

WCAP-10584

TECHNICAL BASES FOR ELIMINATING LARGE
PRIMARY LOOP PIPE RUPTURE AS THE STRUC-
TURAL DESIGN BASIS FOR MCGUIRE
UNITS 1 AND 2

June 1984

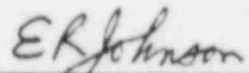
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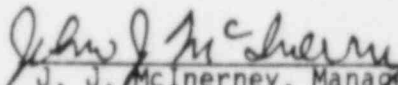
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1.0 INTRODUCTION

1.1 Purpose

This report applies to the McGuire Units 1 and 2 plant reactor coolant system primary loop piping. It is intended to demonstrate that specific parameters for the McGuire plants are enveloped by the generic analysis performed by Westinghouse in WCAP-9558, Revision 2 (Reference 1) (i.e., the reference report) and accepted by the NRC (Reference 2).

1.2 Scope

The current structural design basis for the Reactor Coolant System (RCS) primary loop requires that pipe breaks be postulated as defined in the approved Westinghouse Topical Report WCAP-8082 (Reference 3). In addition, protective measures for the dynamic effects associated with RCS primary loop pipe breaks have been incorporated in the McGuire plant design. However, Westinghouse has demonstrated on a generic basis that RCS primary loop pipe breaks are highly unlikely and should not be included in the structural design basis of Westinghouse plants (see Reference 4). In order to demonstrate this applicability of the generic evaluations to the McGuire plants, Westinghouse has performed a comparison of the loads and geometry for the McGuire plants with envelope parameters used in the generic analyses (Reference 1), a fracture mechanics evaluation, a determination of leak rates from a through-wall crack, a fatigue crack growth evaluation, and an assessment of margins.

1.3 Objectives

The conclusions of WCAP-9558, Revision 2 (Reference 1) support the elimination of RCS primary loop pipe breaks for the McGuire plants. In order to validate this conclusion the following objectives must be achieved.

- a. Demonstrate that McGuire plant parameters are enveloped by generic Westinghouse studies.

be 10^{-7} per reactor year. Thus, the results previously obtained by Westinghouse (Reference 5) were confirmed by an independent NRC research study.

Based on the studies by Westinghouse, LLNL, the ACRS, and the AIF, the NRC completed a safety review of the Westinghouse reports submitted to address asymmetric blowdown loads that result from a number of discrete break locations on the PWR primary systems. The NRC Staff evaluation (Reference 2) concludes that an acceptable technical basis has been provided so that asymmetric blowdown loads need not be considered for those plants that can demonstrate the applicability of the modeling and conclusions contained in the Westinghouse response or can provide an equivalent fracture mechanics demonstration of the primary coolant loop integrity.

This report will demonstrate the applicability of the Westinghouse generic evaluations to the McGuire plants.

2.0 OPERATION AND STABILITY OF THE REACTOR COOLANT SYSTEM

The Westinghouse reactor coolant system primary loop has an operating history which demonstrates the inherent stability characteristics of the design. This includes a low susceptibility to cracking failure from the effects of corrosion (e.g., intergranular stress corrosion cracking), water hammer, or fatigue (low and high cycle). This operating history totals over 400 reactor-years, including five plants each having 15 years of operation and 15 other plants each with over 10 years of operation.

2.1 Stress Corrosion Cracking

For the Westinghouse plants, there is no history of cracking failure in the reactor coolant system loop piping. For stress corrosion cracking (SCC) to occur in piping, the following three conditions must exist simultaneously: high tensile stresses, a susceptible material, and a corrosive environment (Reference 10). Since some residual stresses and some degree of material susceptibility exist in any stainless steel piping, the potential for stress corrosion is minimized by proper material selection immune to SCC as well as preventing the occurrence of a corrosive environment. The material specifications consider compatibility with the system's operating environment (both internal and external) as well as other materials in the system, applicable ASME Code rules, fracture toughness, welding, fabrication, and processing.

The environments known to increase the susceptibility of austenitic stainless steel to stress corrosion are (Reference 10): oxygen, fluorides, chlorides, hydroxides, hydrogen peroxide, and reduced forms of sulfur (e.g., sulfides, sulfites, and thionates). Strict pipe cleaning standards prior to operation and careful control of water chemistry during plant operation are used to prevent the occurrence of a corrosive environment. Prior to being put into service, the piping is cleaned internally and externally. During flushes and preoperational testing, water chemistry is controlled in accordance with written specifications. External cleaning for Class 1 stainless steel piping includes patch tests to monitor and control chloride and fluoride levels. For

preoperational flushes, influent water chemistry is controlled. Requirements on chlorides, fluorides, conductivity, and pH are included in the acceptance criteria for the piping.

During plant operation, the reactor coolant water chemistry is monitored and maintained within very specific limits. Contaminant concentrations are kept below the thresholds known to be conducive to stress corrosion cracking with the major water chemistry control standards being included in the plant operating procedures as a condition for plant operation. For example, during normal power operation, oxygen concentration in the RCS is expected to be less than 0.005 ppm by controlling charging flow chemistry and maintaining hydrogen in the reactor coolant at specified concentrations. Halogen concentrations are also stringently controlled by maintaining concentrations of chlorides and fluorides within the specified limits. This is assured by controlling charging flow chemistry and specifying proper wetted surface materials.

2.2 Water Hammer

Overall, there is a low potential for water hammer in the RCS since it is designed and operated to preclude the voiding condition in normally filled lines. The reactor coolant system, including piping and primary components, is designed for normal, upset, emergency, and faulted condition transients. The design requirements are conservative relative to both the number of transients and their severity. Relief valve actuation and the associated hydraulic transients following valve opening are considered in the system design. Other valve and pump actuations are relatively slow transients with no significant effect on the system dynamic loads. To ensure dynamic system stability, reactor coolant parameters are stringently controlled. Temperature during normal operation is maintained within a narrow range by control rod position; pressure is controlled by pressurizer heaters and pressurizer spray also within a narrow range for steady-state conditions. The flow characteristics of the system remain constant during a fuel cycle because the only governing parameters, namely system resistance and the reactor coolant pump characteristics are controlled in the design process. Additionally, Westinghouse has instrumented typical reactor coolant systems to verify the flow and vibration characteristics of the system. Preoperational testing and

operating experience have verified the Westinghouse approach. The operating transients of the RCS primary piping are such that no significant water hammer can occur.

2.3 Low Cycle and High Cycle Fatigue

Low cycle fatigue considerations are accounted for in the design of the piping system through the fatigue usage factor evaluation to show compliance with the rules of Section III of the ASME Code. A further evaluation of the low cycle fatigue loadings was carried out as part of this study in the form of a fatigue crack growth analysis, as discussed in Section 6.

High cycle fatigue loads in the system would result primarily from pump vibrations. These are minimized by restrictions placed on shaft vibrations during hot functional testing and operation. During operation, an alarm signals the exceedance of the vibration limits. Field measurements have been made on a number of plants during hot functional testing, including plants similar to the McGuire Units. Stresses in the elbow below the reactor coolant pump have been found to be very small, between 2 and 3 ksi at the highest. These stresses are well below the fatigue endurance limit for the material and would also result in an applied stress intensity factor below the threshold for fatigue crack growth.

3.0 PIPE GEOMETRY AND LOADING

A segment of the primary coolant hot leg pipe shown below to be limiting is sketched in Figure 3-1. This segment is postulated to contain a circumferential through-wall flaw. The inside diameter and wall thickness of the pipe are 29.2 and 2.31 inches, respectively. The pipe is subjected to a normal operating pressure of []^{a,c,e} psig. Figure 3-2 identifies the loop weld locations. The material properties and the loads at these locations resulting from deadweight, thermal expansion and Safe Shutdown Earthquake are indicated in Table 3-1. The primary loop material is cast type SA-351-CF8A. As seen from this table, the junction of the hot leg and the reactor vessel outlet nozzle (Location 1) is the worst location for crack stability analysis based on the highest stress due to combined pressure, dead weight, thermal expansion, and SSE (Safe Shutdown Earthquake) loading. At this location, the axial load (F_x) and the bending moment (M_b) are []^{a,c,e} (including axial force due to pressure) and []^{a,c,e}, respectively. This location will be referred to as the critical location. The loads of Table 3-1 are calculated as follows:

The axial force F and transverse bending moments, M_y and M_z , are chosen for each static load (pressure, deadweight and thermal) based on elastic-static analyses for each of these load cases. These pipe load components are combined algebraically to define the equivalent pipe static loads F_s , M_{ys} , and M_{zs} . Based on elastic SSE response spectra analyses, amplified pipe seismic loads, F_d , M_{yd} , M_{zd} are obtained. The maximum pipe loads are obtained by combining the static and dynamic load components as follows:

$$F_x = |F_s| + |F_d|$$

$$M_b = \sqrt{M_y^2 + M_z^2}$$

where:

$$M_y = |M_{ys}| + |M_{yd}|$$

$$M_z = |M_{zs}| + |M_{zd}|$$

The corresponding geometry and loads used in the reference report (Reference 1) are as follows: inside diameter and wall thickness are 29.0 and 2.5 inches; axial load and bending moment are []^{a,c,e} inch-kips. The outer fiber stress for either McGuire Unit is []^{a,c,e} ksi, while for the reference report it is []^{a,c,e} ksi. This demonstrates conservatism in the reference report which makes it more severe than the McGuire Units 1 and 2 analyses.

The normal operating loads (i.e., algebraic sum of pressure, deadweight, and 100 percent power thermal expansion loading) at the critical location, i.e., the junction of the hot leg and the reactor vessel outlet nozzle, are as follows:

$$F = []^{a,c,e} \text{ (including internal pressure)}$$

$$M = []^{a,c,e}$$

The calculated and allowable stresses for ASME Code Section III, NB-3600 equation 9 (faulted, i.e., pressure, dead weight and SSE) and equation 12 (thermal) at the critical location are as follows:

Equation Number	Calculated Stress (ksi)	Allowable Stress (ksi)	Ratio of Calculated/ Allowable
[] ^{a,c,e}

TABLE 3-1

McGUIRE UNITS 1 AND 2 - PRIMARY LOOP DATA

a, c, e

a the highest stressed location

b includes the axial load due to internal pressure

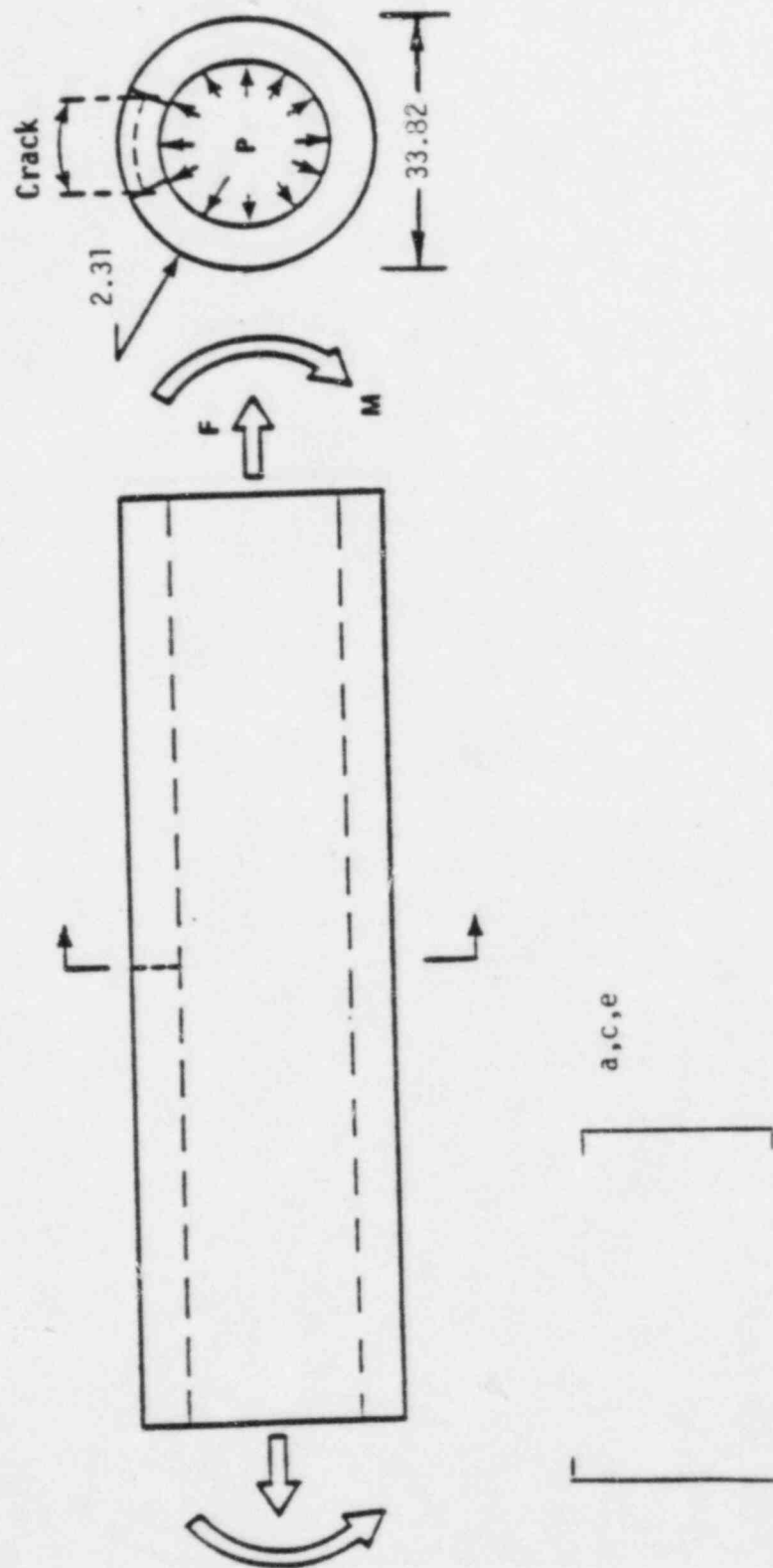
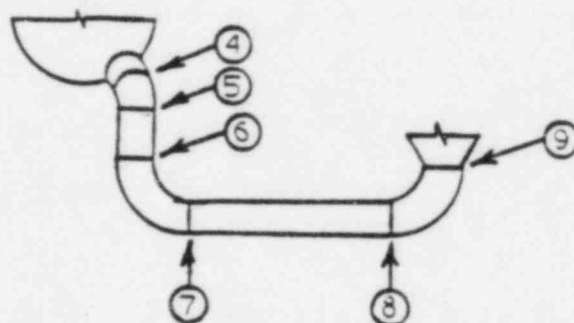
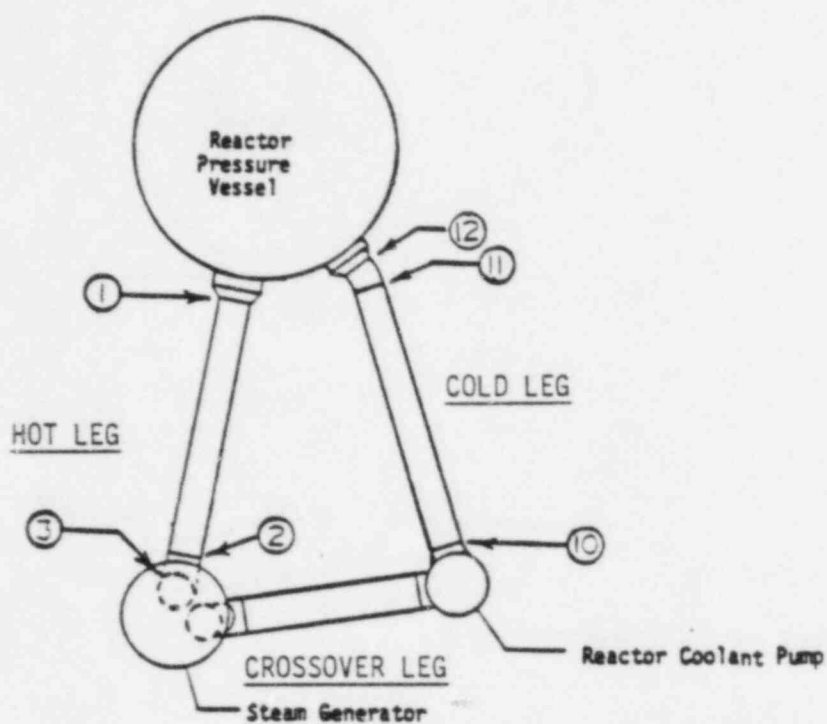


FIGURE 3-1 Reactor Coolant Pipe



<u>HOT LEG</u>	[a, c, e]
Temperature:	
<u>CROSSOVER LEG</u>	
Temperature:	
<u>COLD LEG</u>]
Temperature:	

FIGURE 3-2 Schematic Diagram of Primary Loop Showing Weld Locations - McGuire Units 1 and 2

4.0 FRACTURE MECHANICS EVALUATION

4.1 Global Failure Mechanism

Determination of the conditions which lead to failure in stainless steel must be done with plastic fracture methodology because of the large amount of deformation accompanying fracture. A conservative method for predicting the failure of ductile material is the [

] ^{a,c,e} This methodology has been shown to be applicable to ductile piping through a large number of experiments and will be used here to predict the critical flaw size in the primary coolant piping. The failure criterion has been obtained by requiring [

] ^{a,c,e} (Figure 4-1) when loads are applied. The detailed development is provided in Appendix A for a through-wall circumferential flaw in a pipe with internal pressure, axial force, and imposed bending moments. The [

] ^{a,c,e} for such a pipe is given by:

[] ^{a,c,e}

where:

[] ^{a,c,e}

a, c, e

a, c, e

4.2 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. Depending on the material properties and geometry of the pipe, flaw size, shape and loading, the local failure mechanisms may or may not govern the ultimate failure.

The 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_{IN} (i.e., J_{IC})^a from a J-integral resistance curve is a material parameter defining the crack initiation. If, for a given load, the calculated J-integral value is shown to be less than J_{IN} of the material, then the crack will not initiate. If the initiation criterion is not met, one can calculate the tearing modulus as defined by the following relation:

a The notation J_{IN} instead of J_{IC} was used in Reference 1 to designate the value of the J-integral at crack initiation; the J_{IN} notation will be used in this report in keeping with Reference 1.

$$T_{app} = \frac{dJ}{da} \frac{E}{\sigma_f^2}$$

where:

T_{app} = applied tearing modulus

E = modulus of elasticity

$\sigma_f = [\quad]^{a,c,e}$ (flow stress)

a = crack length

[$]^{a,c,e}$

In summary, the local crack stability will be established by the two-step criteria:

$$J < J_{IN}$$

$$T_{app} < T_{mat}, \text{ if } J \geq J_{IN}$$

4.3 Material Properties

The materials in the McGuire Units 1 and 2 primary loops are cast stainless steel (SA 351 CF8A) and associated welds. The tensile and flow properties of the critical location, the hot leg and the reactor vessel nozzle junction are given in Table 3-1.

The fracture properties of CF8A cast stainless steel have been determined through fracture tests carried out at 600°F and reported in Reference 12.

This reference shows that J_{IN} for the base metal ranges from [$]^{a,c,e}$ for the multiple tests carried out.

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, the degree of degradation being proportional to the level of ferrite in the material. To determine the effects of thermal aging on piping integrity, a detailed study was carried out

in Reference 13. In that report, fracture toughness results were presented for a material representative of []^{a,c,e}

Toughness results were provided for the material in the fully aged condition and these properties are also presented in Figure 4-2 of this report for information. The J_{IN} value for this material at operating temperature was approximately []^{a,c,e} and the maximum value of J obtained in the tests was in excess of []^{a,c,e}. The tests of this material were conducted on small specimens and therefore rather short crack extensions, (maximum extension 4.3 mm) so it is expected that higher J values would be sustained for larger specimens. The effect of the aging process on loop piping integrity for McGuire was addressed in Reference 13, where the plant specific material chemistry for all the loop materials was considered. []

[]^{a,c,e} This reference shows that the degree of thermal aging expected by end-of-life for these units is less than that which was produced in []^{a,c,e}. Therefore the J_{IN} values for the McGuire Units 1 and 2 at end-of-life would be expected to be considerably higher than those reported for []^{a,c,e} in Figure 4-2 (also see Reference 14). In addition, the tearing modulus for the McGuire Units 1 and 2 materials would be greater than []^{a,c,e}

Available data on stainless steel welds indicate the J_{IN} values for the worst case welds are of the same order as the aged material, but the slope of the J - R curve is steeper, and higher J -values have been obtained from fracture tests (in excess of 3000 in-lb/in²). The applied value of the J -integral for a flaw in the weld region will be lower than that in the base metal because the yield stress for the weld material is much higher at temperature. Therefore, weld regions are less limiting than the cast material.

4.4 Results of Crack Stability Evaluation

Figure 4-3 shows a plot of the []^{a,c,e} as a function of through-wall circumferential flaw length in the []^{a,c,e} of the main coolant piping. This []^{a,c,e} was calculated for McGuire from data for a pressurized pipe at []

[]^{a,c,e} properties.

The maximum applied bending moment of []^{a,c,e} in-kips can be plotted on this figure and used to determine a critical flaw length, which is shown to be []^{a,c,e} inches. This is considerably larger than the []^{a,c,e} inch reference flaw used in Reference 1.

[

] ^{a,c,e} The axial load used in the present case is 12.6 percent higher than that used in Reference 1. However, the []^{a,c,e} percent of the moment load used in Reference 1. The maximum outer fiber stress for McGuire is only 82.4 percent of that of Reference 1. [

] ^{a,c,e} On this basis it is judged that the conclusions of Reference 1 are applicable to the McGuire primary loops. Specifically, it can be concluded that a postulated []^{a,c,e} inch through-wall flaw in the McGuire loop piping will remain stable from both a local and global stability standpoint.

A [] ^{a,c,e} analysis was performed for a [] ^{a,c,e} through-wall flaw using the same approach and material properties described in detail in Reference 1. The purpose of this calculation was to investigate the crack stability for a postulated flaw larger in size than the [] ^{a,c,e} reference flaw. For the McGuire Units 1 and 2 maximum load of [] ^{a,c,e} the maximum applied J was calculated to be [] ^{a,c,e} Therefore, it is further concluded that a postulated [] ^{a,c,e} through-wall flaw in Units 1 and 2 primary loop piping will remain stable from both a local and global stability standpoint. Accordingly, the "critical" flaw size will be even greater than [] ^{a,c,e} All calculations for the 10-inch flaw were performed using the [] ^{a,c,e} code.

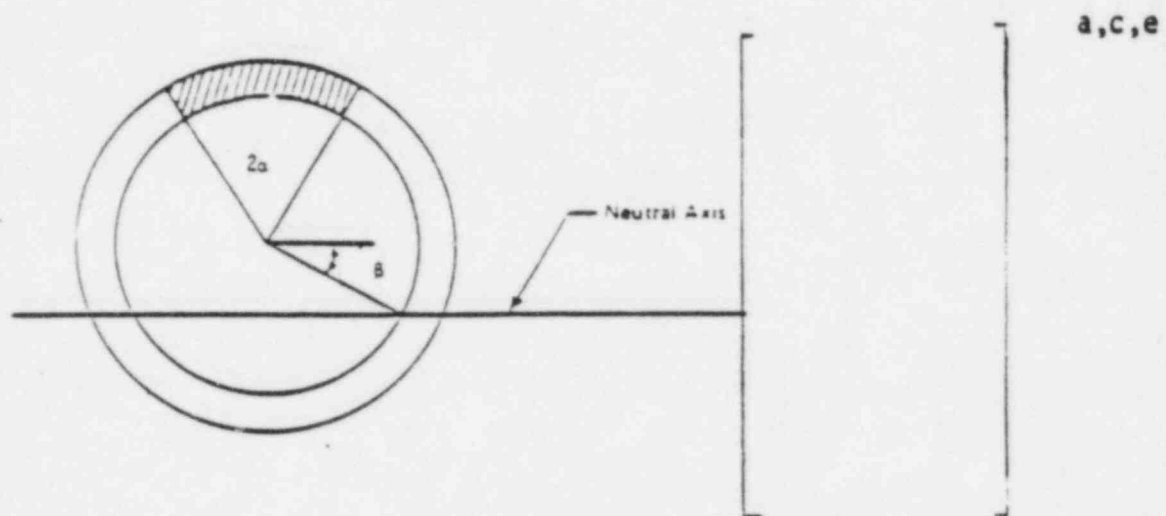


FIGURE 4-1 [a, c, e] STRESS DISTRIBUTION



FIGURE 4-2 J- Δa CURVES AT DIFFERENT TEMPERATURE. AGED MATERIAL [$]^{a,c,e}$
(7500 HOURS AT 400°C)



Figure 4-3 Critical Flaw Size Prediction

+a,c,e

5.0 LEAK RATE PREDICTIONS

Leak rate estimates were performed by applying the normal operating bending moment of []^{a,c,e} in addition to the normal operating axial force of []^{a,c,e}. These loads were applied to the hot leg pipe containing a postulated []^{a,c,e} through-wall flaw and the crack opening area was estimated using the method of Reference 15. The leak rate was calculated using the two-phase flow formulation described in Reference 1. The computed leak rate was []^{a,c,e}. In order to determine the sensitivity of leak rate to flaw size, a through-wall flaw []^{a,c,e} in length was postulated. The calculated leak rate was []^{a,c,e} flaw produced a leak rate of []^{a,c,e}.

The McGuire Units have RCS pressure boundary leak detection systems which are consistent with the guidelines of Regulatory Guide 1.45 of detecting leakage of 1 gpm in one hour. Thus, for the []^{a,c,e} inch flaw, a factor in excess of []^{a,c,e} exists between the calculated leak rate and the criteria of Regulatory Guide 1.45. Relative to the []^{a,c,e}

6.0 FATIGUE CRACK GROWTH ANALYSIS

To determine the sensitivity of the primary coolant system to the presence of small cracks, a fatigue crack growth analysis was carried out for the []^{a,c,e} region of a typical system [

] ^{a,c,e} This region was selected because it is one of the important cross sections in the primary loop. The crack growth calculated here will be typical of that in the entire primary loop.

A [

] ^{a,c,e} of a plant typical in geometry and operational characteristics to any Westinghouse PWR System. [

] ^{a,c,e}

All normal, upset, and test conditions were considered and circumferentially oriented surface flaws were postulated in the region, assuming the flaw was located in three different locations, as shown in Figure 6-1. Specifically, these were:

Cross Section A:	[] ^{a,c,e}
Cross Section B:	
Cross Section C:	

Fatigue crack growth rate laws were used [

] ^{a,c,e} The law for stainless steel was derived from Reference 16 with a very conservative correction for the R ratio, which is the ratio of minimum to maximum stress during a transient. For stainless steel, the fatigue crack growth formula is:

$$\frac{da}{dn} = (5.4 \times 10^{-12}) K_{eff}^{4.48} \text{ inches/cycle}$$

$$\text{where } K_{eff} = K_{max} (1-R)^{0.5}$$

$$R = K_{min}/K_{max}$$

[

] a,c,e

[

]

a,c,e

where: [

] a,c,e

The calculated fatigue crack growth for semi-elliptic surface flaws of circumferential orientation and various depths is summarized in Table 6-1, and shows that the crack growth is very small, regardless [

] a,c,e

TABLE 6-1

FATIGUE CRACK GROWTH AT [] ^{a,c,e} (40 YEARS)	
		FINAL FLAW (in)	
INITIAL FLAW (IN)	[^{a,c,e}	[^{a,c,e}	[^{a,c,e}
0.292	0.31097	0.30107	0.30698
0.300	0.31949	0.30953	0.31626
0.375	0.39940	0.38948	0.40763
0.425	0.45271	0.4435	0.47421

+a,c,e

]a,c,e

FIGURE 6-1 Typical Cross Section of [

CRACK GROWTH RATE, da/dN (MICRO-INCHES/CYCLE)

a, c, e

Figure 6-2 Reference Fatigue Crack Growth Curves for [
] a, c, e

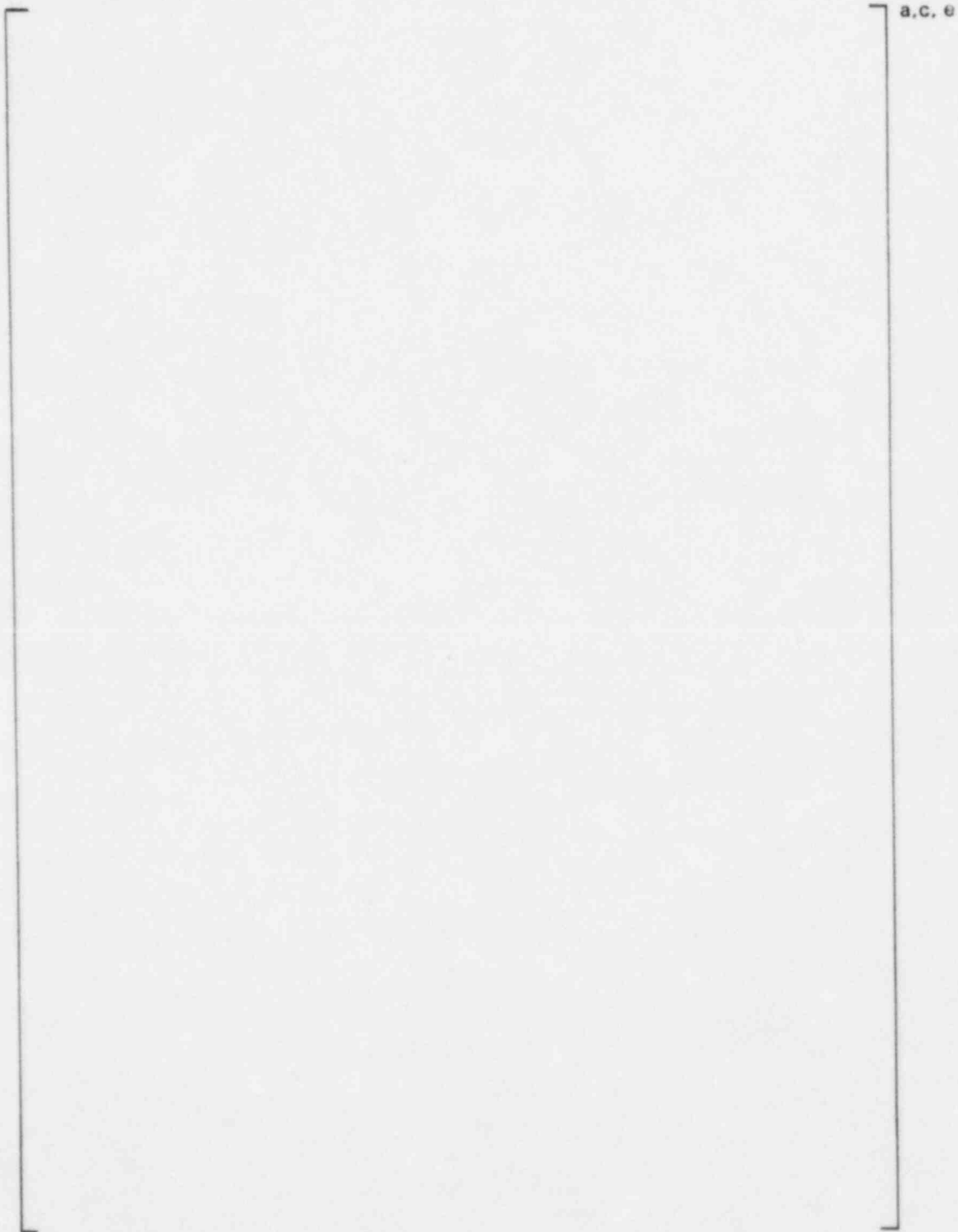


Figure 6-3 Reference Fatigue Crack Growth Law for [a,c,e]
in a Water Environment at 600°F

7.0 ASSESSMENT OF MARGINS

In Reference 1, the maximum design load was []^{a,c,e} in-kips, whereas, the maximum load as noted in Section 3.0 of this report is significantly less, []^{a,c,e} in-kips. For the current application, the maximum value of J []^{a,c,e} in-lb/in² compared with the value of []^{a,c,e} in-lb/in² in Reference 1. Furthermore, Section 4.3 shows that the testing of fully aged material of chemistry worse than that existing in cast piping extended to J values of []^{a,c,e}. Thus, at maximum load the McGuire Units 1 and 2 applied J-value is enveloped by the J_{max} of Reference 1 as well as the values used in testing fully aged materials.

In Section 4.4, it is seen that a []^{a,c,e} flaw has a J value at maximum load of [] in-lb/in² which is also enveloped by the J_{max} of Reference 1 and the value used for testing of aged material. In Section 4.4, the "critical" flaw size using the []^{a,c,e} methods is calculated to be []^{a,c,e} inches. Based on the above, the "critical" flaw size will, of course, exceed []^{a,c,e}.

Again, referring to Section 4.3 the estimated tearing modulus for McGuire Units 1 and 2 cast SS piping in the fully aged condition is greater than []^{a,c,e}. T_{applied} as taken from Reference 13 is []^{a,c,e}. Consequently a margin on local stability of at least []^{a,c,e} exists relative to tearing.

In Section 5.0, it is shown that a flaw of []^{a,c,e} would yield a leak rate of []^{a,c,e}. Thus, there is factor of at least []^{a,c,e} on flaw size between the minimum flaw size that gives a leak rate of []^{a,c,e} and the "critical" flaw size of []^{a,c,e}.

In Section 5.0, it is shown that a flaw of []^{a,c,e} would yield a leak rate in excess of []^{a,c,e} while for a []^{a,c,e} inch flaw, the leak rate is []^{a,c,e}. Thus, there is margin of more than []^{a,c,e} between a flaw size that gives a leak rate significantly exceeding the 1 gpm criterion of Regulatory Guide 1.45 and the "critical" flaw size of []^{a,c,e}.

In summary, relative to

1. Loads

- a. McGuire Units 1 and 2 are enveloped both by the maximum loads and J values in Reference 1 and the J values employed in testing of fully aged material.
- b. Margins at the critical location of []^{a,c,e} on faulted conditions and thermal stresses, respectively, exist relative to ASME Code allowable values.

2. Flaw Size

- a. A margin of at least []^{a,c,e} exists between the critical flaw and a flaw yielding a leak rate of []^{a,c,e} which in turn exceeds the 1 gpm criterion of Regulatory Guide 1.45.
- b. A margin exists of at least []^{a,c,e} relative to tearing.
- c. If []^{a,c,e} is used as the basis for critical flaw size, the margin for global stability would exceed []^{a,c,e} based on the []^{a,c,e} reference flaw size.

3. Leak Rate

A margin in excess of []^{a,c,e} exists for the reference flaw ([]^{a,c,e}) between the calculated leak rate and the criteria of Regulatory Guide 1.45.

8.0 CONCLUSIONS

This report has established the applicability of the generic Westinghouse evaluations which justify the elimination of RCS primary loop pipe breaks for the McGuire plants as follows:

- a. The loads, material properties, transients, and geometry relative to the McGuire Units 1 and 2 RCS primary loop are enveloped by the parameters of WCAP-9558, Revision 2 (Reference 1) and WCAP-10456 (Reference 13).
- b. Stress corrosion cracking is precluded by use of fracture resistant materials in the piping system and controls on reactor coolant chemistry, temperature, pressure, and flow during normal operation.
- c. Water hammer should not occur in the RCS piping because of system design, testing, and operational considerations.
- d. The effects of low and high cycle fatigue on the integrity of the primary piping are negligible.
- e. A large margin exists between the leak rate of the reference flaw and the criteria of Reg. Guide 1.45.
- f. Ample margin exists between the reference flaw chosen for leak detectability and the "critical" flaw.
- g. Ample margin exists in the material properties used to demonstrate end-of-life (relative to aging) stability of the reference flaw.

The reference flaw will be stable throughout reactor life because of the ample margins in e, f, and g above and will leak at a detectable rate which will assure a safe plant shutdown.

Based on the above, it is concluded that RCS primary loop pipe breaks should not be considered in the structural design basis of the McGuire plants.

9.0 REFERENCES

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| 17. | [| |] | a,c,e |
| 18. | [| |] | a,c,e |
| 19. | [| |] | a,c,e |

APPENDIX A

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FIGURE A-1 PIPE WITH A THROUGH-WALL CRACK IN BENDING