Break Area for Use in Determining Debris Generation

1.0 INTRODUCTION

One of the primary safety concerns regarding long-term recirculation cooling following a Loss of Coolant Accident (LOCA) is the debris materials transported to the debris interceptors (i.e., trash racks, debris screens, suction strainers) inside containment and the potential for debris accumulation to result in adverse blockage effects. Debris resulting from a LOCA, together with debris that exists before a LOCA, could block the emergency core cooling (ECC) debris interceptors and result in degradation or loss of NPSH margin. Such debris can be divided into the following categories: (1) debris that is generated by the LOCA and is transported by blowdown forces (e.g., insulation, paint), (2) debris that is generated or transported by washdown, and (3) other debris that existed before a LOCA (dust, sand, etc.).

The first step to evaluating post-accident sump performance is to determine the amount of debris generated from a postulated breach in the piping system. Presented here is a method for use by the PWR Industry to define the piping breach size for evaluating debris generation following a postulated LOCA. This methodology utilizes fracture mechanics techniques as the basis for determining the debris generation resulting from a postulated piping break. This method does not apply to debris resulting from washdown or debris that pre-existed the LOCA.

The application of fracture mechanics to demonstrate that a through-wall flaw is stable (will not grow) has been previously demonstrated (Reference 1). The fracture mechanics techniques described in the current document are the same techniques that have been used successfully in the demonstration of Leak-Before-Break (LBB) and the application of LBB to postulated leakage cracks in large reactor coolant piping in PWR's. These leakage cracks have leak rates well above the demonstrated PWR leak detection capabilities (typically 10 gpm), while at the same time are shown to remain stable under all normal and off-normal plant operating conditions. However, application of leak-before-break to sump performance evaluation would suggest that no consequential pipe rupture occurs and therefore no debris is generated. Alternatively, the method presented herein applies the same techniques but assumes that a breach does occur and establishes its size conservatively with respect to assuring the necessary performance of the containment sumps. Therefore, this method credits the demonstrated toughness of PWR piping yet defines a reasonable design input for sump performance evaluation.

2.0 TECHNICAL BASIS FOR FRACTURE MECHANICS APPROACH

Significant testing and analyses have been performed to characterize the behavior and response of flaws that may be present in reactor coolant piping. These efforts have provided a comprehensive and realistic basis for defining stable through-wall cracks in large PWR reactor coolant piping. The fracture mechanics analytical techniques, applied reactor coolant system loadings, actual material properties, and installed leak detection capabilities are discussed below. Combined in a comprehensive plant-specific analysis, these techniques demonstrate that a conservatively postulated through-wall crack would be large enough to be detected by plant leak detection systems, yet remain stable in the full power operating environment, including faulted loading conditions (References 2, 3, and 4).

The following discussion is applicable to and includes both stainless steel and carbon steel piping with stainless steel clad.

2.1 Piping System Loading Conditions

The loads resulting from both normal operating conditions and faulted plant conditions are applied in the evaluation of both the stability and leakage of through-wall cracks or flaws. These conditions conservatively bound other loading conditions on the piping systems of interest. The components for normal loads are pressure, dead weight and thermal expansion.

Normal condition loads are used in the leak rate calculations. For a given length crack or flaw, the application of normal operating condition loads determines the flow area and leakage rate.

For the faulted condition loading, loads associated with the safe shutdown earthquake (SSE) are considered in addition to the normal loads. This load combination is used in the demonstration of crack stability.

2.2 Material Characterization

Material properties for the fracture mechanics evaluations are taken from the certified material test reports (CMTRs). Properties are determined both at room temperature and/or at operating temperature. Forged and cast stainless steels both typically have high fracture toughness values. However, cast stainless steels are subject to thermal aging during service. This thermal aging causes an elevation in the yield strength of the material and a degradation of the fracture toughness. Detailed fracture toughness testing has been performed for cast stainless steel, the results of which are used to establish the end-of-service life (40 or 60 years, as determined by the plant) fracture toughness values for specific materials. Detailed fracture toughness testing has also been performed for the low alloy ferritic steel pipe materials and associated weldments.

2.3 PWR Primary Loop Piping Leak Rate Determination

The determination of leakage crack size is based on the leak detection capability of the plant leak detection systems.

LEAK DETECTION:

Early detection of leakage in components of the reactor coolant pressure boundary (RCPB) system is necessary to identify deteriorating or failed components and minimize the release of fission products. Regulatory Guide (R.G.) 1.45 (Reference 5) describes acceptable methods to select leakage detection systems for the RCPB.

R.G. 1.45 specifies that at least three different detection methods should be employed. Plant sump level flow monitoring and airborne particulate radioactivity monitoring are specifically recommended. A third method can be either monitoring of condensate flow rate from air coolers or monitoring of airborne gaseous activity.

R.G. 1.45 also recommends that flow rates from identified and unidentified sources should be monitored separately, the former to an accuracy of 10 gpm and the latter to an accuracy of 1 gpm. (Note that plants with coolant activity levels sufficiently low as to suggest radiation monitoring will not detect leakage with an accuracy of 1 gpm have implemented alternate leakage monitoring methods.) Indicators and alarms for leak detection should be provided in the main control room. The sensitivity and response time for each leakage detection system used should be such that each is capable of detecting 1 gpm or less in one hour.

All US PWR's meet or exceed the leak detection guidance of the preceding paragraph. Specific leak detection capabilities of a plant are identified in its technical specifications.

LEAK RATE CALCULATIONS:

The first step for calculating the leak rates is to determine the crack opening area when the pipe containing a postulated through-wall flaw is subjected to normal operating loads. Using the crack opening area, leak rate calculations are performed for the two-phase choked flow condition. From the actual pipe stress analysis, deadweight, normal 100% power thermal expansion and normal operating pressure loads are used in the calculation of the crack opening area and hence the leak rate. All loads are combined by the algebraic summation method.

It is noted that a through-wall circumferential flaw is postulated in the piping that would yield a leak rate of 10 gpm. A flaw that results in a 10 gpm flow rate is used to assure a factor of 10 in margin between the calculated leak rate compared to the leak detection capability of the plant.

2.4 Fracture Mechanics Evaluation

The stability of a calculated leakage crack or flaw is demonstrated based on material properties and faulted applied load conditions. Based on extensive analyses, significant margins on crack stability have been demonstrated for the calculated leakage cracks.

Local Failure Mechanism

The local mechanism of failure is primarily dominated by the crack tip behavior in terms of crack-tip blunting, initiation, extension and finally crack instability. The local stability will be assumed if the crack does not initiate at all. It has been accepted that the initiation toughness measured in terms of J_{Ic} from a J-integral resistance curve is a material parameter defining the crack initiation. If, for a given load, the applied J-integral value is shown to be less than the J_{Ic} of the material, then the crack will not initiate.

If the initiation criterion is not met, then stability is said to exist when the applied tearing modulus value is less than the material tearing modulus value, and the applied J-integral value is less than the J_{max} value of the material.

Global Failure Mechanism

Determination of the conditions which lead to failure in stainless steel is done with plastic fracture methodology because of the large amount of deformation accompanying fracture. One accepted method for predicting the failure of ductile material is the plastic instability method, based on traditional plastic limit load concepts, but accounting for strain hardening and taking into account the presence of a flaw. The flawed pipe is predicted to fail when the remaining net section reaches a stress level at which a plastic hinge is formed. The stress level at which this occurs is termed as the flow stress. The flow stress is generally taken as the average *of* the yield and ultimate tensile strength of the material at the temperature of interest. This methodology has been shown to be applicable to ductile piping through a large number of experiments.

3.0 APPLICATION OF FRACTURE MECHANICS RESULTS TO DEBRIS GENERATION

As stated in the Introduction, the fracture mechanics approach will be used to identify pipe breach areas for the evaluation of debris generation for post-accident containment sump performance evaluation. The debris generated from these pipe breach areas would be meaningfully conservative with respect to sump performance, yet have as a basis the actual behavior of the piping material under normal and off-normal conditions.

This method for determining the size of the pipe breach will utilize stable yet detectable leakage cracks already calculated for PWR primary coolant piping as a key input parameter. Compilations of stable leakage cracks that have been calculated for a number of PWR plants are presented in Table 1 (Westinghouse designed plants), Table 2 (CE designed plants), and Table 3 (B&W designed plants), along with the crack opening area for each crack. As can be seen from these tables, the crack opening areas of the stable leakage cracks are quite small and would have little debris generating capability.

For the purposes of conservatively calculating debris generation for a postulated through-wall flaw, the breach area associated with the stable leakage crack will be increased by a factor of 1000. Use of a pipe breach area that is three orders of magnitude larger than the calculated area of the associated stable leakage crack results in maximum pipe breach areas for use in evaluating debris generation as follows:

- For B&W / Framatome plants 83 in^2
- For Combustion Engineering plants 40 in^2
- For Westinghouse plants 40 in^2

For a given plant, a number of postulated LOCAs of different sizes and break locations will be used to evaluate debris generation. The break area that would be used in that evaluation would be based on the largest stable leakage crack calculated for the primary loop piping that results in a 10 gpm leakage, multiplied by 1000. The geometry of the breach in the piping will be assumed to be a circular hole in the pipe centered at the midpoint of the through-wall crack or flaw.

Using a circular hole for the break geometry, the equivalent hole diameters for the break areas identified above are calculated as:

- For B&W / Framatome plants 10.28 inch diameter

- For Combustion Engineering plants 7.10 inch diameter
- For Westinghouse plants 7.10 inch diameter

It is noted that the equivalent diameters listed above are comparable to the range of through-wall flaw lengths listed in Tables 1 through and including 3 for the respective NSSS plant designs.

This approach will also be applied to surge line piping, if fracture mechanics analysis results are available for determining stable leakage crack areas. Again, the pipe breach area would be taken as an area that is three orders of magnitude larger than the area of the stable leakage crack calculated using fracture mechanics techniques.

In considering other reactor coolant system piping for which the calculation of stable leakage cracks do not exist, the pipe breach area for evaluation of debris generation will be taken as the cross sectional area of the inside diameter of the pipe.

4.0 BENEFITS OF THE FRACTURE MECHANICS PIPE BREACH AREA METHODOLOGY

NRC research performed in support of GSI-191 has included, in part, the postulation of non-mechanistic double-ended pipe breaks (Reference 6). While this approach is certainly conservative, it may result in plant design changes that may not benefit the overall operation of the plant.

- Utilities may conclude that the only practical way to reduce the debris generation source term to a manageable size is to limit break size by installing guard pipes, piping restraints, or other similar devices. The end result of such action is that the reactor coolant piping would be less accessible than was the case prior to these modifications. The modifications will result in less accessibility inside containment. This, in turn, will result in making the performance of some inspections no longer practical, cause other inspections to take longer, and cause plant personnel to receive increased doses for routine maintenance and inspection procedures.

- Another physical solution may be to greatly increase sump screen areas to accommodate large debris loadings, particularly for sump screens that are inside of the crane wall. Screens could likely become so large as to touch or partially enclose reactor coolant piping. This may entail other plant modifications, such as the addition of piping restraints, since either the debris generation could be postulated to occur inside the sump, or damage to the sump screen may be postulated.

- In addition, order of magnitude increases in sump screen flow areas are likely to greatly impede access inside containment. This would make maintenance and inspection activities more difficult, and potentially impractical.

5.0 SUMMARY AND CONCLUSIONS

This paper outlines a method of using fracture mechanics analysis techniques to define pipe breach areas for the evaluation of consequential debris generation for post-accident containment sump performance evaluation. The size of the pipe breach will utilize stable leakage crack sizes already calculated for PWR primary coolant piping and, where available, surge line piping. The debris generated from these pipe breach areas is meaningful with respect to sump performance, yet the breach areas have as a basis the actual behavior of the piping material under normal and off-normal conditions.

A factor of 1000 will be applied to the flow area of a stable through-wall flaw for which a 10 gpm leakage is calculated to define the break size to be used evaluate possible debris generation in the area adjacent to the breach. The geometry of the breach will be taken to be a circular hole in the pipe of interest. The combination of the factor of 1000 on crack opening area and the circular hole geometry result in a break diameter that is in the range of the flaw length.

Fracture mechanics analysis techniques have been used successfully, in conjunction with plant leak detection systems, to determine the size of stable cracks for PWR primary loop piping. The leakage flow of these stable cracks has been evaluated to be 10 gpm, or a factor of 10 above the leak detection capability of PWR plants.

It is therefore concluded that the postulation of a pipe breach based on calculated stable leakage cracks using proven fracture mechanics techniques provides an acceptable, conservative, yet realistic approach for the evaluation of containment sump performance.

6.0 REFERENCES

1. WCAP-9558, Revision 2, *Mechanistic Fracture Evaluation of Reactor Coolant Pipe Containing a Postulated Circumferential Through-Wall Crack*, May 1981, [Proprietary],
2. WCAP-15131, Revision 1, *Technical Justification for Eliminating Large Primary Loop Pipe Rupture as the Structural Design Basis for the D. C. Cook Units 1 and 2 Nuclear Power Plants,* [Proprietary] (This topical report is representative of a large number of plant specific analyses performed for Westinghouse designed plants.)
3. CEN-367-A, Revision 000, *Leak-Before-Break Evaluation of Primary Coolant Loop Piping in Combustion Engineering Designed Nuclear Steam Supply Systems*
4. BAW-1847, Revision 1, *The B&W Owners Group Leak-Before-Break Evaluation of Margins Against Full Break for RCS Primary Piping of B&W Designed NSS*, September 1985 [Proprietary] (This topical report is representative of the evaluations performed for the B&W designed plants.)
5. USNRC Regulatory Guide 1.45, *Reactor Coolant Pressure Boundary Leakage Detection Systems*
6. LA-UR-01-4083, Revision 1, *GSI-191: Parametric Evaluations for Pressurized Water Reactor Recirculation Sump Performance,* August 2001

Table 1: Stable Leakage Crack Sizes for PWR Primary Loop Piping

Westinghouse Designed Plants

Pipe OD (in)	**Pipe Wall Thickness (in)**	**Stable Crack Length [Note 1] (in)**	**Crack Opening Area (in^2)**
32.12 – 37.75	2.21 – 3.27	2.5 – 8.55	0.030 – 0.040

Notes: 1) Stable crack length is based on a leak rate of 10 gpm.

Table 2: Stable Leakage Crack Sizes for PWR Primary Loop Piping

CE Designed Plants

Case	Pipe Wall Thickness (in)	Stable Crack Length [Note 1] (in)	Crack Opening Area (in^2)
Circumferential Crack in Pump Discharge	3.0	7.0	0.040
Circumferential Crack in Hot Leg	3.75	7.0	0.040
Axial Slot in Pump Suction Elbow	3.0	4.0	0.040
Circumferential Crack in Pump Suction Elbow	3.0	11.0	0.040
Circumferential Crack in Pump Discharge	2.5	7.0	0.040

Notes: 1) Stable crack length is based on a leak rate of 10 gpm.

Table 3: Stable Leakage Crack Sizes for PWR Primary Loop Piping

B&W Designed Plants

Applicable Plants	Piping Segment	Stable Crack Length [Note 1] (in)	Crack Opening Area (in^2)
Plants A, B, C, D, E, and F	Cold Leg, Straight	9.2	0.075
	Cold Leg, Elbow	9.0	0.075
	Hot Leg, Straight	8.0	0.068
	Hot Leg, Elbow	10.8	0.083
Plant G	Cold Leg, Straight	9.39	0.065
	Cold Leg, Elbow	9.41	0.074
	Hot Leg, Straight	11.39	0.074
	Hot Leg, Elbow	12.63	0.083

Notes: 1) Stable crack length is based on a leak rate of 10 gpm.