PROPOSED WHIPJET PROGRAM FOR

BEAVER VALLEY POWER STATION 2

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1.0 WHIPJET PROGRAM

1.1 INTRODUCTION

This proposal presents the Duquesne Light Company (DLC) WHIPJET program for a pressurized water reactor (PWR). Specifically, WHIPJET is designed for balance-of-plant high energy piping at Beaver Valley Power Station - Unit 2 (BVPS-2). This program provides pipe break protection by using state-of-the-art engineering analyses to evaluate plant piping design and by considering plant operations. WHIPJET will significantly improve worker safety and the understanding of piping system operation at BVPS-2. It provides the research and analyses required for an alternative engineering approach to pipe break protection, thereby eliminating massive whip restraints and jet shields.

This proposal is divided into eight sections. The background section reviews past and present forms of pipe break evaluation. The WHIPJET engineering program demonstrates the leak-before- break (LBB) approach, develops a material testing program, and performs pipe crack analyses. The LBB methodology that will be employed to provide pipe break protection is explained in detail. Methods are outlined to evaluate all pipe material properties, associated weld data, fatigue properties and related fracture data. Leak detection methods and capabilities are assessed for LBB applicability. The proposal develops a stress corrosion evaluation program which applies to piping at BVPS-2. An analyses explaining potential water hammer damage is given. Also, WHIPJET provides a fatigue analyses program for Class 1, 2, 3, and nonnuclear safety (seismic) pipes.

The WHIPJET program provides for pipe break protection by using advanced engineering methods. Because pipe leaks are more probable than pipe breaks, explicitly designing for leaks will improve plant safety. The WHIPJET engineering program is divided into the following areas:

- o Engineering indoctrination
- o Stress corrosion analyses

- o Water hammer analyses
- o Fatigue analyses
- o Equipment support analyses
- o Leak-Before-Break (LBB) approach
- o Leak detection

A cost benefit analysis is also performed.

The WHIPJET program is immediately applicable to the BVPS-2 nuclear power plant. An estimated 470 required pipe-terminal-end breaks and intermediate breaks will require the installation of pipe rupture restraints and/or jet impingement shields. The WHIPJET program is designed to provide an improved alternate method of pipe break protection which, in general, will not require an additional 136 rupture restraints and jet shields. The WHIPJET program will show that pipe leaks will occur before the pipe breaks for a range of postulated crack sizes. No further whip restraints will be designed or purchased. The purchased portion of the restraints will not be installed. If for any reason the fracture analysis is inconclusive, the whip restraints/jet shields will be retained.

1.2 ENGINEERING BACKGROUND

The LBB approach is an acceptable elastic-plastic fracture mechanics process which demonstrates that fluid piping is very unlikely to experience a double-ended guillotine break (DEGB).

The current Nuclear Regulatory Commission (NRC) regulations and guidance documents specify the postulation of piping ruptures in high energy fluid systems. The ruptures include circumferential and longitudinal breaks, up to and including a DEGB. The direct result of such postulated piping ruptures led to USI-A2, "Asymmetric Blowdown Loads on PWR Primary Systems," and criteria to protect structures, systems and components against the consequences of pipe breaks. Protective measures include installation of pipe whip restraints or jet impingement shields.

The concept of the DEGB was originated by the United States Atomic Energy Commission for the purpose of sizing containments and emergency core cooling systems. An instantaneous DEGB of a major primary pipe establishes an upper bound for the containment design pressure. Later, changes in seismic design shifted the DEGB from a hypothetical accident to one having more credence. Next, the assumption of a pressure vessel terminal end break and the subsequent asymmetric loading (Generic Issue A-2) led to pipe restraint requirements to minimize pipe deflection. The backfitting of nuclear power plants followed. Probabilistic studies on PWRs, deterministic studies, and an assessment of failure statistics in large pipes concluded that the probability of a DEGB is extremely low. Work performed by Lawrence Livermore National Laboratory showed that the probability of a direct DEGB in Westinghouse PWR's east of the Rocky Mountains is about 10 E-12 events per plant year [1]. The probability of an indirect DEGB is about 10 E-5 events per plant year [2].

The NRC and the nuclear industry have spent considerable time and effort in developing advanced fracture mechanics techniques for piping systems. The behavior of flawed piping under normal and accident loads is now better understood. The objective of the nuclear industry studies is to detect small pipe flaws either by in-service inspection or by leakage monitoring systems. Crack detection will occur before the cracks grow to unstable sizes which could lead to a DEGB. This approach is referred to as leak before break. The conclusion - reached after many years of operating experience, as well as these fracture studies - is that cracked piping is much more likely to leak before it breaks. Piping failure can still occur, but improved knowledge of the failure modes and appropriate remedial measures can reduce the probability of catastrophic failure to insignificant values.

1.2.1 Regulations

Various regulations and Regulatory Guides are involved in the revision process that has emerged because of the LBB approach. Appendix A of 10 Code of Federal Regulations (CFR) part 50, "General Design Criteria (GDC) for Nuclear Power Plants," requires postulation of pipe breaks and provision for appropriate protection against associated dynamic effects.

Regulatory Guide 1.45, "Reactor Coolant Pressure Boundary Leakage Detection Systems," [3] describes acceptable methods for selecting leakage detection systems. At least three different leak detection methods should be used, two of which are sump level flow monitoring and airborne particulate radioactivity monitoring. The sensitivity for each leakage detection system should be 1 gallon per minute (gpm) or less in a one hour time span. Unidentified leakage flow should be monitored to an accuracy of 1 gpm.

Regulatory Guide 1.46, "Protection Against Pipe Whip Inside Containment," [4] is a quantitative attempt (1) to determine locations and orientations of postulated breaks in pipes and (2) to determine the restraints for pipe rupture. This guide includes all ASME Code Classes of piping inside containment. It states that piping systems (1) pressurized to 275 psig or more or (2) with a design temperature of 200 F or more (e.g., high energy lines), should be provided with protection against pipe whipping.

1.2.2 Objectives

If WHIPJET is to be a viable program, two general objectives must be accomplished. These objectives are:

1) Demonstrate that the LBB approach is applicable to the high energy piping at BVPS-2.

2) Develop the required technical justification for a LBB submittal.

The first objective will have the following strategies:

- o Ensure that none of the pipe whip restraint removal limitations described in NUREG 1061, Vol. 3 apply to BVPS-2

- o Outline the necessary tasks to show that fatigue, stress corrosion, and water hammer are not problem areas

- o Identify piping locations, if any, where whip restraints and jet shields should be retained due to severe corrosion, brittle materials, weld, or highly probable indirect failure modes.

The second objective will have the following strategies:

- o Review and follow the general technical guidance described in NUREG 1061, Volumes 3 and 5.
- o Develop and implement a materials testing program
- o Review existing pipe base metal and weld material properties
- o Review stress analyses for pipe loadings
- o Perform crack growth, crack stability, and crack opening versus leak rate analyses
- o Establish fracture safety margins
- o Demonstrate a safe leakage margin within leak detection system capabilities.

1.2.3 Program Tasks

A list of tasks required to complete the program follows:

Task 1.0 Stress Corrosion Analyses

Task 2.0 Water Hammer Analyses

Task 3.0 Equipment Support Analyses

Task 4.0 Fatigue Analyses

Task 5.0 LBB Analyses

Task 6.0 Leak Detection Studies

Task 7.0 Cost Benefit Analysis

1.3 STRESS CORROSION ANALYSES

1.3.1 Background

In order for stress corrosion cracking (SCC) to occur in piping, three conditions must exist

simultaneously: high tensile stresses, a susceptible material condition, and a corrosive fluid environment. Normally, the water chemistry or material condition will be the most controllable conditions due to the less controllable residual weld stresses. Since all steels are susceptible to stress corrosion cracking, some more than others, material selection becomes a parameter that can be effectively used to minimize the potential for pipe cracking. Finally, the most important controllable parameter, used to minimize the potential for PWR SCC, is the environment.

The elements known to increase the susceptibility of austenitic stainless steel to stress corrosion are: Oxygen, fluorides, chlorides, hydroxides, and reduced forms of sulfur (e.g., sulfides and sulfites). In carbon steel, hydroxides, caustics, and nitrates increase susceptibility.

BWRs, unlike PWRs, have encountered more problems with SCC. But, BWR experiences with SCC have led to residual weld stress improvement methods such as last pass heat sink welding and subassembly annealing, thereby minimizing as-welded stress conditions to field welds only.

High tensile stress may be due to residual welding stresses, operating stresses, vibrational stresses, and/or thermal stresses. Studies of PWR piping conducted in 1979 and 1980 concluded that SCC was not a problem for the primary coolant system. SCC was considered to be a secondary contributor to lower pressure, thin-walled secondary or tertiary systems [5]. Also, it is generally accepted that SCC at temperatures below 200 F would be very slow.

1.3.2 Methodology

The potential for SCC near welds in high energy lines has been minimized by controlling the water chemistry parameters which promote corrosion. By maintaining a high degree of fluid cleanliness and controls on the water chemistry, SCC will be insignificant. Anti-corrosive steels also inhibit SCC. All high energy stainless steel piping at BVPS-2 is made of alloy Type 304 or Type 316. All high energy piping made with carbon steel is made of medium carbon steel, typically SA-106 Gr B and some SA-106 Gr C. Piping welds are made of Type 308 stainless steel.

WHIPJET conducts a specific review of SCC of piping on a system-by-system basis. For each class of piping material, the combination of stress levels, material, and corrosive fluid environment is assessed. Methods used to control and monitor piping fluid chemical and corrosive make-up also will be assessed.

1.3.3 Stress Corrosion Program Tasks

Item 1. Material Selection

The stainless, carbon steel, and weldment material properties and heat numbers used for high energy piping will be tabulated. The susceptibility of these materials to SCC will be assessed.

Item 2. Corrosive Environment

Chemical make-up criteria for primary and secondary piping fluids will be indicated. Methods used to control and monitor piping fluid chemical and corrosive make-up will be indicated. Procedures taken to assure a clean pipe prior to operation will be documented.

Item 3. Operating Temperature

The maximum normal and upset operating temperature for each high energy piping system being considered will be tabulated.

Item 4. Conclusions

The WHIPJET program will assess the potential for SCC and formulate a conclusion.

1.4 WATER HAMMER ANALYSES

1.4.1 Background

Over 125 instances of water hammer events have occurred in nuclear power plants since the late 1960's [6]. In the early 1970's the frequency of occurence increased and, in one plant, a water hammer event caused a feedwater line rupture [7]. Since then, only one incident has resulted in pressure boundary failure due to water hammer. Total elimination of water hammer occurrences is not possible because inherent in the design of nuclear power plants is the possible existence of steam and water voids in the various systems.

Operator awareness of water hammer potential and avoidance training has been stressed. Findings and preventive measures are reported in NUREG-0927, "Evaluation of Water Hammer in Nuclear Power Plants - Technical Findings Relevant to Unresolved Safety Issue A-1." For example, methods to detect voids and vent systems to prevent water hammer are presented [7].

1.4.2 Methodology

In general, Westinghouse PWR's are not susceptible to water hammer. The reactor coolant, chemical and volume control, and residual heat removal systems have been specifically designed to preclude water hammer damage. Operating experience at other plants with Westinghouse systems have verified this design approach. Potential water hammer sources considered during the operation of BVPS-2 were based on industry experience and the concerns presented in NUREG-0582, "Water Hammer in Nuclear Power Plants." Water hammer caused by steam voids, condensation, flashing, and thermal mixing are controlled through system design and operating procedures.

WHIPJET assesses the potential for harmful pipe water hammer on each system. Also, transients considered applicable to BVPS-2 water hammer analyses will be reviewed.

1.4.3 Water Hammer Program Tasks

Item 1. Technical Justification

On each piping system, provide technical justification for concluding that water hammer caused by steam voids, condensation, flashing, and thermal mixing are adequately controlled and minimized.

Item 2. Flow Transient Study

Provide an applicability study of flow transients listed in NUREG-0582 for BVPS-2.

Item 3. Calculation Index

Provide a calculation index (e.g., a list) for those flow transients found applicable to BVPS-2.

1.5 FATIGUE ANALYSES

1.5.1 Background

Fatigue induced cracking can occur when stresses, resulting from thermal cyclical loading, are concentrated at a discontinuity. Depending on the range of stresses and the magnitude of stress near the discontinuity, continued cyclic loading may produce a crack or a leak. The source of the cycling may be due to either thermal or mechanical loading (external or flow induced).

To prevent harmful fatigue effects, the ASME Code Section III [8], requires satisfaction of specific stress and cumulative fatigue usage factor criteria for Class 1 piping systems. The Code requires the use of specific cyclical loading information and performance of a fatigue analysis.

For Class 2, 3, and nonnuclear safety (seismic) piping systems, fatigue effects are controlled by limiting the number of thermal cycles to below 7000 and meeting lower allowable stress criteria [8]. A reduction in the allowable stress is taken if the number of cycles exceeds 7000. No cumulative usage factor is developed as part of these analyses.

Fatigue effects on all pipe classes are minimized by designing the piping system and developing operating procedures which minimize the magnitude and number of loading cycles.

The mechanical loading from steady-state vibration is minimized in the design of piping systems by controlling fluid velocity. Also, cavitation fluid transients are minimized by (1) preventing pipe support column separation and (2) carefully controlled pump and valve operation sequences. System design is evaluated in order to determine the potential for transients in BVPS-2. Any transients which remain are evaluated to assure that design criteria for stress and support/equipment loading are met. Steady state and transient vibrations are evaluated by visual inspection during outages and/or instrumented techniques.

Thermal transients resulting from thermal mixing are controlled by the system layout and by use of fluid control valves. The mixing of feedwater with steam generator fluid at a higher temperature is further minimized by the use of inverted "J" tubes in the feedwater distribution rings.

1.5.2 Fatigue Program Tasks

Item 1. Pipe System Selection Criteria

Class 2, 3, and nonnuclear safety (seismic) piping will be reviewed and assessed for susceptibility to fatigue based on the expected cumulative usage factor (CUF) as defined in Reference 8. This will be determined by engineering judgment and then justified. The CUF is defined as the sum of various loading cycle ratios which alone are below the failure limit but can still cause damage. The amount of damage is determined in part by the ratio of actual cycles to allowable cycles. When the individual fatigue usage factor ratios are summed, the cumulative effect is known. Reference 8 allows the CUF to be less than or equal to 1.0.

Two groups of piping systems shall be identified:

(a) Those piping systems which, by virtue of their location to the Reactor Coolant System (RCS), system operation, or other attribute are assessed as having a CUF less than or equal to 0.1. Typical examples would be piping systems:

- With little or no flow
- With low fluid temperatures
- With as-analyzed CUF less than or equal to 0.1. (Class 1 line extensions)

(b) Those remaining piping systems which have a CUF greater than 0.1.

Item 2. Determination of Thermal Transients

Piping systems included in 1.5.2 Item 1 (a) will not require further evaluation for fatigue effects since significant cyclic loading does not occur.

Piping systems included in 1.5.2 Item 1 (b) require a more extensive review. Before any transients are developed, each system will be assessed for:

(a) The number of pipe breaks and the required number of whip restraints or jet shields. For some pipes, it may be more cost effective to install whip restraints and jet shields than to do the analyses to justify not installing these restraints. An example might be pipes with few restraints.

(b) The availability of existing thermal transient data that can be used in lieu of generating new data. An example might be the chemical and volume control system (CHS) which is connected to the RCS. Use of RCS transients would be applicable and conservative.

(c) Piping with similar dynamic loading conditions. Only one or two pipes representative of this group should be analyzed.

(d) Analyze only the worst-case portion of the piping systems.

(e) Develop transients in a conservative manner. Only those piping systems very likely to be accepted shall be analyzed. Also, the cost of developing thermal data must significantly out-weigh the cost of providing restraints and/or shields.

Item 3. <u>Performance of Fatigue Analysis</u>

Those piping systems that cannot be justified as having adequate fatigue resistance, using comparison and judgment methods, will be analyzed for fatigue. Simplified methods shall be used using conservative assumptions as required. The peak stress range equation (Equation 11) will be used to determine the Class 2 and 3 pipe stress condition [8]. Only selected worst-case locations will be analyzed. Since existing Class 2 and 3 stress calculations already include pressure and moment loading terms, only the thermal expansion portion of equation 11 requires investigation. Thermal transients from Item 2 above can be used to determine the thermal terms. Equation 11 [8] includes stress

multipliers or indices which account for fabrication techniques, surface condition, and other stress discontinuities. These indices will be applied conservatively. Hand calculation methods will be used. Other simplified analytical techniques will be developed as required.

1.6 EQUIPMENT SUPPORT ANALYSES

As part of the WHIPJET program, the effect of failure of major equipment supports must be considered. Support failure must be examined to ensure that piping integrity is not compromised. Generic Letter 84-04 discusses pump support, steam generator support, and core support modifications required in some Westinghouse plants for primary coolant loop whip restraint removal [9]. For the non-primary coolant loop piping, different equipment supports will be involved.

First, a criteria on which equipment supports need to be examined will be established. This criteria will be based on which supports can cause pipe failure. Next, a structural analysis will be performed to prove that the critical equipment supports do not cause failure. Should modifications to equipment supports be necessary, they will be made.

1.7 LEAK-BEFORE-BREAK APPROACH

1.7.1 Background

The LBB approach does not reduce safety margins at BVPS-2. In theory, the LBB approach uses state-of-the-art fracture mechanics technology to demonstrate that high energy fluid piping is very unlikely to experience double-ended guillotine breaks (DEGB). The LBB approach does not eliminate the loss of coolant criteria for engineered safety features, and it will not

reduce the safety margin for the FSAR (Final Safety Analysis Report). The FSAR provides the design measures for BVPS-2. These measures ensure that equipment in containment is adequately protected against the effects of a blowdown jet and pipe whip resulting from a postulated pipe rupture [10]. Although the LBB approach is relatively new, it is widely accepted and is a reliable alternative to the DEGB criteria. The WHIPJET LBB approach includes the following programs:

- Material classification
- Material testing
- Experimental testing analyses
- Pipe crack analyses

1.7.2 Methodology

Representative high energy lines at BVPS-2 will be chosen to demonstrate the scope of applicability of the advanced engineering analyses. These lines will have properties, welding processes and characteristics typical throughout BVPS-2. Worst-case conditions will be studied to establish upper and lower bounds.

The WHIPJET program will review applied forces, bending moments, and torsional moments for selected pipes in the systems listed above. Loading conditions will be converted to actual applied stresses. Past experience has shown that torsion is not a concern for opening mode pipe cracking. This review includes load type, magnitude, source (e.g., thermal, pressure, displacement, etc.), and method of combinations. Also, the points where worst-case material properties coincide with peak stresses for the base metal, welds and safe ends will be anlayzed. Long term effects such as thermal aging (not expected to be of concern) will be considered.

A step-by-step methodology for worst-case situations will be established. This approach will be conservative because (1) archival material will be tested, and (2) the pipe crack stability analyses is conservative (see Appendix A). An example of the methodology is outlined as follows:

- o Assume a part-through crack (Class 1 pipes)
- o Input pipe geometry, crack geometry, pipe wall stresses, and fracture properties into a crack growth computer code
- o Derive crack growth versus time relationship
- o Next, assume a through-wall crack
- o Input geometry, loading values, and material chracteristics derived from the WHIPJET testing program
- o Determine crack stability parameters
- o Compare resultant crack size with unstable crack size to derive a safety margin
- o Compute leak rates from the crack sizes to determine whether or not the leak detection system is sensitive enough to detect the leak.

1.7.3 Material Classification

The high energy piping at BVPS-2 is made of four steels:

No.	Type
1	SA-312/376 Type 316 stainless
2	SA-312/376 Type 304 stainless
3	SA-106 Gr B carbon
4	SA-106 Gr C carbon

The WHIPJET program will review toughness and tensile data for welds, base metal material properties, and Certified Material Testing Reports (CMTR). Also, a material and weld heat number tabulation will be developed.

1.7.4 Material Testing

Stress-strain curves and material toughness J-R curves for Type 316, Type 304, Type 106-B and Type 106-C steel at 550 F will be developed during the testing program. This data will be obtained from archival material for both the piping and weldments. Comparisons with published nuclear industry tension test data will be made whenever possible. Sample industry stress-strain curves are given in Appendix C. The stress-strain curves will be obtained over the range from proportional limit to the maximum load.

To ensure stable crack extensions, the J-R resistance curves will be obtained with throughwall flawed actual pipe specimens for base metal and compact tension specimens whose thickness is equal to or greater than the pipe wall for weld metal. New J-R fracture toughness curves will be determined for archival steels from BVPS-2, but results are not expected to vary significantly from previous nuclear industry experimental data and associated curves. Sample industry J-R resistance curves are given in Appendix C.

Archival materials from some of the same heats are proposed to be tested (or, in the case of welds, will be generated with fabricated weldments using the same welding procedures). A testing plan for non-archival material will be employed; two stress-strain curves and two J-resistance curves from three heats of the material and welds will be derived. Tests will be conducted at 550 F. Also, one stress-strain curve and one J-R curve will be derived at the hot standby temperature. Therefore, a range of material toughness data will be obtained. Heat numbers for the on-site piping fabrication material (i.e., archival material), for use in the testing program, will be determined. In many cases, other than stress-corrosion cracking, the critical break location will occur in the pipe base metal rather than in or near the weld material. Whenever possible, standard industrial data for piping base metal steels and welds will be compared. Should BVPS-2 piping properties differ from industrial data, this condition will be noted. Details of the material testing program are provided in Appendix B.

The purpose of doing these tests is to generate plant specific data for comparison with material property curves like those in Appendix C for BVPS-2 fracture calculations.

1.7.5 Pipe Fracture Analysis

The high energy piping is postulated to have pre-existing part-through semi-elliptical cracks at the interior or exterior pipe surface. Generally, the circumferential welds and axial loads produce circumferentially oriented semi-elliptical cracks or complete circumferential cracks. Should the need arise, long axial and axially oriented semi-elliptical part-through cracks can also be analyzed for fatigue crack growth. A sketch of various hypothetical pipe crack configurations is shown in Figure 1. A typical through-wall crack is shown in Figure 1a. A typical interior circumferential semi-elliptical crack is shown in Figure 1b. A complete circumferential crack is illustrated in Figure 1c. An interior axial semi-elliptical crack is shown in Figure 1d, a long axial crack is shown in Figure 1e.

Section XI of the ASME Code [11] allows a reference crack depth of about 2 or 3% of the pipe wall thickness for a crack length to depth ratio, $l/a = 6$. This applies to ferritic steels. For austentic steels and submerged arc welds, the criteria for allowable crack sizes is more complicated. Assuming (1) allowable crack sizes, (2) reasonable crack aspect ratios (e.g., $l/a=6$), (3) determining the through-wall stress distribution (4) using linear elastic fracture mechanics influence function techniques [12], the fatigue crack growth analysis at the critical pipe locations can be performed. Various initial crack depths can be assumed. These fatigue growth calculations will demonstrate that significant pipe thermal fatigue crack growth will not occur during service. If necessary, vibrational fatigue effects can be considered using experimentally determined fatigue growth (da/dn versus K) properties.

Should part-through flaws in these selected high energy lines grow through the pipe wall, leakage will occur. Postulated through-wall cracks are most likely to be oriented circumferentially, however, axial through-wall cracks can also be analyzed. Crack lengths, up to half the pipe circumference, will be examined and the critical crack lengths will be calculated. The critical crack size is determined by the net section plastic collapse criterion (see page A-15 of Reference 2) and the J-T instability criterion. For given tension and bending loads acting on a pipe, the

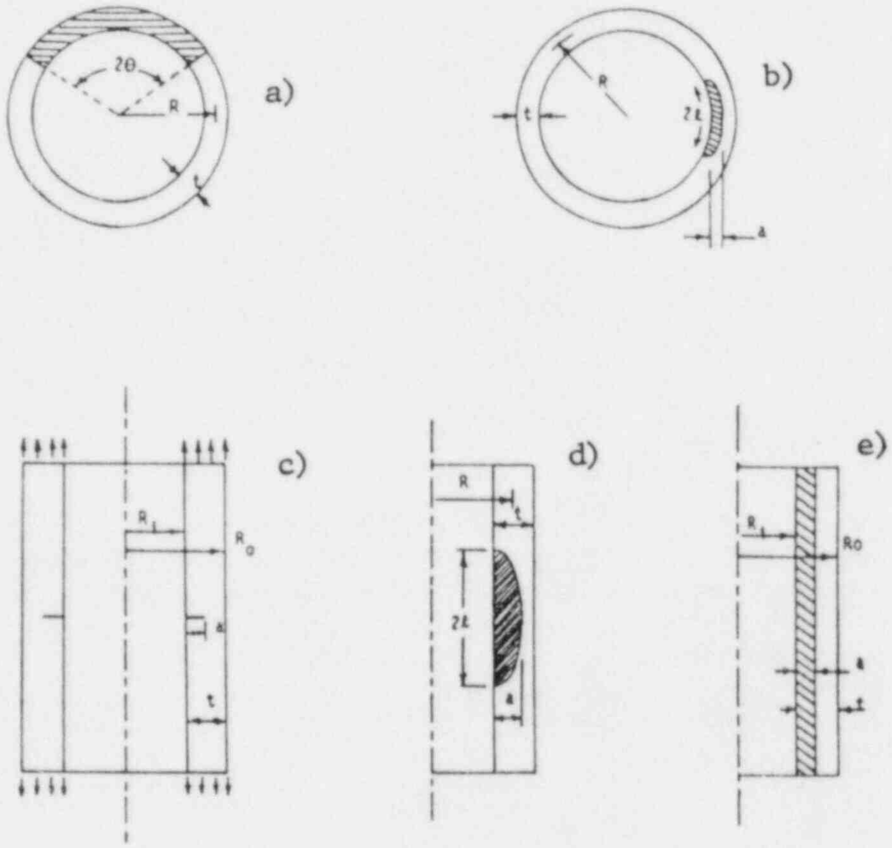

Figure 1 Typical Crack Geometries

a) Complete Through-Wall Crack
b) Circumferential Semielliptical Crack
c) Complete Circumferential Crack
d) Axial Semielliptical Crack
e) Long Axial Crack

crack opening area for a through-wall flaw can be computed using elastic-plastic fracture mechanics techniques [13] (See Appendix A for details). Two phase flow calculations then provide leakage estimates. Leakage detection systems must be sensitive to pipe leaks for flows in the range of 1 to 10 gallons per minute. The necessary crack length and safety margins ensuring leak detection will be determined.

1.7.6 Pipe Crack Analysis

Pipe crack stability is determined using the J integral parameter/tearing modulus (J/T) approach. For stable crack growth, the applied tearing modulus must be less than the material tearing modulus. The tearing modulus (T) is proportional to the derivative of the material toughness parameter (J) with respect to the crack length (a). The J parameter can be estimated using several elastic-plastic fracture mechanics techniques. Details on the J parameter are given in Appendix A.

A second technique for determining crack stability is the net-section plastic collapse criterion. This technique is valid for ductile pipes with circumferential through-wall cracks. A slightly different approach is required for axial through-wall cracks.

With known applied piping loads, the safety margin for crack stability can be determined for normal and one-half safe shutdown earthquake (SSE) loads.

Using normal plus one-half SSE loads, a margin of at least 2 will be shown between the leakage size flaw, and the the critical size crack. A leakage size flaw is a through-wall crack of sufficient length such that it leaks at a rate of one to ten gallons per minute. This crack size margin accounts for uncertainties in the analyses and in leak detection systems. If larger loads (e.g., $\sqrt{2}$ times normal plus one-half SSE loads) are applied, then analysis will be provided to show that leakage size cracks will not experience unstable crack growth. Also, the final crack size (determined by the tearing modulus) will be limited so that a double-ended pipe break will not occur. These safety margins will be shown for cracks on selected (worst-case) high energy lines for operating conditions.

1.8 LEAK DETECTION

1.8.1 Background

The capabilities of leak detection systems are an important part of the LBB approach. Because elimination of all equipment leakage is impossible, a small quantity of identified leakage continually drains to low-point sumps in containment. This identified leakage comes from pump seals, valve packing, and other sources. Therefore, during operational periods, increases in sump levels are not uncommon. Any additional leakage is termed unidentified leakage, which includes pipe crack leakage.

The ability to quickly detect a leak from a high energy pipe break varies with certain parameters. Pipe leakage, measured as a leak rate, is dependent on pipe size, pressure, and crack size. In order to measure the leakage, different leak detection systems are employed, depending on their specific capabilities. Some leak detection systems are able to quantify leak rates, but cannot determine the leak location. Some leak detection systems detect leaks but cannot give leakage rates. Similar problems are found in other systems. Therefore, the optimum leak detection technique is a combination of more than one method. These methods include sump flow monitoring, radiogas activity monitoring, primary coolant inventory, radiation monitoring, and visual monitoring [2].

1.8.2 Methodology

In order to identify and locate pipe leaks at BVPS-2, NRC-approved methods will be used. At least three different leakage detection methods are recommended by the NRC in Regulatory Guide 1.45, "Reactor Coolant Pressure Boundary Leakage Detection Systems" [3]. Two methods, sump flow monitoring and airborne particulate radioactivity monitoring will be employed at BVPS-2 because they are referred to specifically.

For the WHIPJET program, leak detection capabilities will be assessed. After performing the pipe crack analysis as outlined in 1.7.5, the leak rate for the leakage size flaw will be determined. Next, the predicted leak rate will be compared to the threshold leak rate of the BVPS-2 leak detection systems. This assessment will be performed for various pipe sizes in the high energy piping systems. For small pipes, a detailed comparison of the leak rate versus leak detection sensitivity will be performed. The objective of this work will be to determine how leakage from high energy lines will be detected.

1.8.3 Leak Detection Program Tasks

Item 1. Instrumentation Assessment

An examination of the existing BVPS-2 instrumentation, which ensures the minimum allowed leak detection rates, will be performed.

Item 2. Sensitivity and Accuracy Assessment

The leakage detection system sensitivity, measurement accuracy, and leak location accuracy will be assessed.

Item 3. Detection Margin Study

The BVPS-2 leak detection system will be studied to establish that there is a factor of ten greater in the detection margin for the smallest postulated leakage size crack for unidentified leakage.

1.9 COST BENEFIT ANALYSIS

1.9.1 Background

As part of the WHIPJET program, a preliminary radiation exposure benefit analysis will be done. The WHIPJET LBB analysis will result in less whip restraint/jet shield hardware at BVPS-2 thereby improving plant accessability and reducing radiation exposure.

A preliminary examination of cost considerations for not installing pipe rupture restraint and jet shields shows that \$12 to \$16 million can be saved if the WHIPJET program is applied to balance-of-plant piping.

Since BVPS-2 is under construction, pipe whip restraints and jet shields have not been or are only partially installed. Implementation of the WHIPJET program will incur the following monetary costs:

- Added engineering costs for performing leak-before-break studies to justify the whip restraint/jet shield exemption
- Potential costs of performing additional fatigue analysis of Class 2, 3, and nonnuclear safety (seismic) pipe to justify this exemption
- Engineering costs for reviewing water hammer and stress corrosion problems

Advanced engineering analyses will improve piping safety. As a result, the WHIPJET program will produce the following monetary benefits:

- Substantially reduced costs for designing the restraint/shield hardware
- Substantially reduced costs for the restraint/shield hardware itself
- Increased PWR efficiency due to better insulated pipes
- Decreased labor costs for inservice inspection and access to the pipes
- Decreased power replacement costs due to shorter PWR outage
- Decreased costs associated with personnel radiation exposure during maintenance and inspection operations

The restraint/shield exemption also has significant personnel radiation exposure benefits which may outweigh the monetary benefits.

1.9.2 Methodology

The costs and benefits for removing BVPS-2 restraints/shields is difficult to quantify. There are no standard methods of computing occupational risk exposure reductions or cost savings. The cost benefit analysis is usually an order-of-magnitude approach with the radiation exposure or monetary benefits of installing versus not installing the restraints outweighing the costs by one or two orders of magnitude. The cost savings can be broken down into engineering, construction, or operational cost savings.

Two examples of cost/benefit analysis are summarized here. One example is for a whip restraint/jet shield exemption in the primary coolant loop and the second example was motivated by removal of whip restraint for arbitrary intermediate breaks.

As a first example, the Westinghouse A2 owners group (for existing PWRs) did a cost benefit analysis for the primary coolant loop [9]. The nominal estimate for reduced radiation exposure is 690 man-rem for each Westinghouse plant. The nominal monetary benefit was $6.8 million. The major portions of the $6.8 million cost were $3.1 million for installation costs and $3.7 million for power replacement costs. The maintenance and inspection cost associated with whip restraint/jet shield removal would be substantial. These cost estimates did not include engineering analyses for asymmetric pressure loads of fracture mechanics.

As a second example, the Bechtel Power Corporation estimated the total (upper bound) cost for design, procurement, and construction of pipe rupture hardware to be $100,000 per restraint. This estimate includes radiation exposures resulting from approximately 670 man hours per restraint [2].

1.9.3 WHIPJET Cost/Benefit Analysis

Cost savings for BVPS-2 would be less than the Bechtel estimate since some whip restraints/jet shields have already been purchased and some have been installed. The WHIPJET program considers more restraints/shields than the Westinghouse A2 Owners Group study. By implementing WHIPJET, 136 whip restraints at BVPS-2 will not be installed.

An estimate of cost savings for BVPS-2 is presented in Table 1. The bulk of the monetary savings is associated with restraint/shield fabrication, \$2.98 million and installation savings, \$1.89 million. The pipe rupture analysis is estimated to be \$1.42 million. The restraints/shield design and computer costs also are estimated to be \$0.33 million. Cost savings of hundred of thousands of dollars due to improved piping insulation have not been included in the cost savings.

1.9.4 Reliability and Safety Improvement

The WHIPJET program will improve plant safety at BVPS-2. At first glance, removing whip restraints and jets shields may seem to decrease plant safety. However, this is not the case. Plant safety will be increased due to several factors. The new advanced engineering analyses of the high energy piping will increase knowledge of potential piping failure mechanisms. Preventative measures and piping modifications, based on this knowledge, will increase safety. A better understanding of piping material properties derived through the material testing program will improve plant safety. Improved leak detection capabilities will serve as an early warning alarm, thereby increasing plant safety. Studies of stress corrosion, fatigue, and water hammer events will help to preclude these failure mechanisms. Should analyses at any piping location prove inconclusive, the whip restraints and jet shields will be installed. Besides the above hardware safety improvements, the worker radiation exposure will be significantly reduced. The absence of restraints and

shields enables timely piping maintenance and inspection, thereby lessening health concerns for BVPS-2 employees and contractors. The overall effect of the WHIPJET program is a large net increase in plant and worker safety.

1.9.5 Summary and Conclusions

At the present time, the nuclear regulatory agencies are receptive to LBB analyses. The concept of providing pipe break protection using improved engineering technology rather than massive whip restraints and jet shields is very appealing. A combination of timing and improved engineering creates a program that makes good engineering sense. WHIPJET is the key to that program.

Because the LBB approach relies on the ability to successfully detect pipe leaks, special consideration will be given to small pipes. These pipes have proportionately small leakage size flaws which results in lower leak rates. Therefore, the leak detection system sensitivity must be capable of finding these smaller leaks.

As we have demonstrated in this proposal, the WHIPJET program covers all areas. An extensive background to the various forms of pipe break protection is given. A comprehensive engineering program provides all required analyses, testing, and assessments. The WHIPJET program will improve the safety and design of BVPS-2, both during operational periods and during outages. Also, a significant cost savings will be realized. Finally, it will show that reasonable, aggressive industry initiative to improve safety and lower costs is being taken.

Table 1

COST BENEFITS FROM RESTRAINT/SHIELD ELIMINATION FOR BALANCE-OF-PLANT PIPING AT BVPS-2

REMAINING ENGINEERING	
HAZARDS ANALYSIS (PIPE RUPTURE RELATED)	$1,420,000
(includes review of high energy piping, postulation of breaks and resolution of unacceptable interactions)	
PIPE RUPTURE RESTRAINT AND SHIELD DESIGN	330,000
REMAINING FABRICATION	2,980,000
(INCLUDES ENGINEERING SUPPORT OF VENDOR INTERFACE)	
REMAINING INDIRECT COSTS	1,400,000
(INCLUDES PURCHASING, CONTRACT ADMINISTRATION, AND EXPEDITING)	
REMAINING INSTALLATION	1,890,000
TOTAL POTENTIAL SAVINGS	$8,020,000

ORDER-OF-MAGNITUDE ENGINEERING ESTIMATE

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APPENDIX A
DUCTILE PIPING FRACTURE MECHANICS OVERVIEW

Details on ductile fracture mechanics methods related to piping are presented in this appendix. These fracture methods are used for (1) determining crack sizes for pipe leakage calculations and for (2) calculating crack initiation, growth, and instability. Background information on elastic-plastic fracture mechanics (EPFM) methods suitable for the LBB approach are presented. Details and formulas can be found in the cited references.

Analyzing pipe fractures involves many variables such as the pipe's base metal and weld material properties, orientation of the pipe welds, presence of initial flaws in the steel, corrosion and vibration factors, pipe size, and pipe loading. For low toughness steel and simple piping geometries, linear elastic fracture mechanics methods (LEFM) have been developed to examine pipe fractures without having to perform expensive finite element calculations for each case [A1]. For complicated loading or complex geometries (for either elastic or elastic-plastic steel) the only alternative for obtaining crack parameters is to use finite element or similar numerical techniques.

For brittle steels, the LEFM parameter that characterizes the crack tip (for an opening mode) is the stress intensity factor KI. When KI exceeds the critical experimental value KIc, crack initiation occurs.

In 1981 the Electric Power Research Institute (EPRI) released an elastic-plastic fracture mechanics handbook. The second part of this fracture handbook, prepared by General Electric in 1984, covered geometries applicable to pipe cracking, e.g. semi-elliptical interior-surface cracks and through-wall cracks [A2]. This fracture handbook enables inexpensive calculations or crack areas for elastic-plastic pipe leakage calculations [A3]. This handbook also allows inexpensive calculation of the J-integral parameter for part-through and through-wall cracks. For elastic-plastic analysis, the EPRI handbook assumes that the stress-strain data has the power law form.

The J parameter measures the elastic-plastic stress-strain field around the crack tip for any specified pipe, crack geometry and loading. The J parameter is a function of the yield stress and the degree of work hardening. When the J parameter exceeds the critical experimental value, JIc, crack initiation occurs. When the amount of plastic yielding is confined to the region near the crack tip (e.g., brittle steel), the J parameter is proportional to the square of the elastic KI parameter. When the (1) crack grows too large, or (2) when the proportional loading condition is not satisfied, or (3) when the region of ductile yielding becomes large; then, the J parameter theory breaks down. Limit load techniques can be used in certain cases with large loadings when the J parameter methods do not apply. Using the derivative of J with respect to crack length, gives the tearing modulus (T) used in pipe stability calculations [A4]. When the applied tearing modulus is greater than the material tearing modulus, crack instability will occur.

During the summer of 1985, the Committee on the Safety of Nuclear Installation (CSNI) and the Nuclear Regulatory Commission (NRC) sponsored a ductile piping fracture mechanics workshop to examine various methods for calculating pipe crack initiation and instability loads. The pipes were subjected to both bending and tensile loads [A5]. The workshop problem was for a circumferential through-wall crack. Several methods were employed by various organizations to solve the workshop problem. These method included the EPRI handbook approach, the J-T method, failure assessment diagram approach (FAD) [A6], and the British R-6 method. The NRC has sponsored other elastic-plastic pipe fracture methods as mentioned in Appendix A to NUREG 1061 Vol. 3 [A7].

One outcome of the CSNI/NRC ductile piping workshop was that a pipe weldment material with a low fracture toughness (compared to the pipe base metal) can have a higher tearing instability load than does the pipe itself. For this case, the weldment has a higher yield strength than the base metal. Hence, the tearing instability load increases with yield strength. Furthermore, the workshop showed that as the pipe diameter increases the tearing instability load decreases.

The NRC-recommended method of calculating J is based upon a pipe kink angle approach. The kink angle, the angular change in the cracked pipe, is a function of crack length, pipe diameter, yield stress, pipe compliance, and the bending/tensile loads (Reference A7). Experiments on pipes with through-wall cracks, subjected to bending and tensile loads, were conducted to access the accuracy of the EPRI J-T handbook approach and the NRC J-T kink angle approach. Significant differences between the computational methods were found. The results from comparisons between theory and experiment showed that the EPRI method is consistently conservative (up to 30%) in predicting the bending moment at crack initiation. The EPRI technique became even more conservative for larger pipes. The NRC approach, on the average, was the best fit to the experimental data although the bending moment at initiation was somewhat unconservative (up to 20%). In conclusion, when performing the J calculations, care must be taken to produce conservative values of the margin against full pipe break.

For the WHIPJET program, a suitable combination of J parameter methods will be used. One likely method will be the EPRI J-T method since it is consistently conservative. The second method may be either the NRC kink angle approach or the FAD approach.

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APPENDIX B

MATERIAL PROPERTIES MEASUREMENT PROGRAM

Elastic-plastic fracture mechanics techniques for piping leak-before-break (LBB) assessment are strongly dependent upon material properties. The material tensile and ductile crack growth resistance (J-R curve) properties are the most important, and these properties must be carefully and consistently measured to ensure their applicability to the fracture mechanics analyses. The first step in the material properties measurement program is to select representative materials from the actual piping systems to be evaluated. Once the representative materials are selected, a test matrix can be developed which will appropriately measure the desired tensile and fracture resistance properties to be used in the LBB fracture mechanics evaluation. This appendix provides more specific details relative to the material properties measurement for the WHIPJET program.

The materials to be tested and the conditions for testing should be representative of the actual piping system and operating conditions. Since BVPS-2 has archival pipe materials which can be used in the testing program, the assessment of base metal properties is straight-forward. Three different BVPS-2 pipe materials have been used in the construction of the following matrix: Type 316 stainless steel (SS), Type 304 SS, and SA106 Grade B (SA106B) ferritic steel. No archival weld metal exists for these materials; therefore, weldments for both representative austenitic stainless steels and ferritic steels will be fabricated to match as closely as possible the welds in the BVPS-2 piping systems. Factors to be considered in fabricating these welds will include chemical composition, fabrication history, and existing tensile, and Charpy impact properties. The tempratures of interest in the testing program will be the normal operating range including the lowest temperature of concern from which a pipe rupture may be possible.

Listed below are the pipe sizes (in inches) involved for the different piping materials:

SA106B	Type 316 SS	Type 304 SS
2-4, Sch. 80	1.5-14, Sch.160	2-3, Sch. 160
2.5, Sch. 160		12, Sch. 40
23, (1-in. thick)		

Most of these sizes are relatively small when considering the possibility of fabricating compact fracture toughness specimens from the pipe material itself. Therefore, tests of the actual pipe itself will be made in order to assess the base metal ductile fracture crack growth resistance. These tests will be conducted in pure bending, with the combined machined notch and fatique crack length in the range of 30 - 37 percent of the circumference, in order to reduce any ovalization that may occur during the tests. Since a range of pipe sizes exist, typical sizes for each material will be selected to give the potentially worst case in crack growth resistance. For example, thicker pipe materials tend to give higher JIc initial toughness values but lower crack extension resistance beyond JIc (i.e., lower tearing modulus, T). This behavior is thought to be independent of actual pipe diameter.

The plan for weld metal evaluation austenetic Type 308 weld metal and ferritic weld metal is different since the welds must be fabricated for the testing program. Welds will be fabricated in a manner best duplicating those in the piping systems, but their welds will be fabricated on flat plate base metal with the same thicknesses as the pipes. This approach allows easy machining and testing of compact fracture specimens which can be sized larger in the flat planar directions relative to the thickness (i.e., the specimen width and height can be larger than normal relative to the thickness). Having a longer crack growth ligament allows measurement of J to much higher values without violating size-limiting criteria; this fact is important in the later analyses since the data will not have to be extrapolated as far when high J data are required.

Following the guidelines in NUREG-1061, Volume 3, a test matrix for the five materials (Type 316 SS, Type 304 SS, SS welds, SA106B, and ferritic welds) has been tentatively made. Final definition of this matrix will be made once the actual archive

materials and welds have been totally evaluated. Typical heats from the BVPS-2 piping systems will be selected. However, due to so many heats involved in assessing the different pipe break locations, a testing plan for "nonarchival material" will be used. Note that actual archive material will be used, but a <u>generic</u> test matrix is being employed due to the large number of pipe sizes and heats. The test matrix for each material is:

Test Type	Temperature*	No. of Heats	No.of Test/Heats	Total No. of Tests
Tensile	High	3	2	6
	Low	1	1	1
J-R Curve	High	3	2	6
	Low	1	1	1

* High refers to the temperature in the high end of the operating range, and low refers to the lowest temperature where pipe rupture is possible (e.g., hot standby temperature).

Thus, for the five materials involved, 35 tensile and 35 J-R curve tests will be required. If the weld metal fabrication evaluation concludes that more than one welding technique was employed at the pipe break locations, other weldments will need to be fabricated and tested which will increase the size of the test matrix. The tensile testing will be performed at conventional strain rates using the largest practical specimen, and detailed data will be obtained covering the range from yield to 10 percent strain or more. The ductile fracture toughness data will be developed using the electric potential technique for monitoring crack extension. Then, evaluations will be made to give a lower bound fracture resistance curve for each material type. Comparisons with other data in the open literature will be made.

Other options available for consideration are direct tension testing (for fracture toughness) of the pipe specimens (rather than pure bending) and actual pipe specimen tests on fabricated welds. The first option of tension testing allows a comparison of J-R curves with different amounts of bending moment as compared to the axial

tension loading. Note that the tensile testing approach requires special fixturing to allow for the natural bending moment that occurs due to the crack in the pipe specimen. It is expected that little, if any, differences in the J-R curves would be found, but these effects have never been fully documented. Testing of cracks in welded pipe sections would allow better documentation of the weld metal behavior as compared to the traditional compact fracture specimen approach.

APPENDIX C
MATERIAL PROPERTY APPENDIX

High enery lines at BVPS-2 are made of Type 316 stainless, Type 304 stainless, Type 106-B carbon, and perhaps some Type 106-C carbon steels. The purpose of this appendix is to present published uniaxial stress-strain and J-R resistance experimental data for these steels. This data is required for comparison purposes for the WHIPJET fracture mechanics analysis.

Stress strain data for Type 304, Type 316, and A106B data is presented in Figure C1. Note that type 304 steel is slightly less ductile than the Type 316 steel [C1, C2, C3]. Next, a comparison of the J-R resistance data for Type 304 and a typical weld is shown in Figure C2 [C1]. The weld metal has a lower toughness (in this case) than the base metal, but the weld has a yield stress about twice that of the Type 304 base metal. A comparison between Type 304, 316 and Type 106-B J-R resistance curves is shown in Figure C3 [C4, C5, C6, C7]. Note that the Type 106-B carbon steel has a lower toughness than the stainless steels. The Type 316 stainless steel J-R curve is similar to that of the Type 304 curve. Although not shown in this appendix, the specimen-to-specimen material property variability for similar materials can be considerable.

For the WHIPJET program, a sufficient number of material tests (See Appendix B) on the BVPS-2 piping will be conducted to show that the material properties curves similar to those in Figures C1, C2 and C3 are suitable for use in the WHIPJET fracture analyses.

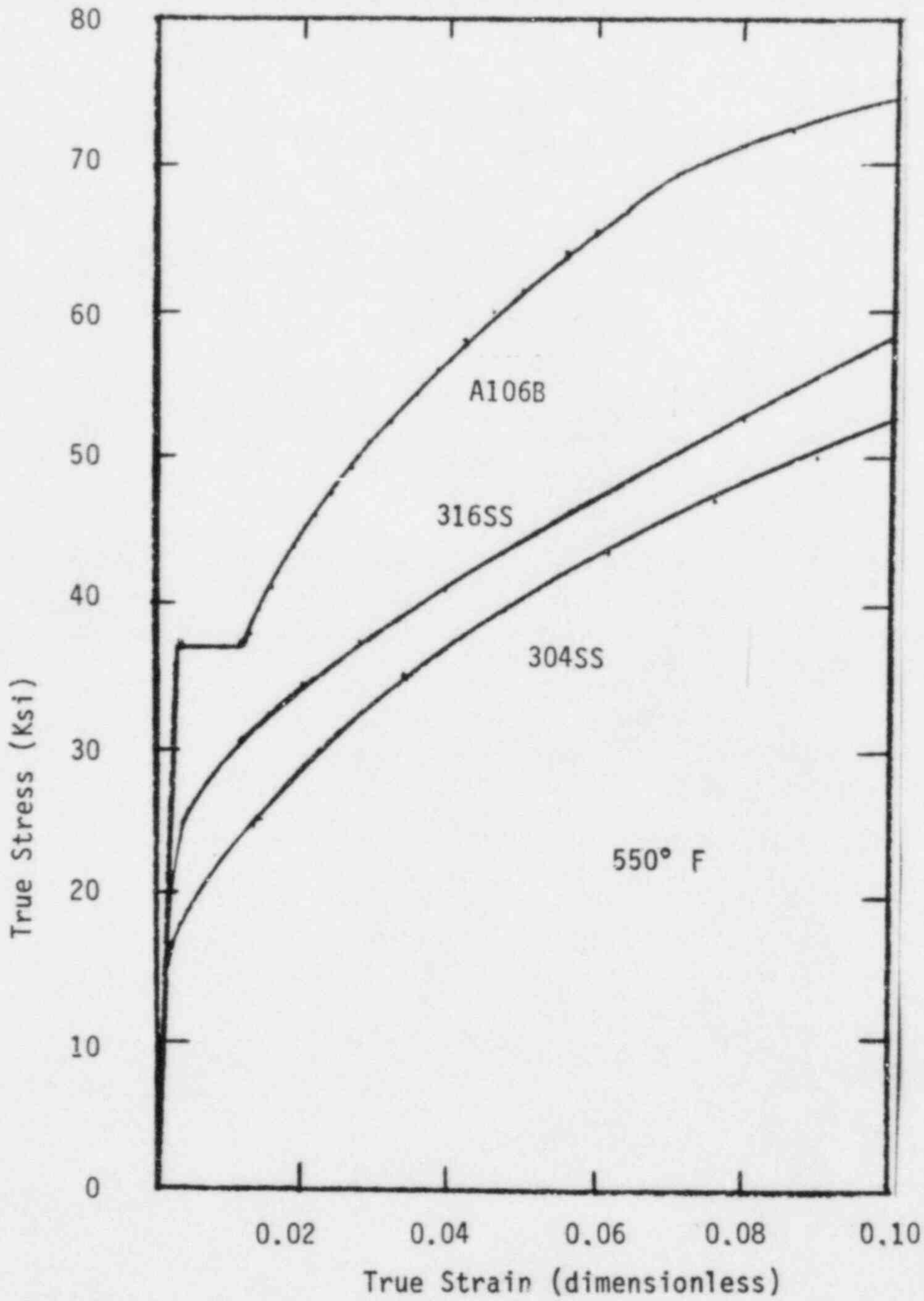

Figure C1 Typical True Stress Strain Curves for SA-312/376 Type 304, SA-312/376 Type 316 stainless, and A106B carbon steels

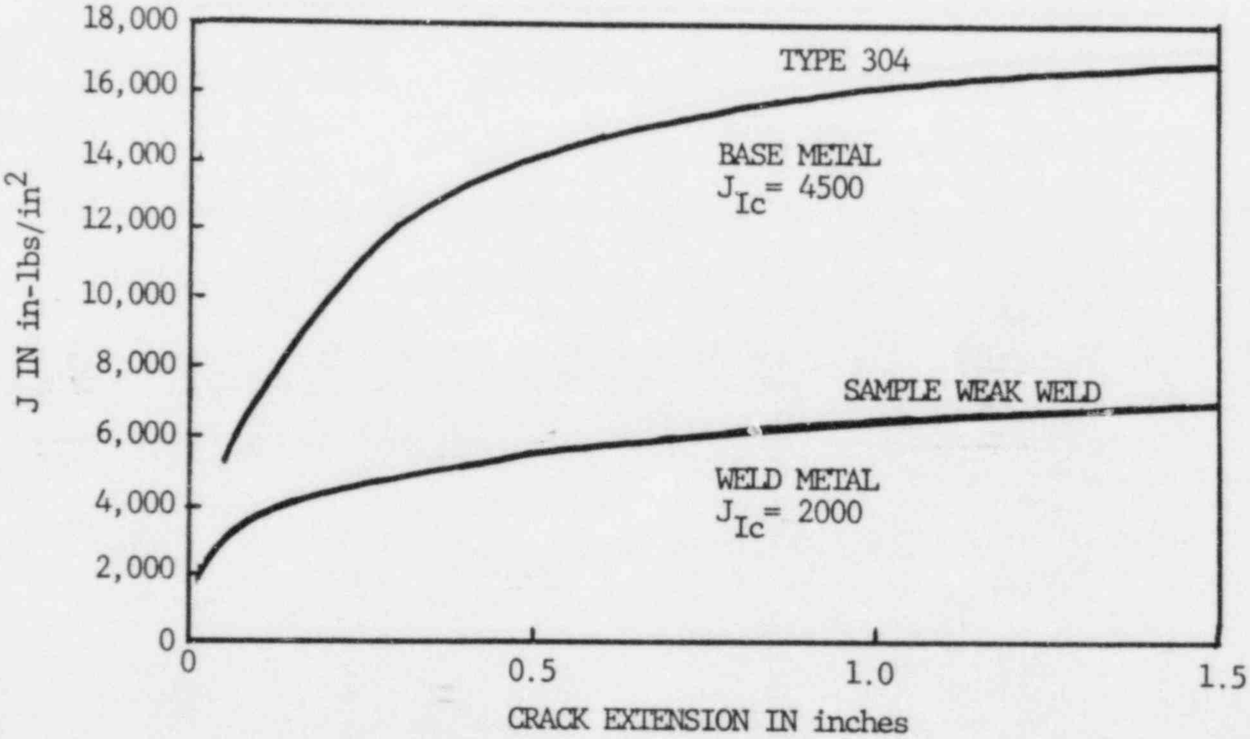

Figure C2 Typical J-R Resistance Curves for Type 304 Base Metal and a Pipe Weld

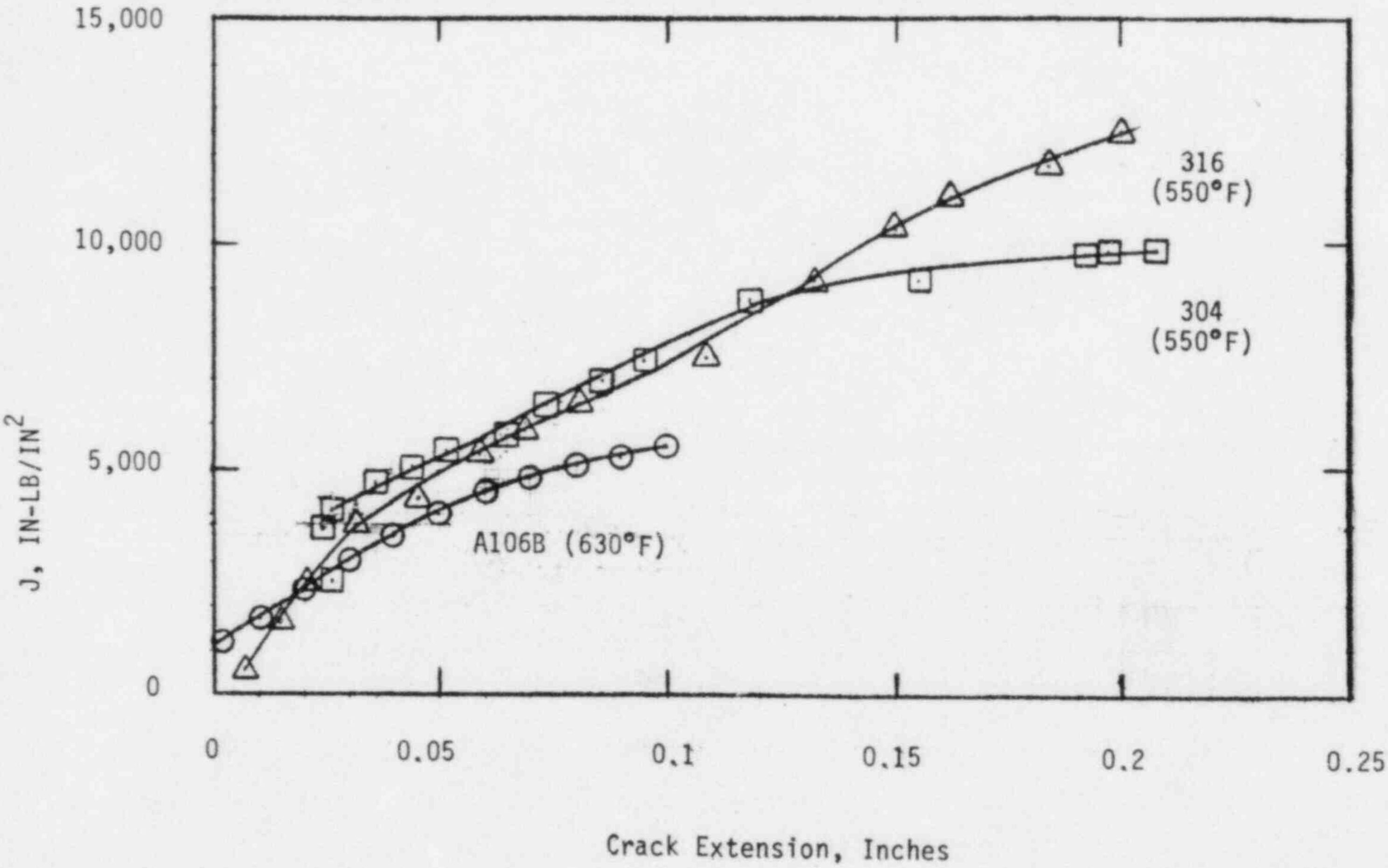

Figure C3 Typical J-R Resistance Curves for SA-312/376 Type 304 and 316 Stainless Steel and SA-106B Carbon Steel

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