U.S. NUCLEAR REGULATORY COMMISSION

STANDARD REVIEW PLAN

OFFICE OF NUCLEAR REACTOR REGULATION

3.6.3 LEAK-BEFORE-BREAK EVALUATION PROCEDURES

REVIEW RESPONSIBILITIES

Primary - Materials Engineering Branch, NRR

Secondary - Mechanical Engineering Branch, NRR

I. AREAS OF REVIEW

General Design Criterion 4 (GDC-4) of Appendix A to 10 CFR Part 50 allows the use of analyses reviewed and approved by the Commission to eliminate from the design basis the dynamic effects of the pipe ruptures postulated in SRP Section 3.6.2. The staff reviews and approves each plant specific and fluid piping system specific submittal from licensees and applicants to eliminate these dynamic effects. Approval of these "leak-before-break" analyses by the staff permits the case-by-case removal of protective hardware such as pipe whip restraints and jet impingement barriers, the redesign of pipe connected components, their supports and their internals, and other related changes in operating plants. Likewise, requirements in plants under construction or to be designed in the future are similarly relaxed. The staff review assures that adequate consideration has been given to direct and indirect pipe failure mechanisms and other degradation sources which could challenge the integrity of piping. The staff review of direct pipe failure mechanisms comprises the following elements:

1. An evaluation over the entire life of the plant of the following:

a. Water Hammer	d. Corrosion
b. Creep Damage	e. Fatigue
c. Erosion	f. Environmental Conditions

2. A deterministic fracture mechanics and leak rate evaluation.

The staff reviews the factors which contribute to the initial quality of the piping and the provisions adopted to maintain this quality. In addition, leak detection methods are examined to assure that adequate detection margins exist for the postulated throughwall flaw used in the deterministic fracture mechanics evaluation.

Indirect failure mechanisms as defined in the plant FSAR which could lead to pipe rupture are investigated. These include seismic events and system overpressurizations due to accidents resulting from human error, fires, or flooding which cause electrical and mechanical control systems to malfunction. Missiles from equipment, damage from moving equipment and failures of structures, systems or components in close proximity to the piping are investigated as well. However, the results of prior analyses conducted to show compliance with Commission regulations can be applicable to potential sources of indirect pipe rupture.

II. ACCEPTANCE CRITERIA

Acceptance criteria are based on meeting the requirements of General Design Criterion 4 as it relates to the exclusion of dynamic effects of the pipe ruptures postulated in SRP Section 3.6.2. Analyses reviewed and approved by the staff must demonstrate that the probability of fluid system piping rupture is extremely low under conditions consistent with the design basis of the piping. The design basis for the piping means those conditions specified in the FSAR, as amended, and may include 10 CFR Part 50, applicable sections of the Standard Review Plan, Regulatory Guides, and industry standards such as the ASME Boiler and Pressure Vessel Code. A deterministic evaluation that demonstrates sufficient margins against failure, and that includes verified design and fabrication in addition to an adequate inservice inspection program, can be assumed to satisfy the extremely low probability criterion.

Leak-before-break should only be applied to ASME Code Class 1 and 2 piping or the equivalent. Applications to other high energy piping will be considered based on an evaluation of the proposed design and inservice inspection requirements as compared to ASME Code Class 1 and 2 requirements.

Approval of the elimination of dynamic effects from postulated pipe ruptures is obtained individually for particular piping systems at specific nuclear power units. Leak-before-break cannot be applied to individual welded joints or other discrete locations. Leak-before-break is applicable only to an entire piping system or analyzable portion thereof. Analyzable portions are typically segments located between anchor points. When leak-before-break technology is applied, all potential pipe rupture locations are examined; the examination is not limited to those postulated pipe rupture locations determined from SRP Section 3.6.2.

III. REVIEW PROCEDURES

The reviewer verifies compliance with the following factors necessary for an acceptable submittal to utilize leak-before-break technology.

1. The leak-before-break evaluation uses design basis loads and is based on the as-built configuration as opposed to the design configuration. Correct location of supports and their characteristics (such as gaps) are verified, as are the weights and locations of components such as valves. Particular attention is given to the reliability of snubbers whose failure could invalidate the stresses used in the fracture mechanics evaluations.

Compliance with the technical specifications can be used to demonstrate that snubber failure rates are maintained at a low level. Leak-before-break technology cannot be applied to piping supported by masonry block walls unless compliance with Multi-Plant Action B-59 is achieved.

2. Degradation by erosion, erosion/corrosion, and erosion/cavitation due to unfavorable flow conditions and water chemistry is examined. Industry experience for specific piping systems plays a major role in the evaluation of these degradation mechanisms. Additionally, an evaluation of fabrication wall thinning of elbows and other fittings is undertaken to assure that Code minimum wall requirements are met. These evaluations must demonstrate that these mechanisms are not potential sources of pipe rupture.

3. Determination of leakage from a system under pressure involves uncertainties and, therefore, margins are needed. Sources of uncertainties include plugging of the leakage crack with particulate material over time, leakage prediction, measurement techniques, personnel, and frequency of monitoring. Leakage detection systems are evaluated to determine that they are sufficiently reliable, redundant, and sensitive so that margin on detection of unidentified leakage exists for the throughwall flaws used in the deterministic fracture mechanics evaluation. Leak detection systems equivalent to Regulatory Guide 1.45 are required for the piping under evaluation inside the containment. The sensitivity and reliability of leakage detection systems used outside the containment must be demonstrated to be equivalent to Regulatory Guide 1.45 systems. Methods that have been shown to be acceptable include local leak detection, for example, visual observation or instrumentation.

   Unless a detailed justification can be presented that accounts for the effects of these sources of uncertainties, a margin of 10 on the leakage prediction will be required for determining the leakage size flaw.

4. A systems evaluation of potential water hammer is made to assure that pipe rupture due to this mechanism is unlikely. Water hammer is a generic term including various unanticipated high frequency hydrodynamic events such as steam hammer and water slugging. To demonstrate that water hammer is not a significant contributor to pipe rupture, reliance on historical frequency of water hammer events in specific piping systems coupled with a review of operating procedures and conditions may be used for this evaluation. Alternatively, design changes such as the use of J-tubes, vacuum breakers and jockey pumps coupled with improved operating procedures can be used to reduce concerns with water hammer. The reviewer establishes that any measures needed to abate water hammer frequency and magnitude will be effective for the life of the plant.

5. A review of creep and creep-fatigue is required. Operation below 700^{o}F in ferritic steel piping and below 800^{o}F in austenitic steel piping can satisfy concerns with creep.

6. The requirement that corrosion resistance of piping be demonstrated can rely on investigations of the frequency and degree of corrosion in the specific piping systems under review. Modification to operating conditions (as for example, controlling water chemistry) or design changes (as for example, replacing piping material) are measures that can be taken to improve corrosion resistance in piping. The staff recognizes that remedial residual stress improvement treatments are effective in reducing susceptibility to intergranular stress corrosion cracking. However, remedial stress improvement treatments of non-conforming materials alone do not provide a sufficient basis to support leak-before-break evaluations. The staff would, however, review such evaluations on a case-by-case basis if hydrogen water chemistry were used as an adjunctive measure with the remedial stress improvement treatments. The licensees' practices with regard to facility water chemistry would be an additional factor considered in the review. Non-conforming piping with any planar flaws in excess of the standards in the ASME Code, Section XI, Tables IWB-3514-1 and -2, would not be permitted to use leak-before-break analyses. However, non-conforming piping that has been treated by two mitigating methods may qualify for leak-before-break if the piping contains no flaws larger than those permitted by the ASME Code Section XI without repair.

7. An assessment of potential indirect sources of pipe ruptures is required to demonstrate that indirect failure mechanisms defined in the plant FSAR are remote causes of pipe rupture. Compliance with the snubber surveillance requirements of the technical specifications assures that snubber failure rates are acceptably low.

8. The reviewer determines that the piping material is not susceptible to brittle cleavage-type failure over the full range of system operating temperatures (that is, the material is on the upper shelf).

9. The reviewer determines that the system(s) under evaluation do not have a history of fatigue cracking or failure. An evaluation is performed to assure that the potential for pipe rupture due to thermal and mechanical induced fatigue is unlikely. Licensees and applicants must demonstrate that there is adequate mixing of high and low temperature fluids so that there is no potential for significant cyclic thermal stresses. In addition, it must also be demonstrated that there is no significant potential for vibration induced fatigue cracking or failure.

10. The following steps constitute an acceptable deterministic leak-before-break evaluation procedure:

    a. Demonstrate the accuracy of both the fracture mechanics and the leak rate computational methods by comparison with other acceptable computational procedures or with experimental data.

    b. Identify the types of materials and materials specifications used for base metal, weldments and safe ends, and provide the materials properties including toughness and tensile data, long-term effects such as thermal aging, and other limitations.

c. Specify the type and magnitude of the loads applied (forces, bending and torsional moments), their source(s) and method of combination. For each pipe size in the functional system, identify the location(s) which have the least favorable combination of stress and material properties for base metal, weldments and safe ends.

d. Postulate a throughwall flaw at the location(s) specified in (c.) above. The size of the flaw should be large enough so that the leakage is assured of detection with the margin specified in III.3 above using the installed leak detection capability when the pipes are subjected to normal operating loads. If auxiliary leak detection systems are relied on, they should be described. For the estimation of leakage, the normal operating loads (i.e., deadweight, thermal expansion, and pressure) are to be combined based on the algebraic sum of individual values.

e. Using fracture mechanics stability analysis or limit load analysis based on (1.) below, and normal plus SSE loads, determine the critical crack size for the postulated throughwall crack. Determine crack size margin by comparing the selected leakage size crack to the critical crack size. Demonstrate that there is a margin of 2 between the leakage and critical crack sizes. The same load combination method selected in (f.) below must be used to determine the critical crack size.

f. Determine margin in terms of applied loads by a crack stability analysis. Demonstrate that the leakage size cracks will not experience unstable crack growth if 1.4 times the normal plus SSE loads are applied. Demonstrate that crack growth is stable and the final crack is limited such that a double-ended pipe break will not occur. However, the 1.4 margin can be reduced to 1.0 if the deadweight, thermal expansion, pressure, SSE (inertial), and seismic anchor motion (SAM) loads are combined based on individual absolute values as follows:

$$F_{Combined} = |F_{Deadweight}| + |F_{Thermal}| + |F_{Pressure}| + |F_{SSE}| + |F_{SAM}|$$

$$(M_i)_{Combined} = |(M_i)_{Deadweight}| + |(M_i)_{Thermal}| + |(M_i)_{Pressure}| + |(M_i)_{SSE}| + |(M_i)_{SAM}|$$

$$(M)_{Combined} = \sqrt{(M_1)^2_{Combined} + (M_2)^2_{Combined} + (M_3)^2_{Combined}}$$

where F denotes the axial force, M_i denotes the i-th component of moment (i = 1, 2, 3), M denotes the total moment, and the subscripts denote the load. An evaluation of seismic anchor motion loads at SSE conditions may be omitted when these are shown to be small at OBE conditions.

g. The piping materials toughness (J-R curves) and tensile (stress-strain curves) properties should be determined at temperatures near the upper range of normal plant operation.

h. The specimen used to generate J-R curves should be large enough to provide crack extensions up to an amount consistent with J/T condition determined by analysis for the application. Because practical specimen size limitations exist, the ability to obtain the desired amount of experimental crack extension may be restricted. In this case, extrapolation techniques may be used as described in NUREG-1061, Volume 3, or in NUREG/CR-4575. Other techniques can be used if adequately justified.

i. The stress-strain curves should be obtained over the range from the proportional limit to maximum load.

j. Preferably, the materials tests should be conducted using archival material for the pipe being evaluated. If archival materia, is not available, plant specific or industry wide generic material data bases can be assembled and used to define the required material tensile and toughness properties. Test material should include base and weld metals.

k. To provide an acceptable level of reliability, plant specific generic data bases must be reasonable lower bounds for compatible sets of material tensile and toughness properties associated with materials at the plant. To assure that the plant specific generic data base is adequate, a determination must be made to demonstrate that the generic data base represents the range of plant materials to be evaluated. This determination is based on a comparison of the plant material properties identified in (b.) above with those of the materials used to develop the generic data base. The number of material heats and weld procedures tested must be adequate to cover the strength and toughness range of the actual plant materials. Peasonable lower bound tensile and toughness properties from the plant specific generic data base are to be used for the stability analysis of individual materials, unless otherwise justified.

   Industry generic data bases must provide a reasonable lower bound for the population of material tensile and toughness properties associated with any individual specification (e.g., A106, Grade B), material type (e.g., austenitic steel) or welding procedures.

   The number of material heats and weld procedures tested must be adequate to cover the range of the strength and tensile properties expected for specific material specifications or types. Reasonable lower bound tensile and toughness properties from the industry generic data base are to be used for the stability analysis of individual materials.

   If the data are being developed from an archival heat of material, three stress-strain curves and three J-resistance curves from that one heat of material is sufficient. The tests should be conducted at temperatures near the upper range of normal plant operation. Tests should also be conducted at a lower temperature, which may represent a plant condition (e.g., hot standby) where pipe break would present safety concerns similar to normal operation. These tests are intended only to determine if there is any significant dependence of toughness on temperature over the temperature range of interest. The lower toughness should be used in the fracture mechanics evaluation. One J-R curve and one stress-strain curve for one base metal and weld metal are considered adequate to determine temperature dependence.

1. There are certain limitations that currently preclude generic use of limit load analyses to evaluate leak-before-break conditions for eliminating pipe restraints. However, a modified limit-load analysis can be used for austenitic steel piping to demonstrate acceptable margins as indicated below:

Construct a master curve where a stress index, SI, given by

$$SI = S + M\,P_m \tag{1}$$

is plotted as a function of postulated total circumferential throughwall flaw length, L, defined by

$$L = 2\,\theta\,R \tag{2}$$

where

$$S = \frac{2\,\sigma_f}{\pi}\,[\,2 \sin\beta - \sin\theta\,], \tag{3}$$

$$\beta = 0.5\,[(\pi - \theta) - \pi\,(P_m/\sigma_f)], \tag{4}$$

θ = half angle in radians of the postulated throughwall circumferential flaw,

R = pipe mean radius, that is, the average between the inner and outer radius,

P_m = the combined membrane stress, including pressure, deadweight, and seismic components,

M = the margin associated with the load combination method (that is, absolute or algebraic sum) selected for the analysis,

σ_f = flow stress for austenitic steel pipe material categories.

If $\theta + \beta$ from Eqs. (2) and (4) is greater than π, then

$$S = \frac{2\sigma_f}{\pi}\,[\,\sin\beta\,], \tag{5}$$

where

$$\beta = -\pi\,(P_m/\sigma_f). \tag{6}$$

When the master curve is constructed using Eqs. (1), (2), and (3) or (5), the allowable circumferential throughwall flaw length can be determined by entering the master curve at a stress index (SI) value determined from the loads and austenitic steel piping material of interest. The allowable flaw size determined from the master curve at the appropriate SI value can then be used to determine if the required margins are met. Allowable values of θ are those that result in S being greater than zero from Eqs. (3) and (5). The flow stress used to construct the master curve and the definition of SI used to enter the master curve are defined for each material category as follows:

Base Metal and TIG Welds:

The flow stress used to construct the master curve is

$$\sigma_f = 0.5\ (\sigma_y + \sigma_u)$$

when the yield strength, σ_y, and the ultimate strength, σ_u, at temperature are known.

If the yield and ultimate strengths at temperature are not known, then Code minimum values at temperature can be used, or alternatively if

$$\frac{(SI)}{17M} < 2.5, \text{ then}$$

$$\sigma_f = 51 \text{ ksi, or}$$

if

$$\frac{(SI)}{17M} \geq 2.5, \text{ then}$$

$$\sigma_f = 45 \text{ ksi,}$$

The value of SI used to enter the master curve for base metal and TIG welds is

$$SI = M\ (P_m + P_b) \qquad (7)$$

where

P_b = the combined primary bending stress, including deadweight and seismic components.

Shielded Metal Arc (SMAW) and Submerged Arc (SAW) Welds:

The flow stress used to construct the master curve must be 51 ksi.

The value of SI used to enter the master curve for SMAW and SAW is

$$SI = M\ (P_m + P_b + P_e)\ Z \qquad (8)$$

where

P_e = combined expansion stress at normal operation,

$Z = 1.15\ [1.0 + 0.013\ (OD-4)]$ for SMAW, (9)

$Z = 1.30\ [1.0 + 0.010\ (OD-4)]$ for SAW, (10)

and

OD = pipe outer diameter in inches.

When the allowable flaw length is determined from the master curve at the appropriate SI value, it can be used to determine if the required margins on load and flaw size are met using the following procedure:

For an absolute sum load combination method, M = 1.0, and if the allowable flaw length from the master curve is equal to at least twice the leakage size flaw, then the margins on load and flaw size are met.

For the algebraic sum method of load combination, first let M = 1.4, and if the allowable flaw length from the master curve is at least equal to the leakage size flaw, then the margin on load is met. Second, let M = 1.0 and if the allowable flaw length from the master curve is at least twice the leakage size flaw, then the margin on flaw size is met.

Additional guidance on the fracture mechanics evaluation can be found in NUREG-1061, Volume 3, Chapter 5, dated November 1984, and entitled "Report of the U.S. Nuclear Regulatory Commission Piping Review Committee" and subtitled "Evaluation of Potential for Pipe Breaks".

IV. EVALUATION FINDINGS

The reviewer verifies that sufficient information has been provided and that his review supports conclusions of the following type, to be included in the staff's safety evaluation report:

The staff evaluation determines on a plant specific and piping system specific basis that the acceptance criteria are satisfied and, therefore that dynamic effects of pipe rupture may be eliminated from design consideration. When dynamic effects of pipe rupture are eliminated, protective devices such as pipe whip restraints and jet impingement barriers are no longer needed, and other related design changes can take place. The staff determination is based on the following:

1. That water hammer, corrosion, creep, fatigue, erosion, environmental conditions and indirect sources are remote causes of pipe rupture.

2. That a deterministic fracture mechanics evaluation has been completed and approved by the the staff.

3. That leak detection systems are sufficiently reliable, redundant, diverse and sensitive, and that margin exists to detect the throughwall flaw used in the deterministic fracture mechanics evaluation.

V. IMPLEMENTATION

The following is intended to provide guidance to applicants and licensees regarding the NRC staff's plans for using this SRP section.

Except in those cases in which the applicant proposes an acceptable alternative method for complying with specific portions of the Commission's regulations, the methods described herein will be used by the staff in its evaluation of conformance with Commission regulations.

Only dynamic effects of postulated pipe ruptures may be eliminated when leak-before-break technology is shown to be applicable. Requirements for containment design, emergency core cooling system performance and environmental qualification of electrical and mechanical equipment are not affected. (See the supplementary information to the final broad scope GDC-4 amendment which permits an exception to this statement for equipment qualification under certain conditions).

Applicants for operating licenses seeking to modify design features to take advantage of leak-before-break technology are required to reflect the revised design in an amendment to the pending FSAR. If the design change modifies design criteria set forth in the PSAR, an amendment to the applicable construction permit may also be necessary.

After leak-before-break technology results are accepted for specific piping systems at specific plants, any proposed future plant modifications in operating conditions or plant features may require an assessment of the impacts on the original conclusions from the initial leak-before-break evaluation.

When leak-before-break is successfully demonstrated, all postulated pipe ruptures are eliminated in the specific piping system under review. Ruptures in branch connections to the piping system under review are still postulated, unless these lines also qualify for leak-before-break. An evaluation of dynamic effects at these branch connections is required, as for example, in heavy component support design or redesign.

When dynamic effects of pipe rupture are eliminated from the design basis, current NRC criteria and industry codes, such as the ASME Code, may be required for calculating the seismic loads in the heavy component support redesign of operating plants or plants under construction (for example, when snubbers are reduced in number or capacity in older operating plants; on the other hand, changing high strength fastener material would not require the use of current codes or NRC criteria). In heavy component support redesign, the already existing SSE may be used, and improved functional reliability must be demonstrated for any changes implemented. Structural capacity associated with the original steel and concrete, including struts, columns, pedestals, hangers, trusses and skirts cannot be diminished in the support system of operating plants or plants under construction. Redesign will be limited to replacing high strength fastener material and reducing the number and capacity of snubbers. Applicants and licensees undertaking heavy component support redesign, with dynamic effects of pipe rupture eliminated, should use independent design and fabrication verification procedures to minimize the potential for design and construction errors. Displacements and rotations resulting from potential failure of redesigned lateral (horizontal) supports should not lead to the rupture of piping connected to the reactor coolant loop heavy components.

VI. REFERENCES

1. 10 CFR Part 50, Appendix A, General Design Criterion 4, "Environmental and Dynamic Effects Design Bases".

2. NUREG-1061, Volume 3, "Report of the U.S. Nuclear Regulatory Commission Piping Review Committee, Evaluation of Potential for Pipe Breaks", November 1984 .

3. Regulatory Guide 1.45, "Reactor Coolant Pressure Boundary Leakage Detection Systems".

4. EPRI Report NT-4690-SR, "Evaluation of Flaws in Austenitic Steel Piping", April, 1986.