1.6 inches or 1.1 inches?

Do the criteria apply to the entire 6 inches if the inspection region does not include the expansion transition region (e.g., 22-inch kinetic expansion located in the mid-radius or center of the bundle)?"

Response

For the first issue identified above, with respect to the structural analysis model of the kinetic expansions, the "defect free" length is 1.1 inches. This length is based on structural analysis only and does not consider examination uncertainties. For the inspection acceptance criteria additional length was added to the dimensions calculated in MPR-1820, Revision 1 to conservatively account for the expected uncertainty in locating eddy current indications along the axial length of the kinetic expansion with respect to the ETL + 0.00" reference point, and the uncertainty in locating the ETL + 0.00" reference point itself. When applied in the field the minimum "defect free" length is 2.1" for a peripheral tube. TMI Unit 1 designated a "minimum axial kinetic expansion length" (AKELmin) for each tube in its generators based in part on MPR-1820, Revision 1. (These were submitted to the NRC in Reference 6 and are listed in Table 1, above.)

Regarding the second issue, the inspection of a kinetic expansion always includes a concurrent inspection of its transition. (This is required by the plant's eddy current guidelines and is also necessary to determine the location of the ETL+0.00" reference point as described above.) All kinetic expansion examination results are referenced to the ETL+0.00" reference point at the top of the expansion transition. All minimum axial kinetic expansion lengths (for both 17" and 22" expansions) are measured from the ETL+0.00" reference point.

Question 8

Reference 1 states, "*Based on several references in documented material, it is not clear if the inspection criteria apply to the 6 inches beginning at the bottom of the expansion transition region, or from the point beginning at which the tube is fully expanded. The licensee verbally stated that the structural criteria were developed with the 6 inches beginning at the bottom of the expansion transition region. However, in the field they conservatively measure the 6 inches beginning at the fully expanded region. The docketed information alludes to two different inspection areas; however, this distinction is not clearly identified.*"

Response

The kinetic expansion acceptance criteria apply only to tubing that has been fully kinetically expanded. As described above, the plant's analysis guidelines require that that point at which the tubing is fully expanded against the tubesheet bore is identified and is given the ETL + 0.00" reference point. This provides a reference point to locate any indications that may be present. (See Figure 1 above.) All kinetic expansion examination results are referenced to the ETL+0.00" reference point All minimum axial kinetic expansion lengths are measured from the ETL+0.00" reference point.

The kinetic expansion transitions, since they are not expanded against the tubesheet bore and do not benefit from any compressive residual stresses such as those present in the expansions, are treated as "freespan" tubing under the plant's inspection criteria. For example, a small circumferentially-oriented indication may be left in service within a 17" long kinetic expansion if sufficient defect-free expansion is present to ensure the structural integrity of the expansion, while any circumferential indication detected in the kinetic expansion transition is removed from service.

Since the expansions and transitions are two distinctly different areas, AmerGen has clearly identified the distinction between the kinetic expansions and the kinetic expansion transitions in its inspection requirements and acceptance criteria.

Question 9

Reference 1 states, "*A statement is made in the August 8, 1997, submittal that requires clarification. On page 7 of 13, in Attachment 1, the licensee states: "The 6" qualification length of the 22" expansion at center and mid-radius locations does not contribute to slip resistance under postulated MSLB conditions due to the tubesheet bowing. Possible indications in the 6" qualification length of the 22" expansions in these locations will be dispositioned using more stringent free span criteria, since this length of expanded tubing loses contact with the tubesheet as a result of postulated tubesheet bow." This statement requires clarification because other docketed material implies that the bottom 5 inches of the 22-inch kinetic expansion does not contribute to slip resistance, not the bottom 6 inches as implied above.*"

Response

Clarification/correction of the subject statement is required: At 17" deep in the upper tubesheets (i.e., near the bottom of a 17" deep expansion, or 5" up into a 22" deep expansion) there is no physical difference between a 17" expansion and a 22" expansion located at the same radial location within the tube bundle in terms of calculated bow or dilation of the tubesheet. Thus, the plant's more stringent "freespan" eddy current extent limits for volumetric IGA indications (i.e., 0 25" axial or 0.52" circumferential) are invoked for only the lower 5" of the 22" expansions located near the center of the generators' tube bundles as measured from the ETL + 0.00" reference point—not the lower 6".

Note that TMI-1 ECR No. TM 01-00328 was incorporated into the plant's Technical Specifications in 2001 and includes a requirement to examine each outage the lower 5" lengths of 22" in-service kinetic expansions located at mid-bundle radial locations (Reference 4, 15).

Question 10

Reference 1 states, "*The licensee submitted a document, dated October 22, 1999, which corrected an error they identified in their July 30, 1999, submittal. The licensee stated that the July 30, 1999, submittal incorrectly noted an additional conservatism associated with the structural flaw acceptance criteria. The paragraph that was deleted read as follows: "Also, the practical implementation of the inspection acceptance criteria introduced another conservatism. The acceptance criteria were applied from the point of full expansion at the bottom of the expansion and above. The analytical model representation of the six-inch kinetically expanded region included the transition where it was less than fully expanded. The load carrying capacity given by the analytical model was based on a reduction to the six-inch qualification length equal to the length of the transition region (about 0.5"). The analysis model results depend on about 0.5" less than the full qualification length as contributing to the pull-out capacity due to the presence of this transition. Therefore, the implementation of the acceptance criteria required approximately 0.5" more defect free expanded tube length than was required analytically." This paragraph agreed with the NRC staff's understanding (based on verbal discussions with the licensee) of the analytical requirements versus implementation practices. Therefore, the reasoning behind the deletion of this paragraph is not understood.*"

Response

The paragraph could perhaps have been retained, but was deleted in 1999 to avoid any possible misunderstanding. Subsequent verbal discussions may have been clearer on this aspect of the implementation practices. As described above in this submittal, TMI-1 increased the minimum length of the kinetic expansions to be examined as part of the field implementation of the analytically-derived inspection criteria. The additional length was added to address uncertainties in the examination techniques and for conservatism.

[The analytical model was a 6" long kinetic expansion. However, only 5.5" of the 6" analytical model was assumed to be fully expanded tubing; the remaining 0.5" was assumed to be kinetic expansion transition having no tube-to-tubesheet contact.]

The paragraph was deleted at the time in order to avoid the possible misunderstanding that the analytically-derived necessary lengths of defect-free tubing could be decreased by 0.5".

Question 11

Reference 1 states, "*In the context of the preceding issues, the licensee needs to specify what actions would be taken if insufficient defect-free tubing is identified in the full qualification length. For example, would the inspection for sufficient defect-free tubing be allowed to continue higher in the tubesheet? The NRC staff requests that the licensee provide the technical basis for continued inspection or for other actions that would be taken.*"

Response

TMI-1 does not use the phrase "full qualification length" in its kinetic expansion acceptance criteria. As described in the above responses, kinetic expansion evaluations are performed beginning at the ETL + 0.00" location to verify that sufficient defect-free lengths are present.

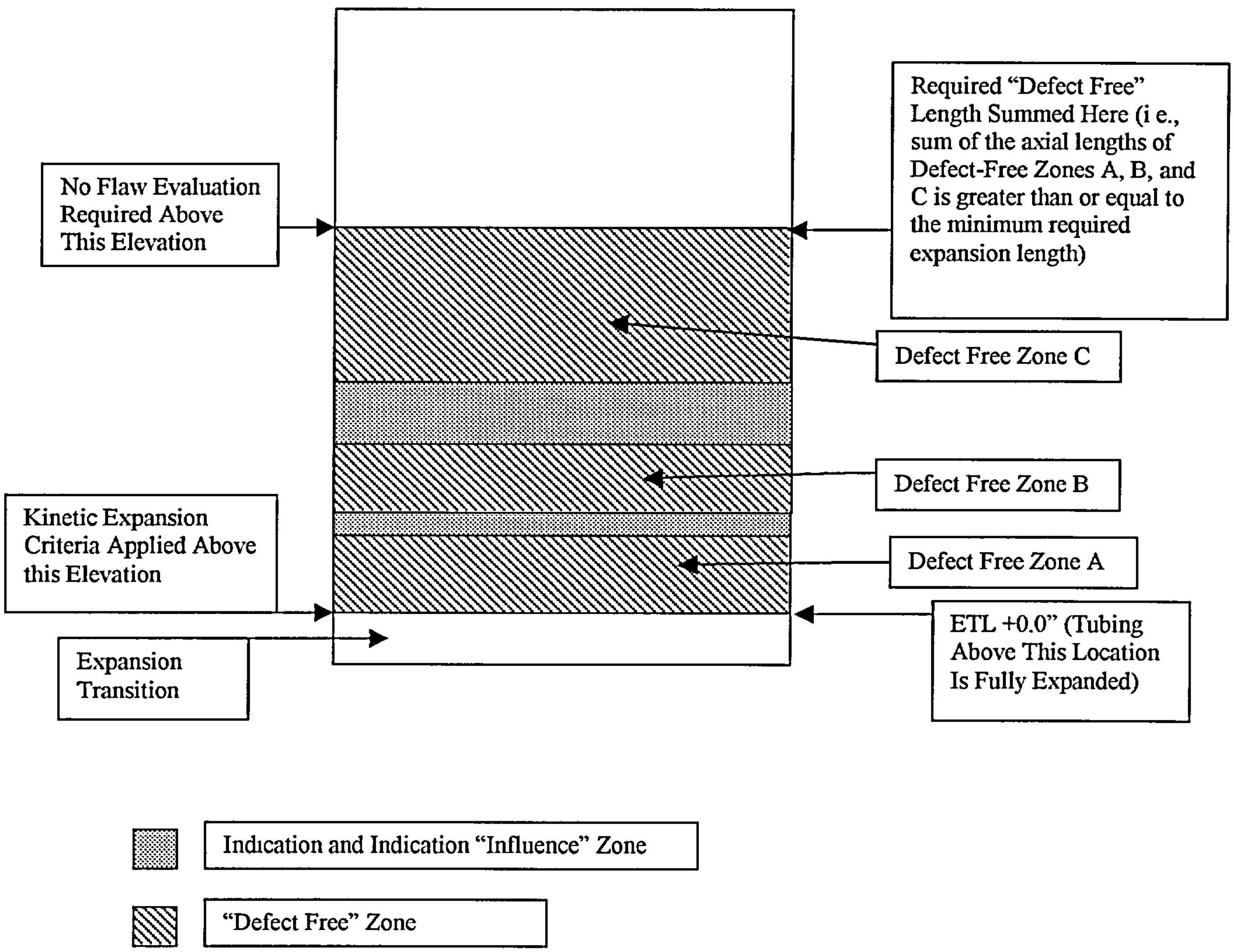
Structural evaluations of the kinetic expansions require that a kinetic expansion be removed from service if insufficient defect-free length is identified over its examined length. That is, if a defect (or a combination of defects) is detected that exceeds the allowable circumferential extent acceptance criterion, or an insufficient axial length of defect-free expansion is present, the expansion is removed from service. The inspection of a kinetic expansion may proceed farther (i.e., higher) in the tubesheet if flaws detected during the course of the examination within that expansion are within the conservative structural acceptance criteria. Figure 2, below, provides a visual presentation of the "defect-free" concept for a kinetic expansion with two indications

MPR Report 1820, Rev 1., Table 3-5, describes the conservative criteria with which flaw indications in the kinetic expansions are evaluated. If a flaw is detected in a kinetic expansion the TMI-1 dispositioning criteria conservatively assume that the joint is not usable for structural purposes over the entire axial length of that flaw. For example, if a small volumetric flaw is detected with an eddy current-measured axial extent of 0.15", the entire 0.15" length of the expansion (360 degrees around the surface of the tube) is not credited in the evaluation of the joint structural integrity. In addition, no credit is taken for defect-free tubing along additional axial lengths of the joints adjacent to flaws (known as flaw "influence zones"). Even small circumferentially-oriented flaws, if present, are assigned axial lengths of flaw influence zone so that no credit is given for that axial influence zone length of the entire joint. In summary, sufficient defect-free tubing must be detected to verify the integrity of an expansion during an inspection; no credit is taken for the length of the kinetic expansion where any defect is present, or where any defect might influence joint integrity.

While these TMI-1 structural dispositioning criteria (described in MPR 1820, Rev. 1) are very conservative, there is no requirement that the defect-free joint length be "continuous". The kinetic expansions are flaw tolerant. (For example, burst is precluded due to the presence of the tubesheet; residual compressive stresses are present, bending stresses and vibration are limited; secondary side loose parts are prevented from impacting the tubing) Small defects do not influence the reliability of the kinetically expanded joints. For example, a small volumetric ID IGA pit on the surface of a kinetic expansion will not impact the ability of defect-free tubing, located above or below that pit, to maintain the structural requirements of the joint (e.g., no tube parting, no joint pullout). Outside of the flaw influence zones a small ID-initiated axial crack present along the length of a kinetic expansion would not adversely affect the structural integrity of defect-free tubing located above or below that crack. From a structural standpoint, so long as no flaw or combination of flaws is present with a circumferential extent greater than 0.64", the defect-free tubing located above or below the flaw is an integral part of the kinetic expansion joint. (If the 0.64" circumferential extent value is exceeded prior to the required defect-free length being observed, the kinetic expansion is repaired, since the tube, conservatively assuming 100% throughwall degradation, could theoretically be parted under calculated accident-induced loads.) The expansion evaluations only "move higher into the tubesheet" if the examination data is available, and the repair criteria are not exceeded. The technical basis for this continued inspection (i.e., higher in the tubesheet) is provided in MPR 1820, Rev. 1.

FIGURE 2
"Defect Free" Concept

(Inside Surface of a Hypothetical Kinetic Expansion "Flattened" for this Sketch)
---Not to Scale---



Question 12

Reference 1 states: *"...Minimal details were provided by the licensee regarding their no-growth-rate assumption. The licensee should provide additional details regarding the basis for concluding that no defect growth has been observed and the statistical methods and criteria used to verify this assumption. The NRC staff's concerns regarding the reliability of the ECT technique for length and depth sizing (see Section 3.4) should be considered when responding to this issue. In addition, the NRC staff believes it is necessary that the licensee continue to monitor the no-growth-rate assumption supporting data each cycle to ensure that this assumption continues to remain valid. The licensee should summarize their plans in this regard...."*

Response

TMI-1 has monitored the growth of eddy current indications within the kinetic expansions for the past several outages (since MRPC inspections were started) and has reported these results to the NRC. Since the 1997 submittal TMI-1 has provided additional details regarding growth of indications in the TMI-1 steam generators. Reference 4 provided information regarding the methods with which TMI-1 has monitored the growth of the ID degradation found in the kinetic expansions, and as well as growth within the unexpanded tubing within the tubesheets. Indications are evaluated for changes in axial extent and circumferential extent over successive outages, and over multiple outages. Analysis of indication growth, and an assessment of that indication growth relative to the repair criteria, is required by the plant as part of operational assessments each outage.

Reference 4 provided information regarding the reliability of ECT techniques used for indication detection and sizing. TMI-1 has examined approximately one third of the population of inservice kinetic expansions during each of the last three plant refueling outages (Outages 12R, 13R and 1R14). MRPC eddy current examinations of each of the in-service kinetic expansions has now been completed. These examinations will serve as "benchmarking" or "baseline" MRPC examinations with which to compare future examination results.

TMI-1 will continue to monitor for growth of flaws in its steam generators, including flaws in the unexpanded tubing within the tubesheets and kinetic expansions. The plant's steam generator program requires growth monitoring for the purposes of operational assessment. The plant will continue to perform a significant number of kinetic expansion examinations each refueling outage. As described above, approximately one third of the plant's kinetic expansions have been examined during each of the plant's last three refueling outages. These samples have been sufficient to detect if significant growth of existing flaws in the kinetic expansions is occurring, or if any new degradation begins to appear within the kinetic expansions. The plant's steam generator program requires that condition monitoring assessments and operational assessments be performed based on the results of the outage examinations. The operational assessments must contain an evaluation of the potential for growth during the following operating cycle.

In addition, as a result of TMI's recent steam generator Technical Specification Amendment No. 237 (Reference 15), the TMI-1 Technical Specifications prescribe statistical tests to be utilized to evaluate the growth of ID volumetric IGA indications (-the predominant degradation mechanism noted to date in the kinetic expansions) following each steam generator inspection. These statistical tests are applied to ID volumetric indications noted in the unexpanded tubing and the kinetic expansion transitions, and the results of these statistical tests are reported to the NRC. These statistical tests, currently prescribed under the plant's Technical Specifications will provide a quantitative assessment of indication growth in tubing regions where growth is more probable than in the kinetic expansions. Monitoring of possible growth of freespan ID IGA using statistical criteria under the current Technical Specifications will provide a conservative representation of the growth potential for indications within the kinetic expansion. The tubing service stresses in the freespan are greater than those in the kinetic expansions. Higher service stresses constitute a more aggressive environment for the potential propagation of stress corrosion cracking (SCC). Circumferential stresses within the kinetic expansion are less than in the freespan due to the participation of the tubesheet ligament in reacting to internal pressure. In addition, residual contact pressure from formation of the kinetic expansion joint causes membrane hoop compression to counteract internal pressure. Axial tube loads in the kinetic expansion are diverted into the tubesheet ligaments due to the friction reaction as a result of residual contact pressure from the formation of the joint. Axial stresses in the kinetic expansion are reduced in proportion to the elevation within the repaired joint. In summary, the current Technical Specification requirements for statistical growth analyses for indications in unexpanded tubing and transitions also enable the plant to conservatively assess the potential for growth of kinetic expansion indications.

Question 13

Reference 1 states, *"Provide a rigorous basis for utilizing a lower contact pressure threshold (250 psi) than that used in the leakrate tests (500 psi)".*

Response

The leakrate test results indicated that there was almost zero correlation between leakage from tube flaws and changes in joint contact pressure at those flaws. Testing was performed at contact pressures of 500, 1500 and 3000 psi, and leak rates at each of these contact pressures were extremely low in comparison to the no contact pressure case. The results suggested that leakage would be reduced at any time where positive contact pressure existed between the tubesheet bore surface and the tube outside diameter surface (i.e., conditions where the tube remained in contact with the tubesheet). Intuitively, these results were logical because the presence of tube-to-tubesheet contact should significantly reduce the leakage in comparison to the case where no such contact is present.

Two hundred and fifty (250) psi was used as the threshold contact pressure at which to consider reduced leakage from the joints based upon the following:

> Two hundred and fifty (250) psi is a significant remaining contact pressure for the joint with respect to the zero contact pressure condition. (Since a positive contact pressure still exists, the expanded tube is still in close contact with, and pressed against, the tubesheet bore. Thus, any annular space between the expanded tube and the tubesheet bore that might create a leakage path should be very small.)
>
> Testing with the leaktest apparatus was very conservative because the test apparatus was not "pre-conditioned" by the kinetic expansion pressure to achieve mating surface-to-surface contact between the tube and mockup test block. In the TMI-1 steam generators, the inservice tubing was kinetically-expanded (with an explosive charge) so that the

tubing was plastically flattened against the inside surface of the tubesheet bore. Contact pressure greater than yield strength was achieved in the kinetically repaired joint. In-service pressures, which are much lower, are actually applied to these surfaces that have been plastically compressed or "flattened". No such effort to plastically expand the tubing against the tubesheet block was attempted for the lab leakrate tests. (The compressed surfaces of the kinetic expansions will remain compressed as the applied contact pressure is reduced--in the same manner that bolted, flanged joints remain leaktight until the bolt preload is exceeded by the applied load.) The demonstrated leak reduction capability of the test apparatus should be considerably less than the leak reduction capability of the kinetically repaired joint since the latter has the benefit of plastically compressed surfaces.

In addition, the results of the leakrate tests were conservatively applied to derive the leakage estimates for flaws in the tube-to-tubesheet joint. For example, peak axial tensile tube load was applied over the full duration of the laboratory leakrate tests. [The axial tube load causes Poisson contraction of the tube within the joint, which tends to decrease the joint contact pressure.] The leakrate test results were used to help estimate leakage from flaws over a postulated MSLB event of 23.5 hrs duration, while the calculated peak axial loads act upon the joint for approximately one minute. (Peak calculated tube load of 1310 lbs. is reached at t= 60 seconds; calculated loads are less than 1000 lbs. after t=115 seconds.) Thus, in implementing the leakage estimate a large amount of Poisson contraction was assumed over the entire course of the event, while this maximum amount should be present for a only relatively short time during an actual event.

An additional conservatism is that the 250 psi contact pressure was used only to derive a "minimum location" at which the Leakage Reduction Factor could be applied to project a leakage volume. The leak tests were conducted on flaws that were only 0.25" and 0.325" from the edge of a mockup tubesheet block (i.e., from the "freespan" condition). No credit was taken for additional leakage reduction that might have occurred for flaws that were a larger distance from the edge of the block. In implementing the leakage estimates for the as-found flaws during inspections this results in cases where flaws may have 2 or 3 inches of expanded tubing between the flaw and the transition, but the leakage estimate is the same that would be estimated if the flaw only had 0.25" of expanded tubing between the flaw and the transition.

In summary, the leakrate projection performed for flaws present in the kinetic expansions is conservative with the 250 psi contact pressure threshold.

Question 14

Reference 1 states: "*...The licensee stated that "the defect must be located at an elevation at which structural analysis results identify a remaining contact pressure at least equal to 250 psi and a leak path length of at least 0.25 inches from the expansion transition. Defects that are not clamped by at least 250 psi over a leak path of at least 0.25 inches were evaluated without a LRF." These two statements made by the licensee are not identical, and it is not clear which interpretation is intended (i.e., there must be a 0.25-inch leak path clamped at a minimum of 250 psi below the area where an LRF is applied, or the LRF is applied when there is a 0.25-inch leak* *path and a minimum of 250 psi in the area the LRF is being applied). This issue must be clarified. In addition, if the second interpretation is the one intended (i.e., a minimum of 250 psi is only necessary in the region the LRF is applied), provide the technical basis for this considering the laboratory tests maintained a 250 psi over the 0.25-inch leak path in addition to where the LRF is applied."*

Response

The interpretation that was intended is that both the location of the defect and the entire length of the 0.25" minimum leak path have a contact pressure of at least 250 psi. TMI-1 performed analyses which demonstrated that a minimum of 250 psi contact pressure was maintained throughout a 17" kinetic expansion at all times during a hypothetical MSLB event, and regardless of the radial location of a tube in the tube bundle. Thus, a 250 psi minimum contact pressure is maintained both at the location of the indication and along the length of the 0.25" minimum leakage path length.

(Note that above NRC text and AmerGen's response apply to the normal case for 17" kinetic expansions. Different lengths are used for the 22" kinetic expansions. Refer to Table 1, above.)

Question 15

Reference 1 states: "*...The licensee indicated that any leakage contribution due to possible defects located further into the expansion than the 'minimum required inspection distance' was considered negligible. The NRC staff verbally questioned during a conference call whether analysis or calculations were performed to determine the minimum-required length of tubing that would be required, such that any flaws located above this distance would contribute negligible leakage. This is of particular interest to the NRC staff because the 'minimum required inspection distance' is variable. (Section 3.1 provides more details on the 'minimum required inspection distance'.) The licensee indicated that analyses were not performed to determine the minimum-required length. Perform an analysis to determine the minimum-required length or provide a justification to explain why this is unnecessary. Provide an expanded discussion quantifying 'negligible' so that these values can be put in perspective."*

Response

The "minimum required inspection distances" for the various TMI-1 kinetic expansions are provided in the Table 1, above. This table was also submitted to the NRC in Reference 6.

Estimated leakage from flaws that are located above these AKELmin expansion lengths will be very small in comparison with flaws that are located nearer to the expansion transitions. In classical equations for laminar flow through a small annular orifice formed by concentric members with circular cross sections - a highly idealized representation of the kinetic expansions in which the tubing was expanded against a drilled tubesheet bore with explosive force - flow is inversely proportional to length of the orifice (Reference 3). Thus, if it was conservatively assumed that a kinetic expansion flaw's leakpath were a concentric annulus, expected leakage from a hypothetical flaw 3.0" into the expansion would be 10% of the expected leakage from an identical flaw located 0.3" into the expansion.

Laboratory leak testing that was performed for the kinetic expansion work demonstrated that even a small length (e.g. 0.25") of expansion, even with no contact pressure, will significantly decrease leakage over the "freespan" condition. (This is consistent with established calculational methods for leakage through cracks where leakage is inversely proportional to the length of the leak path, as described above. This is also consistent with leakage evaluations for other types of expanded tube-to-tubesheet joints where leakage resistance is increased with increased length of the joint.) The laboratory leak testing performed for the TMI-1 kinetic expansions also showed a 20% decrease in flaw leak rate with an additional 0.125" length of leak path—even with no applied contact pressure on the leaking flaws within a loose tubesheet mockup block.

The following discussion is also provided for perspective as to the small amount of leakage that might be expected from flaws located above the minimum expansion lengths in comparison to those flaws located near the kinetic expansion. For example, a flaw that is located 0.2" into the expansion (i.e., at ETL + 0.2") is conservatively treated as a "freespan" flaw, and this flaw has a relatively significant leakrate. If this same flaw were located further into the expansion, for example at 1 inch into the expansion at ETL+1.0", its assigned leakrate is reduced (from that expected at the ETL + 0.2" location) by the Leakage Reduction Factor (LRF) of 1/25th. If this same flaw were located above the "minimum inspection distance", there would be a minimum of 2.1" of defect free kinetic expansion between the flaw and the expansion transition (since the shortest minimum inspection distance is 2.1"). Considering that the kinetic expansion leakage tests showed that even a small length (0.25") of expansion will restrict leakage by more than a factor of 25 with minimal joint contact pressure, 2.1" of defect-free expansion (with installed contact pressures from the expansion process's plastic deformation of the tubing) should prevent additional leakage. Given the above, the estimated leakage from flaws above the minimum inspected lengths of the kinetic expansions should be very small in comparison to the projected leakrates calculated for flaws nearer to the kinetic expansion transitions. Defects that are located near (i.e., within 0.25" of) the expansion transition, and therefore whose leakage is not reduced by the Leakage Reduction Factor of 1/25, are the dominant contributors to the results of the leakage estimates.

Question 16

Reference 1 states, "*...The licensee stated that the circumferential and axial components of the volumetric inside diameter (ID) IGA are evaluated separately, and indicated that this is a conservative representation of a volumetric indication for the purposes of total leakage evaluation. The technical basis supporting this assumption is not clear.*

In addition, the licensee stated that the leakage flow for a given crack opening area (for a given crack) is determined by the PICEP computer code and that the code was validated with experimental data. The licensee should provide technical justification for the use of PICEP, a crack code, for IGA (crack and IGA typically have very different flaw morphologies). Describe the various inputs used for PICEP, if necessary, for this technical justification. In addition, the licensee should provide a brief summary of the PICEP code validation that was performed, including a brief description of the actual flaws that were used for the validation."

Response

It is very conservative to estimate the theoretical leakage from volumetric flaws in the kinetically expanded tubing by considering them as a combination of a 100% throughwall circumferential crack of length equal to the as-called circumferential extent of the volumetric flaw and a 100% throughwall axial crack of length equal to the as-called axial extent of the volumetric flaw. This treatment of the volumetric flaws is conservative for a number of reasons including:

- the fact that the tubing is expanded into the tubesheet and is unlikely to crack axially. (Expansion and deformation of the tube in the hoop direction are prevented by the constraint of the tubesheet.)

- pulled tube examination results from TMI-1 have demonstrated that the MRPC examinations tend to overestimate the extents of the ID volumetric IGA flaws (as a result of the "look-ahead/look behind" effect and the proximity of the ID flaws to the surface-riding coils),

- bending of the tubing is prevented by the presence of the tubesheet. (Crack formation is less likely since movement/displacement of the tubing is severely restricted.).

- the presence of the tubesheet prevents formation of a volumetric "hole"; thus only a tortuous flow path through an intergranular flaw surface (similar to a crack) would be expected.

The PICEP program was used to estimate the theoretical leakage from the axial, circumferential, and volumetric indications in the TMI-1 kinetic expansions. (As described above, volumetric indications were conservatively assumed to result in both a circumferential crack and an axial crack.) The PICEP program predicts the theoretical flow through straight cracks. The volumetric morphology of the ID IGA flaws, the predominant flaws within the kinetic expansions, is dissimilar to the morphology of straight cracks. However, given the constraint of the tubesheet, it is very conservative to predict leakage based on the assumption that each volumetric flaw will result in one circumferential, throughwall, straight crack and one axial, throughwall, straight crack. The PICEP program is described in EPRI NP-3596-SR (Reference 13).

Numerous inputs were required for the PICEP calculations to estimate the leakage from the kinetic expansion flaws:

- Tensile loads on the tube were set to zero for the axial cracks (since tensile loads tend to tighten these cracks and reduce leakage).

- Surface roughness was set to 0.0002 inches, a value of roughness typical for corrosion-induced cracks.

- No credit was taken for any tortuosity of the crack channel. (The number of 45 degree turns was set to zero for the computer code runs.)

- Minimum tube wall thickness of 0.034" was assumed.

Validation/benchmarking of the PICEP program was based on a large number of flaws and is described in Appendix C of EPRI NP-3596-SR. PICEP crack flow results were assessed using several sets of leak data including data from EPRI (Battelle Columbus and Wyle Laboratory), NRC (UC Berkeley), Canada (AECL), Italy and Japan. The types of cracks used for this validation work were varied. For example, PICEP results were compared with flow data from cracks formed by parallel plates, pipes with circumferential cracks, and rectangular slits. Among the test results with which PICEP was compared were those results described in NUREG/CR-3475, "Critical Discharge of Initially Subcooled Water Thru Slits". (The PICEP results showed good agreement with the NUREG's results.) Additional work to benchmark the PICEP code is described in EPRI NP-6897-L, "Steam Generator Tube Leakage Experiments and PICEP Correlations" (Reference 14). In that study the PICEP results were benchmarked against numerous steam generator tube laboratory leak tests. (48 leak tests were conducted on I-600 steam generator tube specimens with laboratory-generated flaws.)

Question 17

Reference 1 states, with respect to the kinetic expansion acceptance criteria, "*Four regions (A, B, C and D) were used above to describe the different methods used by the licensee to calculate leakage volume. Provide further information and/or support for the following:*

A - *"Provide a more detailed discussion on the calculations, leakage values and supporting basis for flaws identified in this region. How does this leakage assessment methodology differ from that used for freespan flaws identified outside the tubesheet? The NRC staff assumes that the region where "calculations" are necessary encompasses the region from the secondary face of the upper tubesheet to the height indicated in each of the tables. Please indicate whether this assumption is correct."*

Response

The assumption is not correct. The regions requiring "calculations" were referenced from the location at the top of the kinetic expansion transition location (ETL); they were not referenced from the secondary face of the upper tubesheet.

Region A is "below" the kinetic expansion and includes unexpanded tubing and the kinetic expansion transition. A table entry for this area was created (i.e., "Calculations Required") that would alert the plant's engineers that the kinetic expansion analyses did not apply in this area of the tubing. Since 1997, when the subject table was created, TMI-1 has used in situ pressure testing in lieu of calculations to assess the possible leakage of indications located in Region A. (When the table was created in 1997 TMI-1 had yet to perform any in situ pressure tests.) Since 1997 TMI-1 has in situ pressure tested many tubes to help assess leakage; in situ pressure testing has provided the plant with empirical data regarding the integrity of steam generator tube indications without the need for calculations.

Leakage assessment of indications in Region A is essentially no different than leakage assessment of indications identified in freespan tubing outside of the tubesheet. (Note that this is different than the situation for burst since burst is precluded for indications within the tubesheet.)

It should also be noted that the vast majority of the indications located in Region A are ID volumetric IGA indications. Therefore, the assessment of possible leakage from these indications during the last plant outage was performed in accordance with ECR No. TM 01-00328. This ECR was incorporated into the TMI-1 Technical Specifications prior to 2001's Outage 1R14 and requires a leakage assessment of the volumetric ID IGA indications. (This ECR is an attachment to Reference 4.) Thus, while Region A was first called out in the 1997 criteria (-to differentiate this region from the kinetically expanded region), volumetric ID IGA indications in this region are now addressed for leakage potential under ECR No. TMI 01-00328.

Question 18

Reference 1 stated the following as regards Region B of the table:

B - "Identify how the calculations performed to create the tables used in this region differ from the calculations used for region A. If the difference in calculational methods is due to the difference in contact pressure (i.e., no contact pressure in region A versus minimal contact pressure in region B), discuss the contact pressure that is utilized as it appears to vary from tube to tube depending on location within the tube bundle."

Response

As discussed in the above response, leakage calculations have not been used in Region A. (In situ pressure testing has been used.) Region B of the table includes the "first" (i.e., lowest) 0.25" length of a kinetic expansion. This region is fully expanded and is located at ETL + 0.00" to ETL + 0.25". To assess possible leakage from indications in Region B, the leakage tables provided in Table 7-1 of Reference 10 are used. These leakage tables assume no contact pressure as a result of the kinetic expansion. As discussed in the responses above, since Region B is within 0.25" of the kinetic expansion transition, no credit was taken for any contact pressure and the Leakage Reduction Factor of $1/25^{th}$ is not used. In summary, neither Region A nor Region B is credited with any contact pressure in the leakage assessment.

The Reference 10 leakage tables were created from evaluations performed specifically for kinetically expanded tubing; therefore the tables of leakage values used for Region B are not used for Region A. (Region A tubing has not been kinetically expanded.) The Region B leakage tables, while they assume there is no joint contact pressure present, take credit for the fact that the tubesheet is present and will prevent deformation of a tube at the location of a leaking defect. In Region A the tube is not adjacent to the tubesheet.

Question 19

Reference 1 stated the following: "*...The attachment to the licensee's November 26, 1997, submittal, "GPU Nuclear Topical Report #116, Revision 0, Leakage Assessment Methodology For TMI-1 OTSG Kinetic Expansion Examination," November 6, 1997, provides the leakage assessment methodology. Page 33 of the topical report states that the "minimum inspection length was 1.8 inches from the transition for peripheral tubes." The basis for this statement is not clear, as it appears to conflict with the structural integrity inspection acceptance criteria".*

Response

The statement is no longer correct. TMI-1 revised its kinetic expansion inspection lengths so that the minimum inspection length is 2.1 inches. The minimum inspection length of 1.8" was never used. (Refer to Table 1 in Response #6 above, which delineates the minimum inspection lengths for the kinetic expansions.)

Question 20

Reference 1 stated the following: "*...The NRC staff has concerns whether the elimination of flaws from the leakage assessment methodology based on depth measurements is appropriate and conservative. This issue is further discussed in Section 3.4.*"

Response

TMI-1 has only used kinetic expansion indication depth measurements for estimates of accident-induced leakage. To implement the kinetic expansion structural criteria, which determine whether or not a tube needs repair, TMI-1 has conservatively assumed that all indications are 100% throughwall over their entire as-called eddy current extent(s).

For the leakage estimates TMI-1 has conservatively assumed that indications within the kinetic expansions whose estimated depth exceeds 67% T.W. will leak under hypothetical MSLB conditions. The derivation of this 67% T.W. figure was based on an evaluation of eddy current performance with machined, laboratory grown, and pulled tube flaws of known depth.

The 67% throughwall threshold is a very conservative criterion considering:

- the 33% TW eddy current accuracy (i.e., 100% minus 67%) is based on the results of the eddy current analysis with a 95% single tailed lower confidence level. A team of analysts was used for the study to evaluate error.

- the majority of the indications within the TMI kinetic expansions are ID volumetric IGA indications. In-situ pressure testing of ID volumetric IGA indications at TMI to date has not identified any indications that have demonstrated measurable leakage (i.e., leakage above detectable levels) at simulated normal operating or accident conditions. For example, 69 ID volumetric indications were in situ pressure tested, without leakage, during the plant's most recent refueling outage (Reference 8).

- A number of additional conservatisms are incorporated into the leakage assessment methodology. For example, volumetric indications are hypothesized to form both a circumferential crack and an axial crack, with the entire measured eddy current extent(s) used to calculate expected accident leakage.

The results of in situ pressure tests performed during recent refueling outages also provide some evidence that the depths of TMI-1 steam generator tube flaws are conservative. For example, during the most recent 1R14 Outage, seven TMI-1 tube indications whose estimated depth by Plus-Point was greater than 80% throughwall were insitu pressure tested. (Reference 8) None of these seven indications leaked at a delta pressure equivalent to three times the delta pressure during normal plant operation (i.e., 3NODP). One of these seven indications leaked at a rate of 0.014 gpm, a small leakrate, at a delta pressure of 6450 psi, approximately five times the delta pressure during normal plant operation. All seven of these indications had estimated depths greater than 67% throughwall and would have been assumed to leak at MSLB delta pressure, which is less than 3NODP delta pressure, under the kinetic expansion leakage criteria.

Question 21

Reference 1 states:"*... The licensee uses "ETL" to describe the location at which to apply different leakage assessment methodologies. This acronym in not defined in the docketed information."*

Response

Refer to Figures 1 and 2, above. ETL is an acronym created by TMI-1 that stands for "Expansion Transition Location". ETL + 0.00" is that point at the top of the kinetic expansion transition where the tubing is fully expanded against the tubesheet bore. Indications in the TMI-1 kinetic expansions are located with respect to this point (e.g., one indication may be located at ETL + 3.45", while another indication might be located at ETL – 0.16".)

Establishing a reference point at the top of the expansion transition (--which is the bottom of the expansion) is important for the implementation of the inspection and dispositioning criteria. Basically, for the standard 17" deep kinetic expansions, the kinetic expansion dispositioning criteria is applicable to indications at "ETL plus" locations (i.e., ETL + some dimension), while indications at "ETL minus" locations (i.e., ETL – some dimension) are located below the expansions and are not dispositioned using the kinetic expansion criteria. Indications located at ETL+0.00" (i.e., on the boundary between the two regions) are dispositioned using the freespan criteria.

The ETL term was defined in Reference 7 (13R Outage Report, TR-135, Appendix III, Page 1), which was submitted to the NRC since the original kinetic expansion submittals. The ETL term is also defined in Reference 8, which was recently submitted to the NRC (1R14 Outage Report, TR-151, Page 12).

Question 22

Reference 1 states: *"The method used by the licensee to determine acceptability of the eddy current technique for use on the IDIGA identified at TMI-1 is not sufficiently rigorous for NRC staff's approval of an alternate repair criteria. There are inherent weaknesses in the information provided by the licensee. Resolution of this concern is crucial to the NRC staff's review of the proposed inspection criteria.*

Three examples of the weaknesses are as follows: the NRC staff does not typically accept machined notches as a substitute for corrosion-induced steam generator tube degradation for eddy current testing qualification purposes; flaws that are utilized in the data set should be shown to be representative of the IDIGA at TMI-1; discussion of the eddy current technique qualification which supports length sizing of flaws was not provided.

The NRC staff suggests the licensee develop a plant-specific performance demonstration which includes a statistically valid sample set shown to representative of TMI-1 IDIGA, and blind data acquisition and analysis. Alternatively, the licensee may consider documenting a convincing technical justification for why industry and TMI experience with IDIGA indicates that the current technique qualification and related uncertainties are bounding for TMI-1."

Response

Axial and circumferential extent of ID IGA indications is measured using the 0.080" shielded high frequency pancake coil. AmerGen's Reference 4, RAI Question 1, response provided to the NRC the following information concerning length and width sizing of ID IGA indications:

> "...TMI-1 has evaluated eddy current techniques and expected analyst uncertainties so as to assure that the dispositioning of the ID IGA indications using MRPC probes is conservative. Before 1997's Outage 12R, a study was performed to evaluate the acquisition, analysis, and technique errors expected during the MRPC examinations of the ID IGA indications. Volumetric flaws manufactured by EDM were used in the 1997 study. This study was updated before 1999's Outage 13R so as to incorporate the data from the ID IGA flaws in the tube samples pulled during the 1997 outage. A team of 5 production analysts and 1 senior (resolution) analyst was used in the study.
>
> "Acquisition variabilities were obtained by running three separate MRPC exams of the ID volumetric flaws. Comparison of the three separate exams by a single analyst enabled the acquisition errors to be evaluated. Since each flaw was a separate test, a pooled variance was used to combine the results. For the 0.080" HF pancake coil (the coil utilized by TMI-1 to measure the extents of the ID IGA indications), the acquisition pooled standard deviations were 0.0114" for axial length and 0.0084" for circumferential length.
>
> "Analysis variabilities were obtained by comparing the different analysis results of the six different eddy current analysts. For the 1999 study, this dataset included 23 EDM flaws and 9 flaws from the 1997 TMI-1 pulled tube, for a total of 32 volumetric flaws. For the 0.080" HF pancake coil (the coil utilized by TMI-1 to measure the extents of the ID IGA indications), the analysis pooled standard deviations were 0.022" for axial length and 0.031" for circumferential length.

> "Technique variabilities were obtained by comparing the results of the eddy current analyses to the actual metallurgy of the flaws. Again, for the 1999 study, this dataset included the 23 EDM flaws and 9 flaws from the 1997 pulled tube, for a total of 32 volumetric flaws. For the 0.080" HF pancake coil (the coil utilized by TMI-1 to measure the extents of the ID IGA indications), the technique standard deviations were 0.039" for axial length and 0.033" for circumferential length. For the 0.080" HF pancake coil, the technique average errors were a 0.124" overestimate of axial extent and 0.127" overestimate of circumferential extent.
>
> "The conclusion of the 1999 error analysis and performance evaluation is that "...the rotating coil techniques have demonstrated that axial and circumferential extents are consistently overestimated. Even when analysis and technique / equipment variability are applied at a 95% confidence level, the extents measured by eddy current are larger than the actual extents." The overestimation of axial and circumferential extents is of sufficient magnitude that no correction to the repair limits is necessary to account for eddy current acquisition, analysis, or technique uncertainty. Since the eddy current coils interrogate a volume of metal larger than the volume of the flaws themselves (i.e., "look ahead" and "look behind") the result is a consistent overestimate of flaw extents.
>
> "Note that tube pull results from the 1997's Outage 12R demonstrated that the MRPC probe typically overestimates the axial extents of the ID IGA flaws by a factor of approximately three. This occurs due to the "look ahead" and "look behind" phenomena of eddy current coils used in steam generator tube examinations. Additional information on analyst uncertainty is provided in the response to RAI Question No. 4."

AmerGen's Reference 4, RAI Question 4, response provided to the NRC the following information concerning length and width sizing of ID IGA indications:

> "...The analyst variabilities during the MRPC probe examinations are inconsequential considering that MRPC probes consistently overestimate the actual length of the volumetric ID IGA flaws as shown in Attachment 2. Tables 2 and 3 in the attachment are excerpts from a 1999 TMI Unit 1 submittal and provide Outage 12R eddy current measured length data prior to tube removal and laboratory destructive examination for a tube removed in 1997's Outage 12R."

Similar length sizing studies were performed for axially- and circumferentially-oriented indications prior to the 1997 and 1999 outages using 30 machined notches and 6 laboratory induced axially oriented PWSCC cracks. These measurements were made using the mid-frequency Plus Point coil similar to measurements made in the field. The results of these studies indicated that the Plus Point coil, like the pancake coils, overestimates crack length.

In the kinetic expansion region flaw depth measurements are made using the mid-frequency Plus Point coil. Prior to the 1997 and 1999 outages Plus Point coil depth sizing performance studies were performed in a manner similar to that described above for the length sizing studies. The 1999 study was performed using 68 total flaws that were comprised of 10 machined axial notches, 20 machined circumferential notches, 23 machined ID volumetric IGA like indications, 6 laboratory grown PWSCC indications in OTSG tubing, and 9 TMI pulled tube ID IGA indications. The studies indicated that the measured 95% lower confidence level (LCL) through wall measurement error is expected to be -28.1% through wall.

It should be noted that, as described in Reference 10, the measured eddy current through wall estimate is used for estimation of accident-induced leakage only. The eddy current measured axial and/or circumferential extent is assumed to be 100% through wall for evaluation of structural integrity (resistance to pull-out) as described in Reference 9. Based on the eddy current examination results, and in situ pressure tests of freespan indications performed at TMI to date (See response to question 20), accident-induced leakage from kinetic expansion indications remaining in service is expected to be very small.

In summary, the eddy current techniques used at TMI-1 are based on qualification datasets that included pulled tube samples from TMI-1 and other samples representative of TMI-1 ID degradation. Performance studies have demonstrated that eddy current sizing is conservative, and both pulled tubes and in situ pressure testing to date have demonstrated that the techniques used at TMI-1 are able to reliably disposition steam generator tube flaws.