WESTINGHOUSE NON-PROPRIETARY CLASS 3

WCAP-14572
Revision 1-NP-A
Supplement 1

Westinghouse Structural Reliability and Risk Assessment (SRRA) Model for Piping Risk Informed Inservice Inspection

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February 1999

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Work Performed by Westinghouse Electric Company in collaboration with Northeast Utilities and Virginia Power for the Westinghouse Owners Group Under MUHP-5090 and MUHP-5091

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UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

December 15, 1998

Mr. Lou Liberatori, Chairman
Westinghouse Owners Group Steering Committee
Indian Point Unit 2
Broadway & Bleakley Ave.
Buchanan, NY 10511

SUBJECT: SAFETY EVALUATION OF TOPICAL REPORT WCAP-14572, REVISION 1, "WESTINGHOUSE OWNERS GROUP APPLICATION OF RISK-INFORMED METHODS TO PIPING INSERVICE INSPECTION TOPICAL REPORT"

The NRC staff has completed its review of the subject topical report which was submitted by the Westinghouse Owners Group (WOG) through the Nuclear Energy Institute (NEI) by letter dated October 10, 1997. The staff has found that this report is acceptable for referencing in licensing applications to the extent specified and under the limitations delineated in the report and the associated NRC safety evaluation, which is enclosed. The safety evaluation defines the basis for acceptance of the report.

Current inspection requirements for commercial nuclear power plants are contained in the 1989 edition of Section XI, Division 1 of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC), entitled *Rules for Inservice Inspection of Nuclear Power Plant Components*. WCAP-14572, Revision 1, provides technical guidance on an alternative for selecting and categorizing piping components into high safety-significant (HSS) and low safety-significant (LSS) groups for the purpose of developing a risk-informed inservice inspection (ISI) program as an alternative to the ASME BPVC Section XI ISI requirements for piping. The RI-ISI programs can enhance overall safety by focusing inspections of piping at HSS locations and locations where failure mechanisms are likely to be present, and by improving the effectiveness of inspection of components by focusing on personnel qualifications, inspection for cause, and the use of the expert panel. The WCAP provides details required to incorporate risk-insights when identifying locations for inservice inspections of piping, in accordance with the general guidance provided in Regulatory Guide (RG)-1.174 and RG-1.178.

The staff will not repeat its review of the matters described in the WOG Topical Report WCAP-14572, Revision 1, when the report appears as a reference in license applications, except to ensure that the material presented applies to the specific plant involved. In accordance with procedures established in NUREG-0390, the NRC requests that WOG publish accepted version of the submittal, within 3 months of receipt of this letter. The accepted version shall incorporate this letter and the enclosed safety evaluation between the title page and the abstract and an -A (designating accepted) following the report identification symbol.

RECEIVED
JAN 2C 1999
WOG PROJECT OFFICE

If the NRC's criteria or regulations change so that its conclusion that the submittal is acceptable are invalidated, WOG and/or the applicant referencing the topical report will be expected to revise and resubmit its respective documentation, or submit justification for the continued applicability of the topical report without revision of the respective documentation.

Should you have any questions or wish further clarification, please call me at (301) 415-1282 or Syed Ali at (301) 415-2776.

Sincerely,

Thomas H. Essig, Acting Chief
Generic Issues and Environmental Branch
Division of Reactor Program Management
Office of Nuclear Reactor Regulation

Project No. 694

Enclosure: Safety Evaluation

cc w/enc: See next page

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

WCAP-14572, REVISION 1, "WESTINGHOUSE OWNERS GROUP

APPLICATION OF RISK-INFORMED METHODS

TO PIPING INSERVICE INSPECTION TOPICAL REPORT"

Enclosure

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ABBREVIATIONS

ASME	American Society of Mechanical Engineers
BWR	Boiling Water Reactor
CDF	Core Damage Frequency
CRGR	Committee to Review Generic Requirements
EC	Erosion Corrosion
EPRI	Electric Power Research Institute
FAC	Flow-assisted Corrosion
FSAR	Final Safety Analysis Report
IGSCC	Intergrannular Stress Corrosion Cracking
ISI	Inservice Inspection
LERF	Large Early Relief Frequency
MOV	Motor-operated Valves
NDE	Nondestructive Examination
NEI	Nuclear Energy Institute
POD	Probability of Detection
PRA	Probabilistic Risk Assessment
PWR	Pressurized Water Reactor
RAW	Risk Achievement Worth
RCS	Reactor Coolant System
RG	Regulatory Guide
RI-ISI	Risk-informed Inservice Inspection
RRW	Risk Reduction Worth
SER	Safety Evaluation Report
SRP	Standard Review Plan
SRRA	Structural Reliability and Risk Assessment
WOG	Westinghouse Owners Group

SAFETY EVALUATION REPORT RELATED TO "WESTINGHOUSE OWNERS GROUP APPLICATION OF RISK-INFORMED METHODS TO PIPING INSERVICE INSPECTION" (TOPICAL REPORT WCAP-14572, REVISION 1)

1.0 INTRODUCTION

On October 10, 1997, Nuclear Energy Institute (NEI), on behalf of Westinghouse Owners Group (WOG), submitted Revision 1 of Topical Report, WCAP-14572, "Westinghouse Owners Group Application of Risk-Informed Methods to Piping Inservice Inspection," (Ref. 1) for review and approval by the staff of the U. S. Nuclear Regulatory Commission (NRC). Supplement 1, "Westinghouse Structural Reliability and Risk Assessment (SRRA) Model for Piping Risk-Informed Inservice Inspection, " (Ref. 2) was included as part of that submittal.

WCAP-14572, Revision 1, provides technical guidance on an alternative for selecting and categorizing piping components as high safety-significant (HSS) or low safety-significant (LSS) groups in order to develop a risk-informed inservice inspection (ISI) program as an alternative to the American Society of Mechanical Engineers (ASME) BPVC Section XI ISI requirements for piping. Current inspection requirements for commercial nuclear power plants are contained in the 1989 Edition of Section XI, Division 1 of the ASME Boiler and Pressure Vessel Code (BPVC), entitled "Rules for Inservice Inspection of Nuclear Power Plant Components", (the Code). The risk-informed inservice inspection (RI-ISI) programs enhance overall safety by focusing inspections of piping at HSS locations and locations where failure mechanisms are likely to be present, and by improving the effectiveness of inspection of components because the examination methods are based on the postulated failure mode and the configuration of the piping structural element. WCAP-14572 provides details required to incorporate risk-insights when identifying locations for inservice inspections of piping, in accordance with the general guidance provided in Regulatory Guide (RG)-1.174 (Ref. 3) and RG-1.178 (Ref. 4).

The WOG has asserted that the WCAP methodology for RI-ISI is a detailed implementation document for ASME Code Case N-577 (Ref. 5). However, the staff has not evaluated Code Case N-577 to determine its acceptability. Also, the staff has not evaluated WCAP-14572 to determine if it is an acceptable document to meet the intent of Code Case N-577.

In developing the methods described in WCAP-14572, Revision 1, the industry incorporated insights gained from two plants, Millstone Unit 3 and Surry Unit 1. The staff's review of WCAP-14572 incorporates information obtained through technical discussions at public meetings and through formal requests for additional information to address the issues related to the analytical methods, observance of the application of the methods to the Surry pilot plant, review of the Surry RI-ISI application, independent audit calculations, and peer reviews of selected technical issues.

2.0 SUMMARY OF THE PROPOSED APPROACH

The scope of the RI-ISI program includes changes in the current ASME XI piping ISI requirements with regard to the number of inspections, locations of inspections, and methods of

inspections. The scope of the RI-ISI program does not include changes in the current ASME XI piping ISI requirements with regard to the inspection intervals and periods, acceptance criteria for evaluation of flaws, expansion criteria for flaws discovered, inspection techniques and personnel qualification. It should also be noted that augmented examination program for degradation mechanisms such as intergrannular stress corrosion cracking (IGSCC) and erosion-corrosion (EC) would remain unaffected by the RI-ISI program.

Page 4 (Section 1.1) of WCAP-14572 states that "This report provides an alternative inspection location selection method for nondestructive examination (NDE) and does not affect current Owner-defined augmented programs." For RI-ISI programs whose scope incorporates augmented inspection programs, the effect of the current augmented programs on risk should be addressed. In most circumstances, the staff believes that the current augmented programs would be found acceptable. However, should the RI-ISI analysis identify that improvements to the augmented programs are warranted to maintain risk at acceptable levels, then those changes should be integrated into the respective programs.

The proposed approach is specifically for the NDE of Class 1 and 2 piping welds, but also includes Class 3 systems and non-Code class components found to be HSS in the risk evaluation. As stated by the Westinghouse Owners Group (WOG), other non-related portions of the Code will not be affected by implementation of WCAP-14572, Revision 1, approach.

The RI-ISI process includes the following steps:

- scope definition
- segment definition
- consequence evaluation
- failure probability estimation
- risk evaluation
- expert panel categorization
- element/NDE selection
- implementation, monitoring, and feedback

3.0 EVALUATION

For this safety evaluation, the NRC staff reviewed the WOG RI-ISI methodology, as defined by WCAP-14572, Revision 1, and its Supplement 1, with respect to the guidance contained in RG 1.178 and Standard Review Plan (SRP) Chapter 3.9.8 (Ref. 6) which describes the acceptable methodology, acceptance guidelines, and review process for proposed plant-specific, risk-informed changes to ISI programs for piping components. Further guidance is provided in RG 1.174 and SRP Chapter 19.0 (Ref. 7) which contains general guidance for using Probabilistic Risk Assessments in risk-informed decision-making.

3.1 Proposed Changes to the ISI Programs

Under the ASME Code, licensees are required to perform inservice inspection (ISI) of Category B-J and C-F piping welds, as well as Examination Category B-F dissimilar metal welds, during

successive 120-month (10-year) intervals. Currently, 25% of all Category B-J piping welds greater than 1-inch nominal diameter are selected for volumetric and/or surface examination on the basis of existing stress analyses. For Category C-F piping welds, 7.5% of non-exempt welds are selected for surface and/or volumetric examination. Under Examination Category B-F, all dissimilar metal welds require volumetric and/or surface examination.

Pursuant to Title 10, Section 50.55a(a)(3)(i), of the *Code of Federal Regulations* (10 CFR 50.55a(a)(3)(i)), licensees proposing to use WCAP-14572 methodology would propose an alternative to the ASME Code examination requirements for piping ISI at their plants. As stated in Section 1.2 of WCAP-14572, Revision 1, the RI-ISI program is intended to improve ISI effectiveness by focusing inspection resources on HSS locations where failure mechanisms are likely to occur. Therefore, the proposed approach meets the intent of ASME Section XI that the flaws are found before they lead to leakage and therefore the approach provides an acceptable level of safety.

Augmented examination program for degradation mechanisms such as IGSCC and EC would remain unaffected by the RI-ISI program. As stated in the WCAP-14572 (page 80, Section 3.5.5) and reiterated in the public meeting (item 11, Ref. 8) with Westinghouse on September 22, 1998, no changes to the augmented inspection programs are being made with the proposed change to the ASME Section XI Program. For calculating risk rankings, augmented programs such as erosion-corrosion and stress corrosion cracking programs are credited when the augmented program is deemed adequate to detect relevant degradation mechanisms. Augmented programs are also credited in the change of risk evaluation for both ASME Section XI programs and RI-ISI programs.

Sections 1.1 and 1.4 of WCAP-14572, Revision 1, describe the proposed changes to the ISI program that would result from applying this methodology. Details of the proposed changes (that is, the specific pipe systems, segments, and welds, as well as the specific revisions to inspection scope, locations, and techniques) are plant-specific and, therefore, are not directly applicable to this evaluation. Section 3.2 of WCAP-14572 describes the process for identifying the piping systems to be included in the scope of the RI-ISI program. Plant functions are considered in the expert panel review process during the consequence evaluation. In response to the staff open item 8(a) (Ref. 9), WCAP-14572 is being revised (Ref. 8) to state that the safety functions of the system and piping segment being reviewed should be presented to the expert panel to ensure that the expert panel specifically addresses the relationship between the systems and piping being evaluated and their associated plant safety functions. WCAP Sections 3.5.2 and 3.5.3 address how industry and plant-specific experience are considered as part of the evaluation process. Finally, Sections 4.4 and 4.5 of WCAP-14572 provide examples from the pilot studies of revisions to inspection scope, locations, and techniques.

3.2 Engineering Analysis

According to the guidelines in RGs 1.174 and 1.178, the licensees proposing an RI-ISI program should perform an analysis of the proposed changes using a combination of engineering analysis with supporting insights from a probabilistic risk assessment (PRA). For the RI-ISI program, engineering analysis includes determining the scope of piping systems included in the RI-ISI program, establishing the methodology for defining piping segments, evaluating the failure

potential of each segment, and determining the consequences of failure of piping segments. The following subsections discuss each of these aspects in greater detail.

3.2.1 Scope of Piping Systems

In accordance with the guidelines in Section 1.3 of RG 1.178, the staff has determined that full scope and partial scope options are acceptable for RI-ISI programs for piping. The full scope option includes ASME Class 1, 2, and 3 piping and piping whose failure would compromise safety related structures, systems, or components (SSC), and non-safety related piping that are relied upon to mitigate accidents or whose failure could prevent safety-related SSC to perform their function or whose failure could cause a reactor scram or actuation of a safety-related system. For the partial scope option, a licensee may elect its RI-ISI program for a subset of piping classes, for example, Class 1 piping only.

Section 3.2 of WCAP-14572, Revision 1, describes the scope of systems to be considered in an RI-ISI program. WCAP-14572 identifies three criteria for system selection. Criterion 1: all Class 1, 2, and 3 systems currently within the ASME Section XI program; Criterion 2: piping systems modeled in the PRA; and Criterion 3: balance of plant fluid systems determined to be of importance (mainly on the basis of NEI guidance for implementation of the Maintenance Rule with respect to safety significance categorization). The Maintenance Rule scope definition is used to provide a starting point for the determination of the scope of the RI-ISI program.

Section 2.3 of WCAP-14572 states that the scope incorporates piping segment cutsets that cumulatively account for about 90 percent of the core damage frequency attributed from piping alone.

In addressing the exclusion of piping systems from the scope of the RI-ISI program, Section 3.2 of WCAP-14572 includes the following explanation:

> "Twenty-one systems were selected to be evaluated in more detail for the representative WOG plant. The remaining systems are excluded from the scope of the risk-informed ISI program. These systems are not addressed by ASME Section XI, but some were considered by the PRA (such as emergency diesel jacket water, containment instrument air, and instrument air). However, each of these systems was reviewed by the plant expert panel using the same criteria as in the determination of risk-significance for the Maintenance Rule. In addition, the consequences postulated from the loss of any of these systems from a pipe failure were determined not to be significant. Therefore, these systems in their entirety, were determined to be outside the scope and not further evaluated."

In order to allow for partial scope, the next revision of WCAP-14572 will add the following statement in Section 3 and 3.2 as stated on page 264 of Ref. 8:

> "A full scope program is recommended because a greater portion of the plant risk from piping pressure boundary failures is addressed in the risk-informed ISI program versus current ASME Section XI requirements since the examination are now placed in several high-safety-significant piping segments that are not currently examined by the current Section XI approach. However, a partial scope evaluation may be performed given that the evaluation

includes a subset of piping classes, for example, ASME Class 1 piping only, including piping exempt from the current requirements."

The staff finds acceptable the discussion of scope since this definition is consistent with guidance provided in RG 1.178 and SRP Chapter 3.9.8. However, the staff notes that the scope of piping systems for RI-ISI should be plant-specific, and the staff is not endorsing WCAP-14572 pilot list of systems for generic use. The staff also finds acceptable the discussion of partial scope option which is consistent with guidance provided in RG 1.178 and SRP Chapter 3.9.8 which state that the partial scope option is acceptable as long as it is well defined, and the change in risk due to the implementation of the RI-ISI program meets the guidelines in RG 1.174.

3.2.2 Piping Segments

Section 3.3 of WCAP-14572, Revision 1 provides a definition for piping segments. The approach used to define piping segments was based on the following considerations:

(1) piping failures that lead to the same consequence determined from the plant-specific PRA and other considerations (e.g., loss of a residual heat removal (RHR) train, loss of a refueling water storage tank (RWST), inside or outside containment consequences, etc.)

(2) where flow splits or joins

(3) piping to a point where a pipe break could be isolated (This includes check valves and motor-operated or air-operated valves. No credit is generally given for manual valves however, situations may occur where manual valves can be used to isolate a failure by plant operators and, in these cases, the decision for crediting manual valves is made by the plant expert panel and documented as such.)

(4) Pipe size changes

In defining pipe segments, the possibility of check valves and other isolation valves failing to close is not considered; that is, proper operation of the valves is assumed when defining segment boundaries. The staff notes that this assumption will not have a significant impact on the results, since the probability of a valve failing to close is small (ranging from 10^{2} per demand for motor-operated valves (MOV) to approximately 10^{4} per demand for check valves) and the consequences from failure will not change in most instances. In addition, when operator action is credited for the isolation of a pipe break, the valve failure probability will be small when compared to the human error probability, and this combined probability will be subject to a sensitivity study as discussed in Section 3.3 of this safety evaluation report (SER). Finally, the treatment of automatic isolation valves will be clarified as follows (item 9 of Ref. 8):

"Automatic isolation valves are assumed to close if the pipe failure in question would create a signal for the valves to close. Containment isolation valves should be carefully considered for segments which contain the containment penetrations. If the segment consequences are significantly different assuming an automatic and/or containment isolation valve failure, then the piping segment definition should be reviewed and if

necessary, the piping segment should be further combined or subdivided such that the failure of the valve, under pipe failure conditions, would be considered in conjunction with the change in consequences."

The staff finds that the definition of a piping segment, as addressed in Section 3.3 of WCAP-14572, Revision 1 (and subject to the revision noted above) is acceptable since this definition is consistent with the expectations expressed in Section 4.1.4 of RG 1.178 which states that one acceptable approach to divide piping systems into segments is to identify segments as portions of piping having the same consequences of failure in terms of an initiating event, loss of a particular train, loss of a system, or combination thereof. The staff's approval is conditioned upon Westinghouse making the change to WCAP-14572 described above.

3.2.3 Piping Failure Potential

WCAP-14572 methodology is based on industry experience and the Structural Reliability and Risk Assessment (SRRA) computer code to determine the failure probabilities of piping segments. The staff believes that the purpose of the piping failure probability estimation is to provide a relative estimate of the piping failure potential in order to differentiate the piping segments based on potential failure mechanism and postulated consequences. The relative failure probabilities of piping segments provide insights for use by the expert panel in defining the scope of inspection for the RI-ISI program. Section 3.4 of this SER provides a detailed discussion of the qualification and role of the expert panel.

At its briefing in July 1997, the NRC's Committee to Review Generic Requirements (CRGR) requested that the staff should have a peer review performed with regard to using structural reliability and risk assessment computer codes to estimate the probability of a piping failure. The peer review, performed by Battelle-Columbus, and documented in a letter report (Ref. 10), concluded that the SRRA computer code is technically sound and within the state-of-the-art, and that its application can facilitate risk-informed regulatory decision-making in the area of ISI.

Over the past 3 years, as ASME-Research and the WOG developed methods to perform RI-ISI programs for piping, the staff held public meetings with both groups to develop guidelines for acceptable uses of probabilistic fracture mechanics computer codes. In addition, with the assistance of Pacific Northwest National Laboratory (PNNL), the staff performed independent audit calculations to validate the results of the SRRA computer code.

Computer programs CLVSQ and other SRRA computer codes for RI-ISI, such as LEAKMENU and LEAKPROF, were developed, verified and controlled in accordance with the Westinghouse Quality Management System.

Section 3.5 of WCAP-14572, Revision 1 presents general discussion of failure probability determinations; the details of the methodology, process, and rationale are contained in Supplement 1 to the WCAP-14572. This includes piping failure modes, degradation mechanisms, SRRA models, program input, uncertainties, and calculation of failure probability over time. Piping failure potential was determined based on failure probability estimates from the SRRA software program. This software uses Monte-Carlo simulation to calculate the probability of a leak or break for Type 304 or 316 stainless steel piping or for carbon steel piping.

It is recommended in Section 3.5.2, that known failures at other plants be considered and evaluated for applicability.

Section 3.4 of WCAP-14572, Supplement 1, addresses the treatment of uncertainties in the failure probability assessments. The statistical variations for a number of input parameters are discussed therein. Material properties such as yield strength, ultimate strength, fracture toughness, and tearing modulus are not mentioned, but inputs for these properties are more appropriately addressed in plant-specific applications of the program.

WCAP-14572 methodology involves assigning all significant degradation mechanisms present in the segment to a single weld, and imposing the operating characteristics and environment to that weld. The failure probability developed from the Monte-Carlo simulation of this weld is subsequently used to represent the failure probability of the segment, regardless of the number of welds in the segment, or the length of the segment. WCAP-14572 states that this approximation is appropriate since the same loadings occur across the segment and a single weld failure will fail the segment. WCAP-14572 also states that failures in a piping segment due to the dominating failure mechanisms are correlated, and that the failure probability of the weld subject to the dominating mechanisms is typically several orders of magnitude higher than those without the dominating mechanisms. When more than one degradation mechanism is present, the combination of all significant degradation mechanisms for the segment failure probability should produce a limiting failure probability. The output of the SRRA code is thus best described as a relative estimate of the susceptibility of a pipe segment to failure as determined by the weld material and environmental conditions within the segment. The WOG methodology primarily uses these estimates in the following ways:

- Combine with quantitative risk estimates from the PRA to support the expert panel's classification of segments into LSS or HSS.
- Provide guidance regarding the susceptibility of each segment to failure during the sub-panel's selection of welds to be inspected under the RI-ISI program.

Since the WCAP-14572 methodology involves assigning all significant degradation mechanisms present in the segment to a single weld, and imposing the operating characteristics and environment to that weld, the staff finds the methodology acceptable to estimate pipe segment failure probabilities, i.e., the estimation of relative failure probabilities is sufficiently robust to support categorization of pipe segments by the expert panel when this information is used in conjunction with considerations of defense-in-depth and safety margins to support the RI-ISI change request.

The staff also finds it acceptable that the SRRA code assumes that unstable fractures (ruptures) of piping are governed by the limit load criterion because it meets the limit load criterion used in the ASME Code, Section XI, Appendix H, for unstable fractures. The Log-Normal distributions of flaw aspect ratios are based on the same assumptions used in the pc-PRAISE code, an NRC sponsored code.

The Monte-Carlo method as implemented into the SRRA code is a standard approach which is commonly used in probabilistic structural mechanics codes including the pc-PRAISE code. Importance sampling, again a common and well-accepted approach, increases the

computational efficiency of the Monte-Carlo procedure by shifting the distributions for random variables to increase the number of simulated failures. The magnitude of shift applied to the variables by the SRRA code is relatively modest and is not believed to be sufficient to cause incorrect estimates of failure probabilities. The staff finds the numerical method acceptable because it represents standard probabilistic fracture mechanics techniques, is based on sound, generally accepted principles of solid mechanics, and is consistent with guidance provided in RG 1.178 and SRP Chapter 3.9.8.

WCAP-14572 states that the median values for stresses were set equal to one-half the stress values calculated by ASME Code stress analysis. In the public meeting on September 22, 1998 [item 2, Ref. 8], Westinghouse stated that in most piping stress analyses, dead weight, thermal, and pressure stresses are calculated on the basis of conservative assumptions such as concentrated dead loads, rigid support stiffnesses, conservative design conditions and stress concentration factors. Westinghouse also stated that the next revision of WCAP-14572 will clarify that if piping stress analysis is performed on the basis of realistic rather than conservative assumptions, higher median values and lower uncertainty can be justified and used in the detailed input options. Conditioned upon this change being incorporated into the next revision of WCAP-14572, the staff concludes that the approach for estimating the median values for stresses is acceptable because it is based on assumptions of conservative stresses in common pipe stress analyses and also accounts for situations when realistic, rather than conservative, values of dead load and thermal stresses are used.

In the public meeting on September 22, 1998 [item 3, Ref. 8], Westinghouse stated that the welding residual stresses used in the SRRA code are consistent with the pc-PRAISE code. Because of conservatism in applying these stresses in the SRRA code, the residual stresses are truncated at a maximum value of 90% of the material flow stress. Westinghouse also stated that the next revision of WCAP-14572 will provide basis for estimating the residual stresses to be used in the SRRA code. The staff finds the estimation of residual stresses to be acceptable because the conservatism that the residual stress is assumed to be constant through the weld wall and around the circumference, and no relaxation of residual stress is assumed for an initial fabrication flaw justifies the assumption that the yield strength of the weld is assumed to be 90% of the flow stress in the SRRA code for RI-ISI. The staff's approval is conditioned upon Westinghouse making the change to WCAP-14572 as described above.

In the public meeting on September 22, 1998 [item 4, Ref. 8], Westinghouse stated that industry experience has shown that axial cracks which could initiate from longitudinal welds are not a serious concern and have a low probability of occurrence because of the normal pressure and temperature ranges associated with nuclear operating plants. ASME Code Case N-524 was written to eliminate the requirement to examine longitudinal welds beyond the region of intersection with circumferential welds. The staff concludes that this approach is acceptable to address the axial cracks that could initiate from longitudinal welds, conditioned on Westinghouse revising WCAP-14572 [item 4, Ref. 8] to state that in the rare situation that a longitudinal weld or nonstandard geometry would need to be evaluated, the failure probability should be estimated by other means, such as expert opinion or advanced modeling.

The PRODIGAL program is used to calculate the number of flaws per weld length near the inner surface of the pipe. The staff concludes that this treatment of near-surface flaws is adequate and acceptable because all near-surface flaws are assumed to be inner surface breaking flaws,

the stress intensity factor for the near-surface flaws are conservatively calculated in the SRRA fracture mechanics models, and the flaw density used for the failure probability calculation is not reduced to eliminate the effect of flaws that are not actually surface flaws. The staff's approval is conditioned upon Westinghouse making the change to WCAP-14572 described above as stated by Westinghouse in the public meeting on September 22, 1998 [item 4, Ref. 8].

The CLVSQ program uses a simplified correlation to calculate leak rates. The staff finds the leak rate model to be acceptable since the accuracy of the correlation for fatigue type cracks is estimated to be within 25% and was judged to be acceptable by the ASME Research Task Force. PNNL's studies with pc-PRAISE also showed that the large leak and break probabilities were relatively insensitive to the actual value of the detectable leak rate in the range of 0.3 to 300 gpm [item 5 (c), Ref. 8].

The staff had identified an open item that WCAP-14572, Revision 1, does not identify the value that is used for the high-cycle fatigue stress for the 1-inch pipe size. Westinghouse clarified in the public meeting on September 22, 1998 [item 6, Ref. 8], that the vibration input for 1-inch pipe size is an input parameter determined by the SRRA user and an insert will be added in WCAP-14572 to provide guidelines for the SRRA user. A correction factor is applied to this stress to obtain the fatigue stress for other pipe sizes. The staff finds this approach to be acceptable since it specifies that the simplified input parameter is the peak-to-peak vibratory stress range in ksi corresponding to a one-inch pipe size. The staff's approval is conditioned upon Westinghouse making the change to WCAP-14572 described above.

Figure 4-2 of WCAP-14572, Revision 1, Supplement 1, graphically compares SRRA model predictions with industry plant data relative to the probability of violating minimum wall thickness criteria because of flow-accelerated corrosion wastage. The staff had expressed a concern (Ref. 9) that the graph indicates that the SRRA model tends to over-predict the failure probability early in plant life and to under predict later in life. In the public meeting on September 22, 1998 [item 7 (a), Ref. 8], Westinghouse explained that the minor over-prediction early in life is attributable to lower plant startup capacity factors (fraction of time at full power and flow), while the minor under-prediction later in life is attributable to higher capacity factors during this more mature period of plant operation. The staff finds this response acceptable since the industry observed failure rates due to wastage are within a factor of 2 to 3 of the SRRA calculated values even though the calculation was based upon data averaged values of pipe size and wall thickness.

Supplement 1 to WCAP-14572 provides information on assumptions made in the SRRA wall thinning model. In the public meeting on September 22, 1998 [item 7 (b), Ref. 8], Westinghouse stated that the next revision of WCAP-14572 will provide guidance for material wastage potential consistent with Ref. 11. The staff concludes that the guidance for estimating the material wastage potential is acceptable since, if material wastage rates are high enough to proceed through the pipe wall, the probabilities of small leak, large leak and break are all calculated to be the same. The staff's approval is conditioned upon Westinghouse making the change to WCAP-14572 described above. In addition, the acceptance is limited to this application, i.e., development of a risk-informed ISI program. As noted elsewhere, the licensees' augmented programs for erosion-corrosion will not be changed as a result of this alternative, and the staff is not endorsing the SRRA code for application in such augmented programs.

The staff had identified an open item that WCAP should provide guidance for the analyst on the SRRA code limitations for complex geometries and guidance for effective use of the code in such applications. In the public meeting on September 22, 1998 [item 12, Ref. 8], Westinghouse stated that the SRRA piping models only apply to standard piping geometry (circular cylinders with uniform wall thickness). Westinghouse further stated that a limitation on the use of nonstandard geometry will be added in the next revision of WCAP-14572. The staff finds this clarification of the code limitation to be acceptable. The staff's approval is conditioned upon Westinghouse making the change to WCAP-14572 described above.

The staff had also indicated that WCAP should specify the level of training and qualification that the code user needs to properly execute the SRRA code. In the public meeting on September 22, 1998 [item 13, Ref. 8], Westinghouse indicated that the next revision of WCAP-14572 will state that to ensure that the simplified SRRA input parameters are consistently assigned and the SRRA computer code is properly executed, the engineering team for SRRA input should be trained and qualified. The revised WCAP will also list the topics covered in this training as described in the September 22, 1998, public meeting [item 13, Ref. 8]. The staff finds the level of training and qualification that the code user needs to properly execute the SRRA code to be acceptable since it includes training on overall risk-informed ISI process , and how SRRA calculated probabilities are used in the piping segment risk calculation. The staff's approval is conditioned upon Westinghouse making the change to WCAP-14572 described above.

It was the staff's understanding that the existing correlation for leak rates are limited to pressurized-water reactors (PWR) reactor coolant system (RCS) conditions. The staff had indicated (Ref. 9) that Westinghouse should clarify whether the SRRA code can be applied to boiling-water reactors (BWR) and justify the applicability of the correlations used to calculate leak rates under BWR operating conditions. In the public meeting on September 22, 1998, Westinghouse stated that the existing correlations for leak rates can be used for other plant conditions beyond the RCS and that the SRRA code can be applied to BWRs; however, care must be exercised in applying this approach to BWR piping systems, particularly those subjected to intergrannular stress corrosion cracking (IGSCC). In addition, Westinghouse indicated that WCAP-14572 will be revised [item 5(d), Ref. 8] to provide guidance on addressing stress corrosion cracking. The staff finds the response acceptable since most piping susceptible to stress corrosion cracking (SCC) is also subject to fatigue loading, such as normal heat up and cool down, and the leak rate correlation for fatigue type cracks was conservatively assumed for the CLVSQ Program. The staff's approval is conditioned upon Westinghouse making the change to WCAP-14572 described above.

The staff had identified an open item that WCAP should describe how proof testing is addressed in the SRRA calculations. In the public meeting on September 22, 1998 [item 14, Ref. 8], Westinghouse stated that the effect of proof testing on the segment risk ranking and categorization would be very small and slightly conservative. Westinghouse also indicated that the next revision of WCAP-14572 will clarify that SRRA models in LEAKPROF do not take credit for eliminating large flaws, which would fail during the pre-service hydrostatic proof test, even though this is allowed as an input option in pc-PRAISE. The staff concludes that the approach for addressing proof testing is acceptable because Westinghouse has demonstrated that the effect of proof testing on the segment risk ranking and categorization would be very small and slightly conservative. The staff's approval is conditioned upon Westinghouse making the change to WCAP-14572 described above.

Before issuing this SER, the staff had identified an open item that the probability of detection curves used in calculations need to be justified for the material type, inspection method, component geometry, and degradation mechanism that apply to the structural location being addressed. In the public meeting on September 22, 1998 [item 15 (a), Ref. 8], Westinghouse stated that the default input values for the probability of detection (POD) curves are consistent with the default input values for pc-PRAISE. The revised WCAP will emphasize that the SRRA code user must ensure that the specified input values for POD are appropriate for the type of material, inspection method, component geometry, and degradation mechanism being evaluated. The staff finds this response acceptable since POD curves are consistent with the default input values for pc-PRAISE code which has been validated and accepted by the staff for various applications. The staff's approval is conditioned upon Westinghouse making the change to WCAP-14572 described above.

Before issuing this SER, the staff had identified an open item that Westinghouse should expand the code documentation to provide additional guidance for selecting the input for the calculation. In the public meeting on September 22, 1998 [item 15 (b), Ref. 8], Westinghouse stated that the next Revision of WCAP-14572, Supplement 1, will provide detailed guidelines for simplified input variables and any associated assumptions that could be important in assigning the input values for the SRRA code. WCAP-14572 will also state that if more than one degradation mechanism is present in a given segment, the limiting input values for each mechanism should be combined so that a limiting failure probability is calculated for risk ranking. The staff finds the guidance in item 15 (b), Ref. 8 to be acceptable because it provides sufficient guidance for the code user for selecting input parameters. The staff's approval is conditioned upon Westinghouse making the change to WCAP-14572 described above.

3.2.4 Consequence of Failure

The consequences of the postulated pipe segment failures include both direct and indirect effects of each segment failure. The direct effects include failures that cause initiating events or disable system trains or entire systems as a result of the loss of flow paths or loss of inventory, and the possible creation of diversion flow paths. Indirect effects include spatial effects, such as flooding, water spray, pipe whip, and jet impingement. WCAP-14572 methodology relies on the use of PRA models and results to gain insights into the potential direct and indirect consequences of pipe failures. Plant walkdowns are also an integral part of the methodology. The staff finds the general guidance provided in WCAP-14572 to determine the direct and indirect consequence of segment failure to be acceptable because it is comprehensive and systematic, and should produce a traceable analysis. WCAP-14572 does not include a detailed discussion of the specific assumptions to be used to guide the assessment of the direct and indirect effects of segment failures. For example, although diversion of flow is included as a direct effect, there is no guidance for determining whether a flow would be sufficiently large to fail a system function. Similarly, WCAP-14572 does not provide clear guidance for calculating flooding effects with regard to the required modeling of flood propagation pathways, modeling of flood growth and mitigation, and assumptions for the failure of critical equipment within a flood zone (e.g., if electro-mechanical components must be submerged before failure, etc.). The staff finds that specific assumptions regarding the direct and indirect effects of pipe segment failure should be developed by the individual licensees and should form part of the onsite documentation. A revision to WCAP-14572 (see item 8 (e) in Ref. 8) will require that details from

the consequence evaluation be maintained onsite for potential NRC audit.

WCAP-14572 methodology recommends considering a spectrum of different size breaks (i.e., failure modes) in every segment. The failure modes considered are the small leak, the disabling leak, and a full break, as discussed in Section 3 of Supplement 1. Failure probability for each of these modes typically decreases as the size of the break increases. WCAP-14572 also defines the direct and indirect effects to be evaluated for each postulated failure mode. The staff finds that the association between failure mode and effects is reasonable when compared to previous results and findings from PRAs of internal flooding events.

In section 3.4.2 of WCAP-14572 it is stated that the indirect effects of a pipe whip need not include the rupture of other piping of equal or greater size, but it should be assumed that a through-wall crack will develop in a line that is impacted by a whipping pipe of the same size. In Ref. 8, Westinghouse stated that the bases for these assumptions are found in Ref. 13 and Ref. 14. These references also provide justification for WCAP-14572 guidance on the location of circumferential and longitudinal breaks in high energy piping runs. In accordance with item 10 of Ref. 8, Ref. 13 and Ref. 14 will be added to the WCAP-14572, and cited appropriately in the text. The staff finds that the bases found in Ref. 13 and Ref. 14 to be acceptable because they represent established and commonly accepted industry practices. The staff's approval is conditioned upon Westinghouse making the change to WCAP-14572 described above.

3.3 Probabilistic Risk Assessment

The requirements of a PRA and the general methodology for using PRA in regulatory applications is discussed in the guidelines in RG 1.174. RG 1.178 provides guidance that is more specific to ISI. It is expected that licensees who wish to apply the WCAP-14572 methodology to an RI-ISI program will also conform to the RGs 1.174 and 1.178 guidelines for PRA quality, scope, and level of detail.

In July 1997, at staff briefing of the CRGR on draft RG 1.178, CRGR suggested that a peer review be performed of the use of PRA methods to support RI-ISI. The methodology proposed in RG 1.178 is similar to that found in WCAP-14572. The peer review, performed by Brookhaven National Laboratory (BNL), and documented in a letter report (Ref. 12), concluded that the PRA approach is technically sound and within the state-of-the-art, and that the approach can facilitate risk-informed regulatory decisionmaking in the area of ISI.

WCAP-14572 does not prescribe the incorporation of pipe segment failure events into the PRA model. Instead, the core damage frequency (CDF)/large early relief frequency (LERF) for each segment is determined by the use of surrogate events (i.e., initiating events, basic events, or groups of events) already modeled in the PRA with failures that are representative of the effects of the piping segment failure. By setting the appropriate surrogate events to a failed state in the PRA and by re-quantifying the PRA, the impact of the pipe segment failure can be estimated. The staff finds this process acceptable as long as the truncation limits used in the baseline calculations are maintained and the model is re-quantified. If a pre-solved cutset/scenario model is used instead of re-quantifying the baseline model, the application should include justification as to why the truncated model still produces reasonable results given that the equipment is assumed to be failed.

The segment failure probability/rate is combined with the results of the risk calculation as described in Equations 3-1 to 3-10 of WCAP-14572, Revision 1. The results are subsequently combined into a total piping segment CDF (or LERF). The staff recognizes that the WCAP equations are approximations for segment failures which do not trip the plant and that are discovered before an unrelated plant trip. Following the discovery of such a rupture, the likely operator action would be to isolate the break and to decide whether to shutdown or to continue plant operation. In some cases, the break may disable equipment required by the technical specifications and plant operation will be governed by allowed outage time (AOT). If the decision is made not to shut down the plant, the licensee would presumably realign the affected systems to facilitate repairs. If the decision is made to shut down the plant, the licensees may realign the systems to provide more robust mitigating function capabilities during the shutdown process, or may simply begin a controlled plant shutdown. In all cases except the long AOT scenario, the degraded condition would only be present during a relatively short time span. Furthermore, a pipe segment rupture is an unusual event and the operations staff would be very aware of the degraded functions and would be prepared to actively intervene if necessary. The staff finds the assumption that short AOT and controlled shutdown risk are minor contributors compared to risks associated with segment failure following an unrelated transients acceptable because of the short exposure time and the heightened awareness by the plant staff.

Short exposure time and heightened plant staff awareness may not, however, be a reasonable assumption if there is a long AOT. In response to staff comments, Westinghouse indicated that in a future revision to WCAP-14572 [item 18, Ref. 8], Equation 3-8 will be modified such that, for systems in which outage times are approximately the same order of magnitude as the test interval (T_1), e.g., approximately ¼T_1, the contribution attributed to maintenance unavailability (expressed as FR_{PB} * AOT) will be added to the total component unavailability.

The staff notes that the description associated with equation 3-5 on page 97 of the WCAP is not an appropriate characterization of the "CCDF" variable in the equation. The equation estimates what the WCAP refers to as a "Conditional Core Damage Frequency" (CCDF) to characterize the risk due to pipe failures that do not cause an initiating event but only fail mitigating systems. The staff believes that the desired quantity is not the conditional core damage frequency given a pipe break as stated, but rather the increase in the core damage frequency when the pipe break probability is changed from zero to unity. This change is multiplied by the pipe break failure probability to obtain the core damage frequency due to the pipe break. With this change in definition (e.g., CCDF as Change in Core Damage Frequency) of the result being calculated by the equation, the equation is correct and acceptable.

The staff notes that Equation 3-8 on page 99 is used to characterize several slightly different failure modes of piping segments. For failure modes where the pipe is continuously degrading and eventually reaches the point that transient or additional stresses associated with a demand following an initiating event would cause the pipe to fail, the equation corresponds to the normal standby failure estimate (e.g., the pipe integrity has failed but the failure only becomes apparent on demand). If the segment does not continuously degrade, but the strength is degraded slightly on each test demand, the equation is also a valid approximation. If the pipe does not degrade, but there are variations in the demand stress, the equation underestimates the failure probability by a factor of two. The staff finds the approximation acceptable since it is valid for the most likely failure modes, and produces a reasonable approximation for the other failure mode.

The staff finds that the methodology will yield results of commensurate precision with the segment failure probabilities and which, after review by the expert panel, can be used to support safety significance determination.

3.3.1 Evaluating Failures with PRA

The staff finds that the discussion in Section 3.6.1 of WCAP-14572, Revision 1, concerning the evaluation of CDF/LERF using surrogate components needs clarification with regard to the incorporation of indirect consequences associated with pipe segment failures. Since WCAP-14572, Revision 1, does not explicitly state that all components subject to a harsh environment, jet impingement, pipe whip, etc., initiated by a pipe segment failure should be failed in the PRA model evaluation, individual applications utilizing WCAP-14572 methodology must assume failure of this equipment in the risk evaluation, or provide justification as to why failure is not assumed in order to be considered an acceptable implementation of WCAP-14572 (e.g., the component is environmentally qualified to the conditions expected from the pipe failure event).

For some initiating events and plant operating modes, the scope of the available plant-specific PRA models may not be sufficient to estimate the impact of a pipe segment failure. For example, some PRAs may not model fires, seismic or other external events, and the shutdown mode of operation to the level of detail required to estimate relative risk importance or risk impact. For these cases, the impact of failure of each pipe segment on risk must then be developed and incorporated in the decision-making process by an expert panel. WCAP-14572 provides sample expert panel worksheets that include a listing and discussion of the safety-significant functions a system must perform. The expert panel is expected to consider the importance of these functions for scenarios not modeled in the PRA so that the categorization of safety significance of the pipe segments reflects all plausible accident scenarios. Since the text in WCAP-14572 does not discuss system functions and their use by the expert panel, individual RI-ISI applications must address this issue in order to be considered an acceptable implementation of WCAP-14572.

3.3.2 Use of PRA for Categorizing Piping Segments

Based on quantitative PRA results which assume no credit for ISI, risk reduction worth (RRW) and risk achievement worth (RAW) measures are developed for each pipe segment as described in Equations 3-11 and 3-12 of WCAP-14572. The RRW calculates the current contribution of the segment failure to risk and the RAW calculates the potential change in risk associated with the failure of the pipe segment. Use of these measures provides useful insights to the integrated decision-making process. The staff finds that the use of quantitative models which assume no credit for ISI is appropriate for the determination of the safety significance of pipe segments because one of the goals of the RI-ISI program is to target the inspection of those elements where inspection will be most efficient. If a pipe segment has one or more welds inspected under an augmented inspection program, WCAP-14572 methodology specifies that the representative weld failure probability is calculated assuming credit for ISI. The use of quantitative models which credit ISI for segments inspected under the augmented program is

appropriate since the augmented program inspection is maintained in the RI-ISI process.

WCAP-14572 recommends that pipe segments with RRW greater than 1.005 should be categorized as HSS while the segments with RRW values between 1.001 and 1.004 should be identified for additional consideration by the expert panel. The staff recognizes the utility of the suggested RRW guidelines and finds that these suggested values may be used for initial screening. WCAP-14572 does not provide guidelines for the RAW values for classification of safety significance. Instead, WCAP-14572 suggests that these values should be generated and supplied to the expert panel for consideration. The staff finds that the RAW values, or some other measure of the consequence of segment failure, provides a valuable input to the decision making process. The expert panel should be aware of the implications of high RAW values (or other consequence measure) so that their decisions are made with a full understanding of the severity of the consequences of each segment's rupture. The appropriateness of the RRW guidelines and use of the RAW values should be documented as part of the licensee's categorization process and should be assessed on a plant-specific basis within the framework of the proposed ISI program and based, in part, on the risk impact from the application.

An integral part of the categorization process is the expert panel which makes a final determination of the safety significance of each pipe segment. The expert panel considers pipe segment characteristics (e.g., Table 3.6-9 of WCAP-14572, Revision 1), the system characteristics (e.g., Table 3.6-12 of WCAP-14572, Revision 1), the risk-related information in the form of relative pipe segment importances and consequences of pipe failure, and information not available from the risk analyses such as the importance of the pipe for mitigating unquantified events (shutdown, external events, etc.). In addition, guidance to be added to Section 3.6.3 of WCAP-14572 [item 8(c), Ref. 8] will ensure consistent application of the expert panel process. Section 3.4 of this SER provides a detailed discussion of the qualification and role of the expert panel. The staff finds that in the categorization of pipe segments, the use of an expert panel (as documented in Section 3.6.3 of WCAP-14572) to combine PRA and engineering information (as described in example Tables 3.6-9 and 3.6-12) is acceptable and necessary. The staff finds the process acceptable since it meets the intent of the integrated decision-making process guidelines discussed in RGs 1.174 and 1.178, in that engineering and risk insights (both qualitative and quantitative) are taken into consideration in identifying safety significant piping segments. The staff notes that the expert panel's records must be retained on site and available for NRC staff audits. The staff's approval is conditioned upon Westinghouse making the change to WCAP-14572 described above.

3.3.2.1 Sensitivity to Modeled Human Actions

Operator actions to isolate a break and mitigate its immediate consequences are credited in the RI-ISI analysis. For example, operator action to close an MOV to stop the loss of water from a break can be credited, if this action is shown to be feasible. WCAP-14572 methodology recommends that two sets of calculations be performed, one assuming all such actions are successful and another assuming that all such actions fail. The RRW and RAW measures are calculated for these different assumptions and if the RRW is greater than 1.005 for the CDF or LERF calculations with or without operator action the segment is classified HSS. If any RRW is between 1.005 and 1.001, safety significance considerations are reviewed and the safety significance determined during the expert panel deliberations. The staff finds it acceptable to

use sensitivity studies to bound the possible impact of operator actions since these sensitivity calculations may point to areas where credit for recovery actions plays a major role in the classification of pipe segments (and where licensee commitment to these actions is important, or dependence on these recovery actions can be lessened).

In addition to operator recovery actions, the modeling of human actions can affect the RI-ISI process in another way. Specifically, choosing a surrogate PRA component to represent the system effects of a pipe failure in a segment must include consideration of how the surrogate component is modeled in the PRA, including the modeling of recovery actions for the component. To emphasize this consideration when choosing surrogate components, the following will be added to a future revision of WCAP-14572 [item 8 (d) of Ref. 8]:

> "When choosing a surrogate component, care must be taken to account for the ways in which the component has been modeled in the PRA, including recovery actions which may have been modeled to restore the operability of the component. If the recovery action was determined to be inappropriate for the postulated consequence given a piping failure, the recovery action basic event should also be failed with a probability of 1.0."

The staff finds the above addition to be acceptable since operator recovery actions that are no longer feasible as a result of a flood, will no longer be credited. The staff's approval is conditioned upon Westinghouse making the change to WCAP-14572 described above.

3.3.2.2 Sensitivity to Segment Failure Probability

WCAP-14572 includes an evaluation in which the impact of the variation in the segment failure probabilities on the safety significance determination is investigated. The analysis was based on assigning a range factor to the pipe failure probabilities. The staff finds that this study is useful and should be performed on a plant-specific basis for RI-ISI applications so that the impact of the variation of the pipe failure probabilities on the safety significance classification process can be evaluated.

As part of the staff's review of the WCAP methodology, independent audit analyses were performed by PNNL to estimate the uncertainties in the calculated failure probability for a piping segment. Highlights of the uncertainty studies are documented in NUREG-1661 (Ref. 15). The results from the uncertainty studies are illustrated in Figure-1 and summarized below:

1. The upper bound curve was based on the largest of the 100 failure probabilities calculated from the 100 pc-PRAISE runs for each given cyclic stress level.

2. The largest uncertainties are for those cases that have very low values of calculated failure probabilities. The uncertainties decrease with increasing failure probabilities.

3. The categorization of piping segments as high- and low-safety-significant is a function of the degradation mechanism and consequences. "Inactive" versus "active" degradation mechanisms result in significant variation in failure probabilities. This variation renders the impact of the large uncertainties for components with low failure probabilities as having a relatively small impact on the categorization. The effects of uncertainties on component categorization can be accounted for through numerical evaluations, such as Monte Carlo

analyses.

4. The calculations for components with very low failure probabilities are particularly sensitive to the tails of the distributions assumed for input parameters such as flaw depths and crack growth rates. The large uncertainties in the calculated failure probabilities are a direct results of the fact that the tails of these input distributions are based on extrapolations from actual data.

5. Failure rates for components with high calculated failure probabilities can be assessed for consistency with plant operating experience and with industry data bases on reported field failures. The ability to make such comparisons helps to minimize the uncertainties in the calculated probabilities.

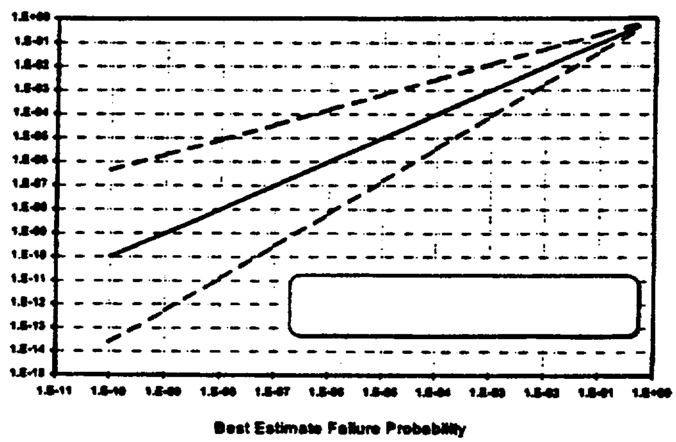

Figure - 1 Uncertainty Bounds Related to Values of Calculated Failure Probabilities

To ensure that the potential impact of uncertainties is adequately addressed in the categorization of piping segments, Westinghouse committed to add the following as part of a future revision to WCAP-14572 [item 19, Ref. 8]:

> "In addition to the sensitivity studies described above, a simplified uncertainty analysis is performed to ensure that no low safety significant segments could move into the high safety significance category when reasonable variations in the pipe failure and conditional CDF/LERF probabilities are considered. The results of the evaluation along with other insights are provided to the plant expert panel."

The staff finds that the sensitivity studies as proposed by WCAP-14572 (and as amended by the above addition) would address model uncertainty in terms of pipe failure probabilities, and would ensure that pipe segment categorization is robust. The staff's approval is conditioned upon Westinghouse making the change to WCAP-14572 described above.

3.3.3 Change in Risk Resulting from Change in ISI Programs

To estimate the change in risk from the implementation of the RI-IST program, WCAP-14572 methodology utilizes the SRRA code to provide a quantitative estimate of the relative susceptibility of pipe segments to failure as determined by the weld material and environmental conditions within the segment. Different weld failure probabilities are calculated depending on whether the weld is inspected or not. The methodology credits the reduction in weld failure probability attributable to ISI at the segment level. If one or more welds within a segment are inspected under the current Section XI program or the RI-ISI program, the selected weld failure probability including credit for ISI is assigned to the segment. That is, the segment failure probability will not change as a result of any changes in the inspection strategy applied to the welds within a segment. If one or more welds were inspected under the Section XI program, but no welds will be inspected under an RI-ISI program, the segment failure probability will increase. If no welds were inspected under the Section XI program, but one or more welds will be inspected under the RI-ISI program, the segment failure probability will decrease. If one or more welds within a segment are inspected in the augmented program, the selected weld failure probability including credit for the augmented program is assigned to the segment. For a selected pipe segment where at least two separate inspections are being performed (one for the primary failure mechanism which is addressed by an augmented program, and other inspection(s) performed under the Section XI program or the RI-ISI program, so that the secondary mechanism is addressed), a factor of three improvement in the failure probability is credited.

The staff finds the above process acceptable, but recognizes that this process underestimates risk reductions arising from changing inspection locations from a weld subject to no degradation mechanism to another with an identified degradation mechanism. It also underestimates risk increases arising from the reduction in the number of welds inspected within each segment. The staff expects that the targeting of inspections to degradation mechanisms should yield relatively large risk reductions, while the reduction in the number of inspections within a segment will yield a larger number of smaller risk increases. However, as discussed in Section 3.2.3 of this SER, the increase in risk resulting from a reduction in the number of inspections should be minimal since WCAP-14572 methodology will characterize the failure probability of a segment by combining the failure probabilities of the dominant degradation mechanisms in that section.

In determining whether the change in CDF and LERF associated with WCAP-14572 methodology is acceptable, the following factors were also considered; the statistical evaluation used to develop an initial estimate of the number of welds to inspect, and the four criteria for evaluation of results found in Section 4.4.2 of WCAP-14572. These are further discussed below.

To ensure that a target leak rate is met with a stated level of confidence, the statistical evaluation methodology proposed in WCAP-14572 uses the probability of a flaw, the conditional

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probability of a leak, and a target leak rate to determine the minimum number of welds to inspect. In discussions with the staff, Westinghouse stated that, in controlling the frequency of pipe leaks, the pipe break frequency (which drives the safety significance classification) is also controlled. This is supported by the pilot WCAP RI-ISI application, which reported that the conditional probability of a pipe break is sufficiently small when compared to the conditional leak probability, and that the level of confidence that the target leak frequency is not exceeded is also the confidence that the pipe break frequency is not exceeded. WCAP-14572 methodology thus provides a systematic evaluation of the required number of inspections that is acceptable for the RI-ISI program, and confidence that the failure likelihood of high safety significant piping segments will not increase above those values used to support the finding.

WCAP-14572 provides guidelines for evaluating the change in plant and system-level risk resulting from changes to the ISI program. The first guideline suggests the addition of examinations until at least a risk neutral change is estimated. The second guideline suggests that the risk-dominant pipe segments within systems which dominate the estimated risk (e.g., greater than 10% of the total) should be reevaluated to identify where additional examinations may be needed so that the overall risk for these systems could be reduced. The third guideline suggests that, for systems where risk increases are identified, additional examinations may be necessary to minimize the risk increase (to less than two orders of magnitude below the RI-ISI CDF/LERF for that system and less than a 10^{-8} CDF increase or a 10^{-9} LERF increase). The staff finds that these WCAP guideline are consistent with the guidance in RGs 1.174 and 1.178 which state that risk increases (if any) resulting from a proposed change should be small and consistent with the intent of the Commission's Safety Goal Policy Statement.

In summary, the staff finds that, although the calculation of the change in risk (CDF/LERF) will not precisely estimate the magnitude of the change, the calculation can illustrate whether the resulting change will be a risk increase or a risk decrease. Using sensitivity studies, the quantitative results can be shown to be robust in terms of credit for operator actions and pipe segment failure probability. By utilizing plant and system-level criteria as discussed above, the risk from individual system failures will be kept small and dominant risk contributors will not be created. When applied as part of an integrated decision-making process, the staff finds that the analyses, results, and decision criteria associated with the determination of segment safety significance and subsequent change in risk estimates provide reasonable assurance that the change in the ISI program would result in a total plant risk neutrality, risk decrease, or a small risk increase that will be consistent with staff guidelines found in RG 1.174. For full scope RI-ISI programs, such as the one performed for Surry Unit 1, the staff anticipates the program to be risk neutral or result in a risk reduction.

3.4 Integrated Decisionmaking

RG 1.178 and SRP Chapter 3.9.8 guidelines describe an integrated approach that should be utilized to determine the acceptability of the proposed RI-ISI program by considering in concert the traditional engineering analysis, risk evaluation, and the implementation and performance monitoring of piping under the program.

In the WCAP-14572 approach to integrated decisionmaking, conventional fracture mechanics analysis methods are combined with Monte-Carlo probabilistic simulations to determine failure

probabilities for the pipe segments, as discussed in Supplement 1 to WCAP-14572, Revision 1. These failure probabilities are used together with the results of consequence evaluations to characterize the conditional risk associated with the failure of each segment, as discussed in Section 3.6 of WCAP-14572. Specifically, section 3.6 explains how this information is integrated with deterministic considerations and an expert panel evaluation to categorize pipe segments as either LSS or HSS. Section 3.7 of WCAP-14572, Revision 1, explains how the results of this risk-ranking process are used in selecting structural elements for examination.

An integral part of the RI-ISI process is the expert panel which makes a final determination of the safety significance of each pipe segment. The expert panel is responsible for the review and approval of all risk-informed selection results by utilizing their expertise and past experience in inspection results, industry piping failure data, relevant stress analysis results, PRA insights, and knowledge of ISI and nondestructive examination techniques. The RI-ISI expert panel should include expertise in the following areas:

- PRA
- Plant Operations
- Plant Maintenance
- Plant Engineering
- ISI
- Nondestructive Examination
- Stress and Materials Engineering

Section 3.6.3 of WCAP-14572, Revision 1, provides details of the WOG expert panel process. Item 8(c) of Ref. 8 provides further details on the role of the expert panel to evaluate the risk-informed results and make a final decision by identifying HSS segments for ISI. Item 8(c) of Ref. 8 also states that segments that have been determined to be HSS should not be classified lower by the expert panel without sufficient justification that is documented as part of the program and that the expert panel should be focussed primarily on adding piping segments to the higher classification.

The expert panel evaluations are an established part of the Maintenance Rule implementation and their use in risk-informed applications is well established. The staff finds that in the categorization of pipe segments, the use of an expert panel (as documented in Section 3.6.3 of WCAP-14572) to combine PRA and engineering information (as described in example Tables 3.6-9 and 3.6-12) is acceptable and necessary. In addition, guidance to be added to Section 3.6.3 of WCAP-14572 [item 8(c), Ref. 8] will ensure consistent application of the expert panel process. The staff finds the process acceptable since it meets the integrated decision-making process guidelines discussed in RG 1.174 and SRP Chapter 1.178, in that engineering and risk insights (both qualitative and quantitative) are taken into consideration in identification of safety significant piping segments. The staff's approval is conditioned upon Westinghouse making the change to WCAP-14572 described above.

3.4.1 Selection of Examination Locations

At its July 1997 briefing, CRGR requested that the staff should have a peer review performed to assess the use of Perdue-Abramson statistical model to determine the number of elements to be inspected within a piping segment. The contractor performing the peer review in this area (Los Alamos National Laboratory(LANL)) concluded (Ref. 16) that the Perdue-Abramson method is a statistically sound method for use in determining the number of welds to be inspected in an RI-ISI program in order to ensure that a specified target leak frequency is not exceeded at the pre-specified confidence level of 95%. LANL further stated that although other sampling schemes could be used (such as classical and/or Bayesian double or sequential sampling schemes), the Perdue-Abramson model is capable of providing the desired confidence or assurance.

Section 3.6.1 of WCAP-14572 addresses evaluation of the classification of piping segments, using sensitivity studies to demonstrate whether changes in assumptions or data can affect these classifications. Piping systems at Millstone Unit 3 and Surry Unit 1 were considered in these studies. Operational insights are addressed in Section 3.6.2 of WCAP-14572, which indicates that information obtained from plant operation and maintenance experience is used to identify piping segments having a history of design or operating issues. Section 3.6.3 states that an expert panel reviews and approves the final classification of piping segments on the basis of their expertise and insights as discussed in Section 3.4. A discussion of the risk ranking process is provided in Sections 3.6.4 and 3.6.5 of WCAP-14572.

Sections 3.7.1 and 3.7.2 of WCAP-14572 address the criteria used to determine the number of structural elements selected for examination, consistent with the safety significance and failure potential of the given pipe segment. The RI-ISI program includes examinations of HSS elements contained in Regions 1 and 2 of the element selection matrix (Figure 3.7-1 of WCAP-14572). By the WCAP-14572 selection process, 100% of the susceptible locations (Region 1A) are examined. Elements in Regions 1B and 2 are generally subject to a statistical evaluation process such as the Perdue Model.

The Perdue Model is intended to be used on highly reliable piping to establish a statistically relevant sample size and verify the condition of the piping. In cases where an active degradation mechanism exists, particularly where there is an ongoing augmented program, it is inappropriate to use the Perdue Model for element selection. In these cases, the expert panel must apply other rationales for selecting the number of elements to examine. At Surry, the licensee selected certain elements to address a secondary degradation mechanism and reduce the delta risk compared to current Section XI ISI. In other cases, elements were selected to address defense in depth considerations. As discussed in the public meeting on September 22, 1998 [page 274, Ref. 8], Westinghouse indicated that additional guidance would be added in Section 3.7 of WCAP-14572 to address sample size selection in cases where the Perdue Model could not be applied to state that "additional rationale must be developed when a statistical model cannot be applied to determine the minimum number of examination locations for a given segment."

The staff finds the methodology to determine the number of elements selected for examination to be acceptable since, all HSS segments with known degradation mechanisms will be subject to 100% examination, HSS segments with no known degradation mechanism will be sampled for examination on a sound statistical basis to ensure that a specified target leak frequency is not

exceeded at the pre-specified confidence level of 95%, LSS segments with known degradation mechanisms will be subject to examination in accordance with the licensees defined program, and the final scope of examination will result in a change in risk consistent with RG 1.174 guidelines. The staff's approval is conditioned upon Westinghouse making the change to WCAP-14572 described above [page 274, Ref. 8].

3.4.2 Examination Methods

Licensees who wish to apply the WCAP-14572 methodology to an RI-ISI program must conform to the guidelines in RG 1.178 for examination and pressure test requirements. Examination methods and personnel qualification must be in accordance with the ASME Section XI Code Edition and Addenda endorsed by the NRC through 10 CFR 50.55a. For inspections outside the scope of Section XI (e.g., EC, IGSCC) the acceptance criteria should meet existing regulatory guidance applicable to those programs.

The objective of ISI and ASME Section XI are to identify conditions (i.e., flaw indications) that are precursors to leaks and ruptures in the pressure boundary that may impact plant safety. Therefore, the RI-ISI program must meet this objective to be found acceptable for use. Further, since the risk-informed programs is predicated on inspection for cause, element selection should target specific degradation mechanisms.

WCAP-14572, Revision 1, specifies that inservice examinations and system pressure tests are to be performed in accordance with Section 4 of WCAP-14572 which should meet the requirements contained in Section XI of the ASME BPVC Code Edition and Addenda specified in the Owner's current ISI program except where specific references are provided that add supplemental requirements, specify other Code editions and addenda, or recommend/require the use of ASME Code Cases. The examination methods for HSS piping structural elements, specified in Table 4.1-1 of WCAP-14572 are taken directly from Code Case N-577, Table 1. As an alternative to Table 4.1-1, additional guidance for the selection of examination methods is provided in Table 4.1-2 of WCAP-14572, which contains suggested examination or monitoring methods consistent with the configuration of the structural element and the postulated failure mode. This guidance is subject to approval by the Authorized Nuclear Inservice Inspector (ANII) under the requirements of Paragraph IWA-2240 of ASME Section XI. Consistent with RG 1.178 guidelines, all ASME Class 1, 2, and 3 piping systems must continue to receive a visual examination for leakage in accordance with the applicable pressure test requirements of ASME Section XI as endorsed by 10 CFR 50.55a.

3.5 Implementation and Monitoring

The objective of this element of RGs 1.174 and 1.178 is to assess performance of the affected piping systems under the proposed RI-ISI program by implementing monitoring strategies that confirm the assumptions and analysis used in developing the RI-ISI program. To satisfy 10 CFR 50.55a(a)(3)(i), implementation of the RI-ISI program (including inspection scope, examination methods, and methods of evaluation of examination results) must provide an adequate level of quality and safety. The plant-specific application process is covered in Section 5 of WCAP-14572, which provides the framework for applying the risk-informed methods to a

specific plant for the ISI of piping.

Considering that the implementation of the proposed RI-ISI program will greatly reduce the number of examinations, limited examinations could have a significant impact on the detection of inservice degradation. In cases where examination methods are not practical or appropriate, RG 1.178 states that alternative inspection intervals, scope and methods should be developed to ensure that piping degradation is detected and structural integrity is maintained. To address this aspect, a stepped approach to limited examinations will be incorporated into WCAP-14572 that may include the examination of adjacent elements and more frequent pressure testing and visual examination for leakage. However, it should be noted that, in accordance with the regulations, limited examinations must be documented and submitted to the staff as relief requests for review and approval.

The qualification of NDE personnel, processes and equipment must comply with Section XI of the ASME Code to meet the requirements of 10 CFR 50.55a. In general, this means procedures must be qualified in accordance with ASME Section XI, Appendix VIII, or in the spirit of Appendix VIII, for techniques. As discussed in response G-19 in the NEI submittal dated March 13, 1997 (Ref. 17), Westinghouse stated that the reference plant "would qualify methods, procedures, personnel, and equipment to a level commensurate with the intent of an Appendix VIII performance demonstration."

Section 4 of WCAP-14572, "Inspection Program Requirements," notes that the use of a number of Code Cases is recommended (i.e., N-416-1, N-498-1, N-532). Staff acceptance of the WOG approach does not automatically imply acceptance of the referenced Code Cases. Licensees proposing to use the WOG approach must submit separate proposed alternatives to use these or other unapproved Code Cases.

Implementation of a RI-ISI program for piping should be initiated at the start of a plant's next ISI interval, consistent with the requirements of the ASME Code Section XI Edition and Addenda committed to by an Owner in accordance with 10 CFR 50.55a, or any delays granted by the NRC staff. In addition to other changes in Section 4.5 of WCAP-14572, Westinghouse stated in the public meeting on September 22, 1998 [item 20, Ref. 8], that the following sentence will be added in the next revision of WCAP-14572:

> "Documentation of program updates shall be kept and maintained by the Owner on site for audit. Changes arising from the program updates should be evaluated using the change mechanisms described in existing applicable regulations (e.g., 10 CFR 50.55a and Appendix B to 10 CFR Part 50) to determine if the change to the RI-ISI program should be reported to the NRC."

The staff finds the periodic reporting requirements to be acceptable since they meet the existing applicable regulations. The staff's approval is conditioned upon Westinghouse making the change to WCAP-14572 described above.

WCAP-14572, Revision 1 states that periodic updates of RI-ISI programs will be performed at least on a period basis to coincide with the inspection program requirements contained in ASME Section XI under Inspection Program B. The staff finds these updates acceptable because they meet ASME Section XI which requires updates following the completion of all scheduled

examinations in each inspection interval. WCAP-14572 also states that RI-ISI programs will be evaluated for changes in safety-significance and inspection requirements due to plant design feature changes, plant procedure changes, equipment performance changes, and examination results including flaws or indications of leaks. This process for RI-ISI program updates meets the guidelines of RG 1.174 that risk-informed applications must include performance monitoring and feedback provisions and hence is acceptable to the staff.

3.6 Conformance to Regulatory Guide 1.174

RG 1.174 describes an acceptable method for assessing the nature and impact of licensing basis changes by a licensee when the licensee chooses to support these changes with risk information. This Reg Guide identifies a four-element approach for evaluating such changes, and these four elements are aimed at addressing the five principles of risk-informed regulation. Section 1.4 of WCAP-14572 Revision 1 summarizes how the proposed WOG RI-ISI process conforms to the RG 1.174 approach. The staff finds that WCAP-14572 approach is consistent with RG 1.174 as discussed below.

In Element 1 of the RG 1.174 approach, the licensee is to define the proposed change. Section 1.1 of WCAP-14572 discusses current regulatory requirements for the ISI program and the changes in regulatory compliance using the RI-ISI approach. The scope of the changes is also discussed, and this scope includes the addition of non-ASME code piping that has been identified as high safety significant. The staff finds that the discussion in Section 1.1 of WCAP-14572 to be consistent with the guidance provided in Section 2.1 of RG 1.174.

Element 2 is the performance of the engineering analysis. In this element, the licensee is to consider the appropriateness of qualitative and quantitative analyses, as well as analyses using traditional engineering approaches and those techniques associated with the use of PRA findings. Regardless of the analysis method chosen, the licensee must show that the principles set forth in Section 2 of RG 1.174 have been met. The staff finds that the evaluation process as described in Section 3 of WCAP-14572 meets the requirements of this Element. WCAP Section 3 describes the probabilistic and deterministic engineering analyses to be performed and integrated through the use of a plant expert panel to define the high and low safety significant piping segments. The results of these analyses are used to select the inspection locations and inspection methods, and a statistical model is used to determine the number of locations to be inspected to meet confidence and reliability goals.

Element 3 is the definition of the implementation and monitoring program. The primary goal of this element is to ensure that no adverse safety degradation occurs because of changes to the ISI program, and the staff finds that the guidance provided in WCAP Section 4.5 is adequate to meet this goal. Section 4.5 of WCAP-14572 discusses how the implementation of the RI-ISI program is consistent with the requirements of ASME Code Section XI. In addition, the monitoring, feedback and corrective action program discussed is consistent with guidelines provided in Section 2.3 of RG 1.174.

Element 4 is the submittal of the proposed change. WCAP-14572 states that each licensee will submit their proposed change at the time they perform a RI-ISI program.

RG 1.174 states that, in implementing risk-informed decision-making, plant changes are expected to meet a set of key principles. The paragraphs below summarize these principles, and staff findings with regard to the conformance of WCAP-14572 methodology with these principles.

Principle 1 states that the proposed change must meet current regulations unless it is explicitly related to a requested exemption or rule change. The proposed RI-ISI change is an alternative to the ASME Section XI Code as referenced by 10 CFR 50.55a(a)(3) for piping ISI requirements with regard to the number of inspections, locations of inspections, and methods of inspections.

Principle 2 states that the proposed change must be consistent with the defense-in-depth philosophy. ISI is an integral part of defense-in-depth. It is expected that as part of the RI-ISI process, the safety significance categorization, the expert panel review and approval, and the subsequent number and location of elements to inspect will maintain the basic intent of ISI (i.e., identifying and repairing flaws before pipe integrity is challenged). Therefore, although a reduction in the number of welds inspected is anticipated, it is expected that there will be reasonable assurance that the program will provide a substantive ongoing assessment of piping condition.

Principle 3 states that the proposed change shall maintain sufficient safety margins. No changes to the evaluation of design basis accidents in the final safety analysis report (FSAR) are being made by the RI-ISI process. In addition, Section 3.7 of WCAP-14572 describes the use of a statistical model to assure that safety margins (in terms of pipe failure probability) are maintained. This statistical model is based on the evaluation of potential flaws and leakage rates that are precursors to piping failure.

Principle 4 states that, when proposed changes result in an increase in core damage frequency or risk, the increases should be small and consistent with the intent of the Commission's Safety Goal Policy Statement. Sections 1.4, 3.6, 3.7, and 4.4 of WCAP-14572 provide arguments that a RI-ISI program is, as a minimum, a risk-neutral application and should result in a risk reduction. Staff findings with regard to principle 4 are found in Section 3.3.3 of this SER.

Principle 5 states that the impact of the proposed change should be monitored using performance measurement strategies. WCAP-14572 conformance to this principle is already discussed in the paragraph on Element 3 above.

4.0 CONCLUSIONS

10 CFR 50.55a(a)(3) states that alternatives to the requirements of paragraph (g) may be used, when authorized by the NRC, if (i) the proposed alternatives would provide an acceptable level of quality and safety or (ii) compliance with the specified requirements would result in hardship or unusual difficulty without a compensating increase in the level of quality and safety. The staff concludes that the proposed RI-ISI program as described in WCAP-14572, Revision 1, conditioned upon the changes to be incorporated as discussed in Ref. 8, will provide an acceptable level of quality and safety pursuant to 10 CFR 50.55a for the proposed alternative to the piping ISI requirements with regard to the number of inspections, locations of inspections, and methods of inspections. This conclusion is founded on the findings discussed in the

remainder of this section.

The methodology conforms to the guidance provided in RGs 1.174 and 1.178, in that applying the methodology results in risk-neutrality or risk-reduction for the piping addressed in the RI-ISI program. According to this methodology, the licensees will identify those aspects of the plants' licensing bases that may be affected by the proposed change, including rules and regulations, FSAR, technical specifications, and licensing conditions. In addition, the licensees will identify all changes to commitments that may be affected as well as the particular piping systems, segments, and welds that are affected by the change in the ISI program. Specific revisions to inspection scope, schedules, locations, and techniques will also be identified, as will plant systems and functions that rely on the affected piping. The WOG procedure to subdivide piping systems into segments is founded on portions of piping having the same consequences of failure to be placed into the same piping segments. In addition, consideration is given to identifying distinct segment boundaries at branching points, locations of pipe size changes, isolation valve, and MOV and air-operated valves (AOV) locations.

Each segment's potential for failure is appropriately represented as failure on demand, unavailability, or frequency of failure. The relative potential for failure is consistent with systematic consideration of degradation mechanisms, segment and weld material characteristics, and environmental and operating stresses. The assessment of component failure potential attributable to aging and degradation takes into account uncertainties. Computer codes used to generate quantitative failure estimates have been verified and validated against established industry codes. Supplement 1 to WCAP-14572, Revision 1, describes the models, software, and validation of the SRRA computer code. The SRRA model is used to estimate the probability of piping failures. Peer reviews of the SRRA code have been performed on several occasions. The author of the code has published several papers for presentation at technical conferences, with technical peer reviews being part of the publication process. Earlier versions of the code have been used by Westinghouse in past research projects which have also been reviewed by the staff. In addition, the methodology of the code parallels approaches used in other generally accepted probabilistic structural mechanics codes, such as pc-PRAISE. Technical reviews of the SRRA code were performed during the Surry Unit 1 pilot plant study by the staff, its contractors, and the ASME Research Task Force on Risk-Based Inservice Inspection. These efforts provided a detailed review of the Westinghouse SRRA code, and comments from this effort resulted in several improvements to the SRRA code, as reflected in WCAP-14572, Revision 1, Supplement 1. The recent reviews were based on (1) documentation of the code, (2) detailed descriptions of example calculations, (3) trial calculations performed with the SRRA code by peer reviewers, and (4) benchmark calculations to compare failure probabilities predicted by the SRRA code and the pc-PRAISE code.

The stress corrosion cracking model of the SRRA code has a relatively simple technical basis, which does not attempt to model the complex failure mechanism in a detailed mechanistic manner. The calculations are based on a number of significant assumptions as discussed in Section A.4.3 of this SER. In particular, the code documentation given in WCAP-14572, Revision 1, Supplement 1, acknowledges the limitations of the model, and recommends the use of the pc-PRAISE computer code if predictions from a more refined mechanistic model are needed. The probabilistic fracture mechanics calculations for IGSCC have not been benchmarked for consistency with plant-specific and industry operating experience. In this regard, the Surry Unit 1 evaluations do not provide a particularly good basis to evaluate the

SRRA stress corrosion cracking model, because IGSCC makes only a small contribution to piping failures for PWR plants. The staff therefore requires that the IGSCC model be further evaluated on future applications to BWR plants, because IGSCC is a major factor governing piping integrity at BWRs.

The staff noted several limitations, e.g., IGSCC modeling, lack of benchmarking of E-C model compared to existing E-C programs, lack of modeling of complex geometries, etc. in the SRRA code. These limitations in the SRRA code result in a need for judicious use of the code and careful attention by the expert panel to ensure that the results of the code seem appropriate. It should be noted that the use of SRRA, or other probabilistic fracture mechanics codes, to estimate relative failure frequencies of piping systems and components is appropriate, but that the ability of such codes to estimate failure frequencies is limited by the quality of the input data and modeling limitations inherent in the code itself. Providing bounding or conservative inputs to the model or relying on the conservative nature of certain aspects of the code can potentially lead to inappropriate conclusions regarding the relative susceptibility to failure of various piping segments and components. Therefore, it is extremely important that these limitations be recognized by the user of the code and by the licensees' expert panel and that the results of the analyses are carefully scrutinized to assure that they make sense when compared to engineering knowledge of degradation mechanisms and plant specific and generic operating experience. Further details of the limitations and staff recommendations on the use of the SRRA code are provided in Section A.25 of this SER.

The impact on risk attributable to piping pressure boundary failure considers both direct and indirect effects. Consideration of direct effects includes failures that cause initiating events or disable single or multiple components, trains or systems, or a combination of these effects. The methodology also considers indirect effects of pressure boundary failures affecting other systems, components and/or piping segments, also referred to as spatial effects such as pipe whip, jet impingement, flooding or failure of fire protection systems.

The results of the different elements of the engineering analysis are considered in an integrated decision-making process. The impact of the proposed change in the ISI program is founded on the adequacy of the engineering analysis, acceptable change in plant risk, and the adequacy of the proposed implementation and performance monitoring plan, in accordance with RG 1.174 guidelines.

WOG methodology also considers implementation and performance-monitoring strategies. Inspection strategies ensure that failure mechanisms of concern have been addressed and there is adequate assurance of detecting damage before structural integrity is impacted. Safety significance of piping segments is taken into account in defining the inspection scope for the RI-ISI program.

System pressure tests and visual examination of piping structural elements will continue to be performed on all Class 1, 2, and 3 systems in accordance with the ASME BPVC Section XI program, regardless of whether the segments contain locations that have been classified as HSS or LSS. The RI-ISI program applies the same performance measurement strategies as existing ASME requirements and, in addition, broadens the inspection volumes at weld locations.

WCAP-14572, Revision 1, has provided the methodology to conduct an engineering analysis of the proposed changes using a combination of engineering analysis with supporting insights from a PRA. Defense-in-depth and quality is not degraded in that the methodology provides reasonable confidence that any reduction in existing inspections will not lead to degraded piping performance when compared to existing performance levels. Inspections are focused at locations with active degradation mechanisms as well as selected locations that monitor the performance of the front-line primary system piping (the second barrier of fission product release).

Safety margins used in design calculations are not changed. Piping material integrity is monitored to ensure that aging and environmental influences do not significantly degrade the piping to unacceptable levels.

Augmented examination program for degradation mechanisms such as IGSCC and EC would remain unaffected by the RI-ISI program and WCAP-14572 should not be taken as a basis to change the augmented inspection program.

Although the staff finds that the general guidance provided in WCAP-14572 Revision 1 (and as amended by Ref. 8) to be acceptable, application of this guidance will be plant-specific. As such, individual applications in RI-ISI must address the various plant-specific issues. These include:

- The quality, scope and level of detail of the PRA used, as described in RG 1.174 and 1.178 (see Section 3.3 and 3.3.1 of this SER).
- The guidelines and assumptions used for the determination of direct and indirect effects of flooding, including assumptions on the failure of components affected by the pipe break (see Sections 3.2.4 and 3.3.1 of this SER)
- The criteria, and the justification for the criteria used for the categorization of piping segments, including sensitivity studies to model human actions and segment failure probability (see Section 3.3.2 of this SER).

In the public meeting on October 8, 1998 (Ref. 18), the staff and the industry discussed the information to be submitted to the NRC and the list of retrievable onsite documentation for potential NRC audits of licensees that seek to utilize the WOG methodology for their RI-ISI program. The staff's expectation is that contents of submittals to NRC listed below will consist of brief statements and results of program development with details available as retrievable onsite documentation for potential NRC audits:

- Submittal Contents

(1) justification for statement that PRA is of sufficient quality
(2) summary of risk impact
(3) current Inspection Code
(4) impact on previous relief requests
(5) revised FSAR pages impacted by the change, if any
(6) process followed (WCAP, Code Case, and exceptions to methodology, if any)

(7) summary of results of each step (e.g., number of segments, number of HSS and LSS segments, number of locations to be inspected, etc.)
(8) a statement that RG principles are met (or any exceptions)
(9) summary of changes from current ISI program
(10) summary of any augmented inspections that would be impacted

- Retrievable Onsite Documentation for Potential NRC Audit

(1) scope definition
(2) segment definition
(3) failure probability assessment
(4) consequence evaluation
(5) PRA model runs for the RI-ISI program
(6) risk evaluation
(7) structural element/NDE selection
(8) change in risk calculation
(9) PRA quality review
(10) continual assessment forms as program changes in response to inspection results
(11) documentation required by ASME Code (including inspection personnel qualification, inspection results, and flaw evaluations)

5.0 REFERENCES

1. Westinghouse Topical Report, WCAP-14572, "Westinghouse Owners Group Application of Risk-Informed Methods to Piping Inservice Inspection Topical Report," Revision 1, October 1997.

2. Westinghouse Topical Report, WCAP-14572, Supplement 1, "Westinghouse Structural Reliability and Risk Assessment (SRRA) Model for Piping Risk-Informed Inservice Inspection," Revision 1, October 1997.

3. U.S. Nuclear Regulatory Commission, "An Approach for Using Probabilistic Risk Assessment in Risk-Informed Decisions on Plant-Specific Changes to the Licensing Basis," Regulatory Guide 1.174, July 1998.

4. U.S. Nuclear Regulatory Commission, "An Approach for Plant-Specific, Risk-Informed Decisionmaking: Inservice Inspection of Piping," Regulatory Guide 1.178 for Trial Use, September 1998.

5. American Society of Mechanical Engineers, Boiler and Pressure Vessel Code, Code Case N-577, "Risk-Informed Requirements for Class 1, 2, and 3 Piping, Method A," September 2, 1997.

6. Standard Review Plan Chapter 3.9.8, "Standard Review Plan for Trial Use for the Review of Risk-Informed Inservice Inspection of Piping," October 1998.

7. Standard Review Plan Chapter 19.0, "Use of Probabilistic Risk Assessment in Plant-Specific, Risk-Informed Decisionmaking: General Guidance," NUREG-0800, July 1998.

8. Letter from Louis F. Liberatori, Jr., Chairman (Westinghouse Owners Group), to Peter C. Wen (NRC), "Transmittal of Responses to NRC Open Items on WOG RI-ISI Program and Reports WCAP-14572, Revision 1, and WCAP-14572, Revision 1, Supplement 1," September 30, 1998.

9. Letter from Peter C. Wen (NRC), to Andrew Drake (Westinghouse Owners Group), "Open Items Related to Westinghouse Owners Group Application of Risk-Informed Methods to Piping Inservice Inspection (WCAP-14572, Revision 1)," September 2, 1998.

10. Letter from P. Krishnaswamy (Battelle-Columbus), to Deborah Jackson (NRC), "Independent Peer Review of Draft Regulatory Guide DG-1063," October 31, 1997.

11. Chexal, B. et al., "CHECWORKS Flow-Accelerated Corrosion, Version 1.0F, User Guide," Final Report TR-103198-P1, Electric Power Research Institute, June 1998.

12. Letter from W.T. Platt and T. L.Chu (Brookhaven National Laboratory), to Jack Guttmann (NRC), "Independent Peer Review of Draft Regulatory Guide DG-1063," October 15, 1997.

13. American Nuclear Society, "Design Basis for Protection of Light-Water Nuclear Power

Plants Against the Effects of Postulated Pipe Rupture," ANSI/ANS-58.2-1988, 1988.

14. Westinghouse Systems Standard Design Criteria (SSDC) 1.19, "Criteria for Protection Against Dynamic Effects Resulting from Pipe Rupture," Revision 1, 1980.

15. U.S. Nuclear Regulatory Commission NUREG-1661," Technical Elements of Risk-Informed Inservice Inspection Programs for Piping" to be published.

16. Letter from Harry Martz (Los Alamos National Laboratory), to Lee Abramson (NRC), "Independent Peer Review of Draft Regulatory Guide DG-1063," September 5, 1997.

17. Letter from Anthony R. Pietrangelo (Nuclear Energy Institute), to Dr. Brian W. Sheron (NRC), containing responses to NRC's Request for Additional Information, March 13, 1997,

18. Minutes for NRC Meeting with Nuclear Energy Institute (NEI) Regarding Risk-Informed Inservice Inspection Programs on October 8, 1998.

APPENDIX A

Review of WCAP-14572, Revision 1, Supplement 1, "Westinghouse Structural Reliability and Risk Assessment Model for Piping Risk-Informed Inservice Inspection"

A.1 INTRODUCTION

Supplement 1 to WCAP-14572, Revision 1, describes the models, software and validation of the SRRA computer code. The SRRA model is used to estimate the probabilities of piping failures, which are input to the PRA in support of the WOG RI-ISI program for piping.

A.2 Background

RG 1.178 provides an option for licensees to *quantitatively* estimate the reliability of individual pipe segments within the scope of the RI-ISI program. These estimates are to be consistent with industry databases on piping failure rates and relevant to plant-specific operating experiences. Detailed knowledge of piping design parameters, materials degradation mechanisms, plant operating conditions, and the likelihood of fabrication and service-induced flaws are elements of a quantitative analysis that need consideration. The use of probabilistic structural mechanics computer codes is an acceptable approach to estimate structural failure probabilities on the basis of such detailed knowledge.

The SRRA computer software was developed by the Westinghouse Electric Company over the last decade and has been enhanced to support the development of risk-informed inservice inspection programs of piping. This software was applied in plant applications of the RI-ISI program development for the Millstone Unit 3 and Surry Unit 1 nuclear power plants. The NRC staff and contractor personnel were briefed at public meetings during the course of these pilot applications. During these studies and methods development activities, the SRRA code was enhanced as issues were identified and resolved.

The current review was performed recognizing that probabilistic structural mechanics codes, including the SRRA code, are limited in their ability to predict absolute values of failure probabilities with a high degree of accuracy. The models themselves, along with the various inputs needed to apply these models, are subject to many uncertainties. In addressing the value of a given computer code to calculate failure probabilities the following considerations were taken to be important:

- While it is expected that advances in the technology will someday reduce the levels of uncertainty in calculated failure probabilities, the ability of the models to estimate relative failure probabilities is considered to be more important than their ability to predict absolute values. In this regard, RI-ISI is largely governed by relative values if risk both for the ranking and selection of components to be inspected and for the evaluation of risk increases or decreases associated with changes in the inspection programs.

- Relative values of failure probabilities are not used directly in the RI-ISI process. However, it is the relative values of failure probabilities along with relative values of failure consequences that are important to the final results of the risk-informed evaluations.

- It is important to the RI-ISI process to calculate absolute values of failure probabilities as accurately as possible, because an increased levels accuracy and consistency in the calculations will contribute to a corresponding enhancement in the accuracy of the relative values of failure probabilities.

- The calculation of failure probabilities with codes such as SRRA should not be performed in isolation of other independent methods of estimating failure probabilities, such as data bases and plant operating experience. Results of calculations should always be evaluated for reasonableness and consistency, and the assumptions and inputs to the calculations should be refined as appropriate.

A.3 Overview of Assessment

Over the past 3 years, as ASME-Research and WOG developed methods to perform RI-ISI of piping, the staff held public meetings with both groups to develop guidelines for acceptable uses of probabilistic fracture mechanics computer codes. In addition, with the assistance of Pacific Northwest National Laboratory (PNNL), the staff performed independent audit calculations to validate the results of the SRRA computer code.

The following discussion addresses the strengths and limitations of the Westinghouse SRRA computer code. Given the broad scope of piping designs and operating conditions, it was not expected that any one computer code could address all of the failure mechanisms and piping designs encountered in a nuclear power plant. Therefore, a key part of this review focused on the documentation for the Westinghouse code and how well it achieved the following objectives:

(1) Inform the code user about code limitations.
(2) Provide technically sound guidance on alternative approaches to estimate piping failure probabilities.

Important elements of this evaluation include the equations and assumptions (inputs) used in the piping reliability models, as well the validation of the estimated failure probabilities. In some cases, it is appropriate to place certain detailed inputs outside the direct control of the user (incorporating inputs into the model itself). In other cases, specific recommendations can be provided in the user document with example problems. Where possible, input values were standardized for specific applications. Many of these inputs were the subject of significant discussions during periodic public meetings on the Surry Unit 1 pilot applications, and are addressed in this review.

A.4 REVIEW OF SPECIFIC ISSUES

This section addresses specific aspects of the probabilistic structural mechanics model from the standpoint of the consistency and reasonableness of the estimated failure probabilities.

A.4.1 Failure Mechanisms

As described in the following sections, the Westinghouse SRRA code addresses with various levels of detailed modeling the degradation mechanisms of (1) fatigue, (2) stress corrosion cracking, and (3) flow-assisted corrosion/wastage or wall thinning. The present review concludes that acceptable technical approaches are used for each of these mechanisms.

A.4.2 Fatigue

The fatigue model assumes that all failures by this mechanism result from preexisting flaws. Inputs to the model are sufficiently flexible to address low cycle fatigue attributable to normal plant transients, high cycle fatigue from thermal fatigue (resulting, for example, from stratification of fluids), and high cycle vibrational fatigue.

Calculations are based on a relatively detailed mechanistic model which relates fatigue crack growth to the amplitude and frequency of the cyclic stresses. The Westinghouse/SRRA model for fatigue is very similar to that used in the NRC developed pc-PRAISE code, and numerical results of the SRRA code have been successfully benchmarked (as described later) against results from the pc-PRAISE code.

In common with the pc-PRAISE code, Supplement 1 to WCAP-14572 does not address fatigue crack initiation except in an indirect manner by conservatively assuming that initiated cracks are present at the beginning of plant operation. The limitations of this approach to fatigue crack initiation are addressed below.

In common with the pc-PRAISE code, fatigue cracks are all conservatively assumed to be located at the pipe inner surface. Crack growth in both the depth direction (through-wall direction) and in the length direction are simulated in a manner essentially the same as that used in the pc-PRAISE code.

The SRRA code permits the simulation of uncertainties in the levels of low and high fatigue stress cycles, which treats the amplitude of fatigue stress as a deterministic parameter.

The staff concludes that the SRRA code addresses fatigue crack growth in an acceptable manner since it is consistent with the technical approach used by other state-of-the-art codes for probabilistic fracture mechanics. It should be noted, however, that realistic predictions of failure probabilities require that the user define input parameters, which accurately represent all sources of fatigue stress and the probabilities for preexisting fabrication cracks in welds. The major limitation of the model is its inability to realistically simulate the initiation of fatigue cracks, which experience has shown to be the primary contributor to fatigue failures at operating plants.

A.4.3 Stress Corrosion Cracking

The stress corrosion cracking model of the SRRA code has a relatively simple technical basis, which does not attempt to model the complex failure mechanism in a detailed mechanistic manner. The calculations are based on a number of significant assumptions as follows:

- All piping failures by this mechanism result from preexisting fabrication flaws, although service experience with stress corrosion cracking indicates that such failures are dominated by cracks in welds that initiate during plant operation.
- The effects of crack initiation can conservatively be estimated by assuming one flaw per weld at the start of plant operation, with the flaw size distribution being the same as that for

welding-related fabrication flaws. Although calculations based on this assumption can provide relative probabilities of failure for different pipe segments, it is important for the expert panel to review the predicted failure probabilities to ensure a selection of input parameters that provides predictions, which are reasonable and consistent with plant operating experience.

- There is sufficient knowledge on the part of the plant technical staff and the expert panel (in combination with plant operating history with the occurrence of IGSCC) of the plant-specific environmental factors (water chemistry, temperature, etc.), levels of weld sensitization, and residual stress levels to identify pipe segments that have a high, medium or low potential for failure by stress corrosion cracking.

- The probability of through-wall cracks for the high failure potential case can be calculated using a bounding crack growth rate curve developed in 1988 (NUREG-0313), this curve relates crack growth rates to crack tip stress intensity factors.

- IGSCC related crack growth rates of moderate and none are assigned in the SRRA code to be a factor of 0.5 and 0.0 less than the bounding rate, with engineering judgement used to assign crack growth rates to these broad categories. Alternatively, the SRRA user can directly assign a numerical factor to be applied to the bounding crack growth rates.

In summary, the stress corrosion cracking model of the SRRA code provides a systematic basis to translate inputs into estimated failure probabilities on the basis of engineering judgement and operating experience. The model combines the inputs for stress corrosion cracking with other factors such as pipe dimensions and applied loads to predict pipe failure probabilities. While some of the modeling assumptions appear to be quite conservative, the calculations for the Surry Unit 1 plant appear to predict reasonable trends.

In particular, the code documentation given in WCAP-14572, Revision 1, Supplement 1, acknowledges the limitations of the model, and recommends the use of the pc-PRAISE computer code if predictions from a more refined mechanistic model are needed. The probabilistic fracture mechanics calculations for IGSCC have not been benchmarked for consistency with plant-specific and industry operating experience. In this regard, the Surry Unit 1 evaluations do not provide a particularly good basis to evaluate the SRRA stress corrosion cracking model, because IGSCC makes only a small contribution to piping failures for PWR plants. The staff therefore requires that the IGSCC model be further evaluated on future applications to BWR plants, because IGSCC is a major factor governing piping integrity at BWRs.

A.4.4 Flow Assisted Corrosion/Wastage

The wastage model of the SRRA code has a relatively simple technical basis and does not attempt to model the complex wall thinning processes in a detailed mechanistic manner. Deterministic models, such as the CHECKWORKS code developed by the Electric Power Research Institute (EPRI) are available to relate wall thinning rates to basic parameters such as flow velocity, chemical composition of the pipe material, fluid temperature, single-phase water versus two-phase steam/water mixture, and pH level of the fluid. However, probabilistic forms of

such deterministic models have not yet been developed.

While a close reading of the code documentation as given in WCAP-14572, Revision 1, Supplement 1, provides information on assumptions made in the SRRA wall thinning model, many users could have difficulty relating inputs to the model to the type of information available to plant technical staff. In addition, users may not have sufficient insight into the assumptions behind the wall thinning model to perform calculations in a correct and consistent manner. However, the calculations for Surry Unit 1 had sufficient participation by the Westinghouse staff to ensure that calculations for the Surry Unit 1 study yielded reasonable results.

Supplement 1 to WCAP-14572, Revision 1, provides information on assumptions made in the SRRA wall thinning model. Before issuing of this SER, the staff expressed a concern that many users could have difficulty relating inputs to the model with the type of information available to plant technical staff. In addition, users may not have sufficient insight into the assumptions behind the wall thinning model to perform calculations in a correct and consistent manner. Consequently, the staff indicated that WCAP-14572 should provide guidance for plant personnel executing the SRRA code for flow-assisted corrosion (FAC) that provides reasonable assurance that the results calculated for FAC failure probabilities are appropriate. In the public meeting on September 22, 1998 [item 7 (b), Ref. 8], Westinghouse stated that the next Revision of WCAP-14572 will provide guidance for material wastage potential. The staff concludes that the guidance for estimating the material wastage potential is acceptable since, if material wastage rates are high enough to proceed through the pipe wall, the probabilities of small leak, large leak and break are all calculated to be the same. The staff's approval is conditioned upon Westinghouse making the change to WCAP-14572 described above.

The wall thinning model in the SRRA code is based on the following assumptions:

- The user of the code is able to estimate the rate of wall thinning (e.g., inches of wall thickness reduction per year) and express this rate in terms of a "best estimate" value and a distribution function (e.g., log-normal distribution) that describes the variability or uncertainty associated with the best estimate.

- Wall thinning can be treated in a simplified manner by assuming that the maximum local rate of thinning occurs uniformly over a substantial length of straight pipe; this is a conservative assumption which does not account for variations (reduced rates of thinning) in the axial or circumferential directions as is case for the important case of local wall thinning at elbow locations.

- Consistent with the previous assumption, all failures of piping resulting from wall thinning will result in pipe breaks rather than leakages; pipe failures will occur when the simulated level of pressure-induced hoop stress becomes equal to the simulated values of the flow stress of the piping material.

Data from industry experience, along with structural mechanics considerations of localized thinning, provide evidence that leak-before-break events are more likely than sudden pipe breaks. The assumption that leak-before-break does not apply, as used in the SRRA code, is a conservative assumption.

The input parameter for the wall thinning rate is expressed in a simplified manner in the SRRA code with a parameter of 1.0 being assigned whenever the user believes that the thinning rate is high. The code assigns a "best estimate" thinning rate of 0.0095 inch per year for this rate parameter along with a variability described by a log-normal distribution which implies that the natural logarithm of the thinning rate has a standard deviation of 0.893 (which corresponds to a value of 2.3714 for the so called "deviation or factor" used as input to the SRRA code). For a rate parameter other than 1.0, the best estimate of the thinning rate is assigned to be proportional to the selected value of the parameter.

The staff concludes that plant technical personnel have sufficient knowledge and field measurements of wall thinning rates to develop reasonable inputs to the SRRA code for estimating failure probabilities for FAC degradation mechanisms. Such information is generally available as a result of the ongoing programs for flow-assisted corrosion which are required at all plants. The approach uses data and/or engineering judgement to estimate a wall thinning rate. The probabilistic structural mechanics model then calculates failure probabilities based on the estimated thinning rates, in combination with other governing parameters such as the pipe dimensions, applied stresses, and material strengths.

Calculations with the model must be closely coordinated with the existing plant programs for the management of wall thinning, because the model requires inputs that can be obtained only from the knowledge gained from ongoing monitoring and evaluations of wall thinning rates. Furthermore, application of the probabilistic model of the SRRA code should not be used to make changes in existing programs for the inspection and monitoring of piping for wall thinning.

A.4.5 Failure Modes (Leaks and Breaks)

The staff finds the code's failure modes capabilities acceptable for RI-ISI application since the SRRA code was modified during the Surry Unit 1 pilot application to address the failure mode of large system-disabling leaks in addition to the failure modes of small leaks (through-wall cracks) and pipe breaks. The disabling leak rate for each system is assigned to be consistent with existing evaluation of plant operational and safety evaluations. The modified program can address the various modes of pipe failure corresponding to consequences identified in plant PRAs and safety analysis reports.

A.5 Component Geometries

The SRRA code was developed to address the simple geometry of a circumferential flaw in a girth welded pipe joint. In this regard, the SRRA code has a capability similar to that of other state-of-the-art probabilistic fracture mechanics codes such as pc-PRAISE.

Application of SRRA to other more complex component geometries (e.g., elbow and tee pipe fittings) requires conservative assumptions founded on treating the maximum local stresses as uniform through the pipe wall, with no credit taken for the mitigating effects of stress gradients. Calculations by Khaleel and Simonen (1997) have shown that this assumption can result in failure probabilities being overestimated by an order of magnitude or more.

With proper attention to stress inputs and the interpretation of calculated results, the SRRA code can be used effectively to estimate failure probabilities for components with more complex geometries. Before issuing this SER, the staff identified an open item that WCAP should provide guidance for the analyst on the code limitations for complex geometries and guidance for effective use of the code in such applications. In the public meeting on September 22, 1998 [item 12, Ref. 8], Westinghouse stated that the SRRA piping models only apply to standard piping geometry (circular cylinders with uniform wall thickness). Westinghouse further stated that a limitation on the use of non-standard geometry will be added in the next revision of WCAP-14572. The staff finds this clarification of the code limitation to be acceptable. The staff's approval is conditioned upon Westinghouse making the change to WCAP-14572 described above.

A.6 Structural Materials

For calculational convenience, structural reliability computer codes should be able to address a range of piping materials. The capabilities of the SRRA code meets this criterion. The code has generally been applied in a mode which uses simplified inputs consistent with standardized material properties for stainless and ferritic piping materials. However, the code can also be operated in a mode which allows greater flexibility for the specification of input parameters for material properties. The staff recommends that licensees apply the code in a manner that accounts for the known plant-specific material characteristics as they may be governed by such factors as carbon content, heat treatments, etc.

As with any computer code, the quality of results often depends on the capabilities of the code user. In this case, the user must first recognize situations for which it is inappropriate to use the standard menu selections of material properties. Before issuing this SER, the staff indicated that WCAP-14572 should specify the level of training and qualification that the code user needs to properly execute the SRRA code. In its response in the public meeting on September 22, 1998 [item 13, Ref. 8], Westinghouse indicated that the next revision of WCAP-14572 will state that to ensure that the simplified SRRA input parameters are consistently assigned and the SRRA computer code is properly executed, the engineering team for SRRA input should be trained and qualified. The revised WCAP will also list the topics covered in this training as presented in the public meeting on September 22, 1998 [item 13, Ref. 8]. The staff has reviewed the additional guidance for training and qualification and determined that it provides reasonable assurance that code users will be able to properly execute the SRRA code. The staff's approval is conditioned upon Westinghouse making the change to WCAP-14572 described above.

A.7 Loads and Stresses

The SRRA code has several inputs to describe the loads and stresses that govern piping failure. The stresses used for plant specific applications should be based on actual plant experience and operational practices (including thermal and vibrational fatigue stresses), which may differ from the stresses used for purposes of the original design of the plant. The types of stresses of concern include residual and vibrational (fast transient) stresses which are specifically addressed below. Other inputs address low cycle fatigue (slow transients) and design-limiting stresses which include the effects of seismic loadings. For applications of RI-ISI programs to

actual plants, plant-specific inputs such for loads and stresses should be used.

All calculations assume that the stresses are uniformly distributed through the thickness of the pipe wall. This simplifying assumption is conservative and could be avoided (with methods currently used in the pc-PRAISE code).

The inputs for low cycle fatigue can address only one type of loading transient, which is assumed to represent the dominant contribution to fatigue crack growth, although well-known methods exist to evaluate the combined effects of many operational transients. However, limiting the evaluation to one dominant transient is a reasonable approach, given the intended scope of the SRRA code, which is to estimate failure probabilities using simplified approaches.

Similarly, the SRRA code requires the user to select a single level of design-limiting stresses and an associated occurrence frequency which best characterizes the loads governing the probabilities of a pipe break. The selection is based on plant experience, records of transients, engineering judgement or other considerations. In some cases, the normal operating loads will be more important (because they occur with a probability of 100 percent) than much larger seismic loads that have lower occurrence rates (e.g., a frequency 10^3 per year). Applications of the SRRA code before the 1996 benchmarking activity were founded on design-limiting stresses related to seismic loads, and with a standardized occurrence frequency of 10^5 per year. Discussions during the 1996 benchmarking effort noted that higher probability loads should also be addressed. These discussions led Westinghouse to use as inputs the design-limiting (e.g., pressure, dead weight, etc.) loads in combination with an occurrence frequency of once per year, or probabilistically distributed as a function of time in the calculations, an approach which may result in conservative predictions of pipe break frequencies.

The staff finds the treatment of loads and stresses as discussed above to be conservative and acceptable for the purpose of RI-ISI program application since the use of less conservative loads and stresses would require more detailed structural analyses and in most cases should not impact either the categorization process or the change in risk calculations. In reviewing plant specific calculations performed with the SRRA code it has been noted that sensitivity calculations have been used to evaluate the effects of conservative inputs for piping stress. For example, failure probabilities associated with high stresses due to postulated snubber lockup have been adjusted to account for the probability that the lockup condition will actually occur. Such evaluations are an important step to ensure that conservative inputs do not unrealistically impact the categorization and selection of piping locations to be inspected. In summary, while an appropriate selection for input parameters for loadings is a critical step in the evaluation, licensees have the needed expertise to identify the required input to the SRRA input menu.

A.8 Vibrational Stresses

The NRC staff and the industry have recommendations that address appropriate levels (as a function of pipe size) for vibrational stresses to be used in failure probability calculations. These recommendations arose from concerns regarding assumptions made for early calculations performed for Surry Unit 1 by Westinghouse and Virginia Power, and were developed with guidance from the ASME Research Task Force on Risk-Based Inspection Guidelines.

Since the Westinghouse SRRA code has incorporated the recommendations of the ASME Task Force as default values for those piping locations at which high levels of vibrational stresses are expected, the staff concludes that the treatment of vibrational stress as in the SRRA code is acceptable. The recommended levels of vibrational stresses will be fully documented in a revision to WCAP-14572. The actual piping locations where vibrational stresses are to be expected are assigned by plant technical staff on the basis of judgement taking into account such factors as proximity to rotating equipment and knowledge of plant operating experience. The staff's approval is conditioned upon Westinghouse making the change to WCAP-14572 described above.

A.9 Residual Stresses

The Westinghouse SRRA code includes inputs for residual stress which describe both median values and variability in the level of stress. The residual stress contribution is an important contribution to the growth of stress corrosion cracks, and can also influence the growth of fatigue cracks through the so-called R-Ratio effect.

Appropriate levels of welding residual stress were discussed in review meetings held during the Surry Unit 1 pilot application, and a consensus was developed to guide the selection of residual stress inputs. Since the SRRA code uses the resulting recommendations which specify a log-normal distribution to describe the uncertainty in residual stress, with an upper bound on the distribution (or truncation) at 90 percent of the flow stress (corresponding to the 90th percentile of the log-normal distribution), the staff finds the treatment of residual stresses acceptable.

A.10 Treatment of Conservatism

RG-1.174 recommends that all calculations used in the categorizing risk (including the calculations of component failure probabilities) should be performed on a "best estimate" basis rather than conservatively. Conservative assumptions can introduce undesirable biases into the ranking process by masking the significance of those components for which realistic rather than conservative evaluations are performed. In the case of inservice inspections, the result could, for example, lead to an inappropriate amount of inspection of small versus large pipes, or excess inspection for stress corrosion cracking versus inspection for flow-assisted corrosion.

With a few exceptions, the Westinghouse SRRA code performs "best estimate" calculations. On the basis of this review, the staff concludes that conservative assumptions are consistent with practices used in similar computer codes, and/or are consistent with limitations of current technology to predict structural failures. Nevertheless, particular applications of the code may address uncertainties regarding code inputs by assigning very conservative values, and thereby generate inappropriately conservative estimates of failure probabilities. The present review also addresses the following potential sources of conservatism on the basis of practices used in the Surry Unit 1 pilot study:

- Inputs for the number and sizes of fabrication flaws are a significant source of uncertainty. In estimating the number of flaw in a weld, the SRRA code accounts for the volume of metal in the weld by relating this volume to the circumference and wall thickness of the pipe. The

SRRA code, like the pc-PRAISE code, places all flaws at the pipe inner surface, and in this step makes conservative assumptions about the fraction of the flaws in each given weld which should be counted as surface flaws. This estimated fraction is believed to be somewhat more conservative for thicker wall piping than for thinner wall piping, and may therefore bias inspections to larger piping.

- The treatment of stress corrosion cracking could give very conservative predictions of failure probabilities because of conservative assumptions in the structural mechanics model. In particular, the model makes three conservative assumptions:

  (1) There is a 100 percent probability that an IGSCC crack will initiate in each weld.
  (2) The crack initiates at time equals zero.
  (3) The size distribution of the initiated cracks is the same as for welding related flaws.

  Evidently, there are offsetting factors which lower the calculated crack growth rates and thereby account for a generally good correlation of the calculated failure probabilities with service experience. The reason for the good correlation with experience is not clear. However, It appears that the SRRA calculations were performed with the intent of achieving qualitative agreement with plant operating experience. In this regard, staff recommendations encourage the use of data and operating experience to augment computer models to estimate piping failure probabilities. The WCAP does not document a formal process to use experience as a means to calibrate the SRRA calculations. Nevertheless, discussions during public meetings for reviews of the Surry Unit 1 pilot application did focus on piping locations with highest values of failure probabilities with attention to the degradation mechanisms involved and how the predictions correlated with service experience. Evidently the SRRA models have been adjusted or calibrated to ensure that the piping locations with the highest potential for IGSCC have calculated failure probabilities that are generally consistent with the experience. Having "anchored" the highest values of calculated probabilities, the model permitted probabilities for locations with lower potentials to be estimated on the basis of the relative values of calculated failure probabilities.

- The review of the Surry Unit 1 pilot study indicates conservative engineering judgements used to assign cyclic and design limiting stress. One example is that vibrational stresses are often assumed to be present (with a probability of 100 percent), where in reality the identified locations only have a potential for the occurrence of such stresses. At other locations, code limiting stress levels are assigned because results of detailed stress calculations were not available. However, review of the predicted failure probabilities calculated for the Surry pilot plant showed consistency with available industry data for the frequency of vibrational failures. As in the case of failures due to IGSCC, the results of SRRA calculations for vibrational failures were reviewed during public meetings. Inputs for vibrational stress levels were refined with an objective to predict failure probabilities that were reasonable and consistent with plant operating experience . The staff, therefore, finds the selected application of conservatism for vibrational stresses acceptable.

A.11 Numerical Methods and Importance Sampling

On the basis of this review, the staff concludes that the SRRA code calculates failure

probabilities using acceptable statistical and probabilistic methods. The Monte-Carlo method as implemented in the SRRA code is a standard approach commonly used in probabilistic structural mechanics codes including the pc-PRAISE code. Importance sampling, again a common and well-accepted approach, increases the computational efficiency of the Monte-Carlo procedure by shifting the distributions for random variables to increase the number of simulated failures. The magnitude of shift applied to the variables by the SRRA code is relatively modest and is not believed to be sufficient to cause incorrect estimates of failure probabilities.

A.12 Documentation and Peer Review

Having reviewed WCAP-14572, Revision 1, Supplement 1, the staff concludes that this document, along with other referenced technical reports and papers, provides an acceptable level of documentation for the SRRA computer code.

Peer reviews of the SRRA code have also been performed on several occasions. The author of the code has published several papers for presentation at technical conferences, with technical peer reviews being part of the publication process. Earlier versions of the code have been used by Westinghouse in past research projects which have also been reviewed by the staff. In addition, the methodology of the code parallels approaches used in other generally accepted probabilistic structural mechanics codes, such as pc-PRAISE.

During the Surry Unit 1 pilot plant study, technical reviews of the SRRA code were performed by the NRC staff, its contractors, and the ASME Research Task Force on RI-ISI. These reviews provided a detailed assessment of the Westinghouse SRRA code on the basis of (1) documentation of the code, (2) detailed descriptions of example calculations, (3) trial calculations performed with the SRRA code by peer reviewers, and (4) benchmark calculations to compare failure probabilities predicted by the SRRA code and the pc-PRAISE code. Related comments resulted in several improvements to the SRRA code, as reflected in WCAP-14572, Revision 1, Supplement 1

A.13 Validation and Benchmarking

Westinghouse has used a variety of approaches to validate the ability of structural mechanics code to predict component failure probabilities. These approaches have included comparing code predictions with plant operating experience, and comparing SRRA predictions with predictions made by other probabilistic structural mechanics codes. Results of these efforts are described in WCAP-14572, Revision 1, Supplement 1, and in a recent ASME technical paper (Bishop 1997). The results of these validation efforts are reviewed in the following subsections.

A.13.1 Benchmarking Against pc-PRAISE

As part of the Surry Unit 1 pilot application during 1996, a benchmarking activity to compare results from the Westinghouse SRRA code with the pc-PRAISE code was completed. The scope of the benchmarking calculations was limited to the failure mechanism of fatigue, because both codes address this mechanism and approach the fatigue evaluation in a similar manner.

The objective of these calculations was to start with identical specifications for input parameters, and to establish whether the two codes predict the same or similar probabilities of failure for small leaks, large leaks, and pipe rupture.

The 1996 benchmarking calculations did not address the failure mechanisms of stress corrosion cracking or wall thinning caused by flow-assisted corrosion. The pc-PRAISE code does not address the failure mechanism of wall thinning, and therefore provided no means to benchmark the predictions derived using the wall thinning model from the Westinghouse SRRA code. In addition, although both codes address stress corrosion cracking, they use significantly different technical approaches which result in very different types of input parameters. Therefore, the appropriate validation approach for this failure mechanism was to validate each code on its own merits against operating experience.

NRC staff and contractors participated in the benchmarking activity, which Westinghouse staff documented in a recent paper presented at an ASME conference (Bishop 1997). This evaluation report summarizes the benchmarking procedures and (in part) the results of that effort.

A wide range of pipe sizes, material types, cyclic stress levels and frequencies, design limiting stresses, and leak detection capabilities were addressed by the calculations. While the present review describes some difficulties and issues encountered in comparing break probabilities for stainless steel piping when leak detection was included in the calculations, the present review agrees with the overall conclusion stated by Westinghouse that the calculations did successfully benchmark the calculations for the small leak, large leak, and full break probabilities..

As stated, the benchmarking calculations of the Westinghouse SRRA code against the pc-PRAISE code were limited to the mechanism of fatigue and more specifically, fatigue-related failures of piping associated with preexisting flaws in circumferential welds. The calculations excluded failures caused by service-related cracks initiated by fatigue. However, the range of cyclic stresses and cyclic frequencies was sufficiently broad to address low cycle fatigue attributable to normal plant transients, and high cycle fatigue caused by pipe vibrations or thermal fatigue conditions.

The benchmarking effort addressed concerns over the number of Monte-Carlo trials and importance sampling implemented within the Westinghouse SRRA code. Both aspects of the numerical approach were found acceptable. Results from the audit calculations led Westinghouse to increase the default number of Monte-Carlo simulations from the original value of 5000. In addition, the review established the correctness of the importance sampling approach, which in the Westinghouse SRRA code involves a shifting of distributions for the random variable in such a direction as to obtain a larger number of simulated failures. Default values for the number of shifting were judged to be modest, and unlikely to be a source of error in calculated failure probabilities. Sensitivity calculations by Westinghouse were performed to establish the amount of shifting which would degrade the accuracy of the calculated failure probabilities, and this level far exceeded the default parameters for shifting distributions.

The benchmark calculations generally showed good agreement in calculated failure probabilities. There were no areas of significant disagreement for probabilities of either small or large leaks over the full range of input parameters, which gave a very wide range of calculated

failure probabilities.

In a few cases, limited to certain calculations involving very low break probabilities, differences in calculated break probabilities amounting to several orders of magnitude were noted between results from the two codes. Calculations with the Westinghouse SRRA code gave higher break probabilities than predicted by pc-PRAISE. The pipe break probabilities were always sufficiently small so that the pipe segments would make only negligible contributions to the core damage frequency or categorization. No significant differences were observed for cases that neglected the effects of leak detection or where the piping material was ferritic steel versus stainless steel.

The benchmarking activity was concluded before all remaining differences in calculated break probabilities were resolved. As a result, some potential sources of numerical differences were not fully explored, including details of the importance sampling procedure, and the logic used to simulate the effects of leak detection. Westinghouse has put forward revised calculations that show relatively good agreement for all break probabilities.

It should be noted that there were significant differences in calculated failure probabilities for small leaks, large leaks, and pipe breaks during the first phase of the benchmarking calculations. It became clear that the codes themselves were not the source of the differences, but rather differences in the selection of numerical values for certain input parameters, which had not been adequately specified during the initial definition of the parameters for the benchmark problems. The most critical inputs were those for flaw density and size distributions, levels of vibrational fatigue stresses, and inputs for the simulation of leak detection.

Participants in the benchmarking efforts subsequently agreed to develop improved and standardized values for the critical inputs. Using results of calculations performed by Rolls Royce and Associates, the participants developed improved inputs for flaw size distributions. Inputs for vibrational stress levels were related to pipe sizes, resulting in reduced levels of vibrational stress for the largest pipe sizes. As a final step, the SRRA code was modified to simulate the effects of leak detection using a technique consistent with the state-of-the-art methodology used by the pc-PRAISE code. These changes resulted in good agreement between the two codes.

A.13.2 Validation with Operating Experience

A number of approaches can be used to validate calculated failure probabilities for consistency with plant operation experience. The documentation given in WCAP-14572, Revision 1, Supplement 1, provides two acceptable examples of such validation for the SRRA code. Both examples address failure mechanisms (FAC and IGSCC) for which there have been a sufficient number of field failures to provide data to permit benchmarking of calculated failure probabilities with observed failure rates. The staff found acceptable the agreement between predictions and operating experience for both failure mechanisms.

For most piping segments, calculations with the SRRA code have predicted relatively small values for failure probabilities. The results indicate that failures for such pipe segments would not be expected to occur for the limited number of years of plant operation accumulated to date. The SRRA code has therefore been shown to predict very low failure probabilities for those

failure mechanisms and piping locations which have exhibited a high level of operational reliability.

The predicted failure probabilities predicted by the SRRA code for the Surry Unit 1 plant have been reviewed from the standpoint of plant-wide trends. The net plant-wide calculated failure frequency (accounting for all pipe segments and all systems) indicates about one pipe leak per year for the entire plant, and a few pipe breaks over the 40-year operating life of the plant. These predictions of overall failure rates, predicted degradation mechanisms, and the most likely locations for piping failures show an acceptable level of agreement with plant operating experience. However, as noted above, most piping locations have experienced no failures or detectable degradation, and for these locations the operating experience provides no means to validate the correctness of the relative values of calculated failure probabilities. In this regard, the RI-ISI process is designed to provide feedback of future operating experience to permit refinement of the predictive models as appropriate.

A.14 Flaw Density and Size Distributions

Inputs for the number and sizes of welding-related fabrication flaws are a large source of uncertainty in performing probabilistic structural mechanics calculations. WCAP-14572, Revision 1, Supplement 1, indicates that the SRRA code uses acceptable inputs for flaw densities and size distributions. The inputs used with the SRRA code are those developed during the 1996 benchmarking activity. These inputs were derived on the basis of trends observed in calculations generated by Rolls Royce and Associates through application of the RR-Prodigal model to simulate flaws in typical nuclear piping welds.

While there remain uncertainties in the estimated absolute values of flaw densities, the technical basis of RR-Prodigal model helps to ensure consistency in the relative values for the number and sizes of flaws as a function of pipe material, welding practice, pipe wall thickness, and volume of weld metal. The 1996 modification of the SRRA code, which included the improved means for describing flaw distributions, significantly enhanced the ability of the SRRA code to predict reasonable values (consistent with data from operating experience) for the relative failure probabilities of large diameter piping versus small diameter piping.

A.15 Initiation of Service-Induced Flaws

The fatigue and stress corrosion cracking models in the SRRA code address only failures caused by preexisting fabrication-related flaws. Such flaws are an important contribution to piping failures, particularly when the service stresses are insufficient to cause cracking of initially un-flawed material. However, many service-related failures have been associated with severe cases of cyclic stress (e.g., thermal fatigue) or aggressive operating environments (e.g., stress corrosion cracking). In these cases service-induced flaws rather than preexisting flaws are the dominant contributor to piping failures.

The documentation provided in WCAP-14572, Revision 1, Supplement 1, appropriately acknowledges the limitations of the SRRA code, and suggests that other approaches may be needed to address failures due to service-induced flaws. These methods include the pc-

PRAISE code which offers the capability to simulate the initiation of stress corrosion cracks in stainless steel welds. In this regard, the diversity of experience represented by the expert panel reviews should ensure that appropriate computer codes and data bases are used to estimate failure probabilities.

In practice, as during the Surry Unit 1 pilot study, calculations with the SRRA code have approximated service-induced flaws by assuming that one flaw per weld initiates immediately upon the start of plant operation. The size of this flaw is described by the same distribution used to describe welding-related flaws. This model is an acceptable basis to calculate conservative or bounding values of failure probabilities. However, failure probabilities calculated using this approach must be used with caution, because the overly pessimistic predictions could result in assigning inappropriately high rankings to certain pipe segments at the expense of other components which could have larger contributions to risk.

A.16 Preservice Inspection

There are no simulations within the SRRA code to account for preservice inspections as a means to reduce the number of initial fabrication flaws. Effects of preservice inspections must be included indirectly through the inputs for flaw densities and size distributions. The staff finds the flaw distribution parameters described in WCAP-14572, Revision 1, Supplement 1, to be acceptable since they were derived from predictions by the RR-Prodigal flaw simulation model, which accounts for the effects of inspections performed after completion of welding. Using these input parameters, the calculations with the SRRA code have properly addressed the effects of preservice inspections.

A.17 Leak Detection

Consistent with the objective of calculating "best estimate" rather than conservative failure probabilities, the effect of leak detection in preventing catastrophic piping failures should be included in determining the change in CDF/LERF that lead to changes in the inspection program. The Westinghouse SRRA code includes a simulation of leak detection as an enhancement to the code made during the 1996 code benchmarking activity (It should be noted that for categorizing piping segments, leak detection is not normally credited, except for the reactor coolant system where redundant leak detection capabilities exist.). It is important that inputs to the SRRA code specify realistic values of detectable leak rates. This requires an understanding of the reliability of the techniques used to detect leaks in the various plant systems of interest.

The simplified leak rate model in the Westinghouse SRRA code is based on a correlation of calculated data on leak rates obtained from a more detailed model which is part of the pc-PRAISE code. This correlation provides an acceptable basis for addressing leak detection for the specific pressure and temperature conditions for the primary coolant loop of PWR plants having fatigue type cracks. The correlation accounts for effects of crack size, pipe stress, and internal pressure, and gives approximate predictions leak rates suitable for use in leak detection models. However, the correlation can give incorrect simulations of leak detection (due to over prediction of leak rates) for systems operating at the pressures and temperatures for BWR

plants that have IGSCC cracks with morphologies differing from those of fatigue cracks.

Before issuing this SER, the staff had identified an open item that Westinghouse should address the applicability of those correlations to other plant conditions. The staff also indicated that Westinghouse should clarify whether the SRRA code can be applied to BWRs and justify the applicability of the correlations used to calculate leak rates under BWR operating conditions. In the public meeting on September 22, 1998 [item 5 (d), Ref. 8], Westinghouse stated that the existing correlations for leak rates can be used for other plant conditions beyond the RCS and that the SRRA code can be applied to BWRs; however, care must be exercised in applying this approach to BWR piping systems, particularly those subjected to IGSCC. In addition, Westinghouse indicated that WCAP-14572 will be revised to provide guidance on addressing stress corrosion cracking. The staff finds the response acceptable since most piping susceptible to stress corrosion cracking (SCC) is also subject to fatigue loading, such as normal heat up and cool down, and the leak rate correlation for fatigue type cracks was conservatively assumed for the CLVSQ Program. The staff's approval is conditioned upon Westinghouse making the change to WCAP-14572 described above.

A.18 Proof Testing

The Westinghouse SRRA code does not explicitly address the potential benefits of preservice proof tests (e.g., pressurization tests) as a means to reduce piping failure probabilities. As such, the calculated failure probabilities are likely to be somewhat conservative. Components having very low failure probabilities are likely to be those most affected by proof testing (i.e., potential service failures are attributable to very deep cracks which can be discovered during proof testing).

Proof testing can be addressed indirectly by the SRRA code with a modification to the inputs for the number and sizes of initial fabrication flaws. The proof test serves to reduce the number of very large flaws.

Before issuing this SER, the staff had identified an open item that WOG should describe how proof testing is addressed in the SRRA calculations, and should clarify what impact its neglect would have on the calculated failure probabilities and categorization. In the public meeting on September 22, 1998 [item 14, Ref. 8], Westinghouse stated that the effect on the segment risk ranking and categorization would be very small and slightly conservative. Westinghouse also indicated that the next revision of WCAP-14572 will clarify that SRRA models in LEAKPROF do not take credit for eliminating large flaws, which would fail during the pre-service hydrostatic proof tests, even though this is allowed as an input option in pc-PRAISE. The staff concludes that the approach for addressing proof testing is acceptable because Westinghouse has demonstrated that the effect of proof testing on the segment risk ranking and categorization would be very small and slightly conservative. The staff's approval is conditioned upon Westinghouse making the change to WCAP-14572 described above.

A.19 Inservice Inspection

The Westinghouse SRRA code can simulate the reduction in piping failures resulting from ISI.

However, the methodology described in WCAP-14572, Supplement 1, assumes no inservice inspection for purposes of establishing risk importance measures, but does credit inservice inspection in calculating the change in CDF/LERF that results in changes to the ISI program.

Inservice inspections are simulated by the SRRA code following an approach which is similar but not identical to the pc-PRAISE code. In most cases, the approach should give acceptable predictions of the effects of inspections. Nevertheless, due care must be taken to avoid overly optimistic evaluations. Before issuing this SER, the staff had identified an open item that the probability of detection curves used in calculations need to be justified for the material type, inspection method, component geometry, and degradation mechanism that apply to the structural location being addressed. In the public meeting on September 22, 1998 [item 15 (a), Ref. 8], Westinghouse stated that the default input values for the probability of detection (POD) curves are consistent with the default input values for pc-PRAISE. The revised WCAP will emphasize that the SRRA code user must ensure that the specified input values for POD are appropriate for the type of material, inspection method, component geometry, and degradation mechanism being evaluated. The staff finds this response acceptable since (POD curves are consistent with the default input values for pc-PRAISE code which has been validated and accepted by the staff for various applications. The staff's approval is conditioned upon Westinghouse making the change to WCAP-14572 described above. In addition, the detection probabilities used in SRRA calculations should be justified and documented as part of plant specific submittals.

A.20 Service Environment

Service environments (characterized by pressure, temperature, water chemistry, flow velocity, etc.) can affect corrosion rates and crack growth rates. These effects must be addressed on a segment-by-segment basis in probabilistic structural mechanics model since the classification of high-safety-significance and low-safety-significance is based on a segment-by-segment basis.

The SRRA code allows the effects of service environment to be included in calculations of piping failure probabilities. For the failure mechanism of fatigue crack growth, the equations for predicting crack growth rates are appropriate since they have been derived on the basis of tests performed with specimens exposed to reactor water environments.

Crack growth rates (for stress corrosion cracking) and wall thinning rates (for flow-assisted corrosion) can be specified by the inputs in a manner that includes appropriate effects of operating environments. Crack growth rates are appropriate since the SRRA code has incorporated bounding rates for these two degradation mechanisms, bounding rates are founded on laboratory data and service experience corresponding to high failure probabilities, and the user should specify numerical factors to be applied to these bounding rates, with the assigned factors derived from plant operating experience and engineering judgement.

In summary, the SRRA code provides an acceptable method to account for the effects of the operating environment since the method is largely reliant on qualitative judgments to indirectly assign quantitative factors. This is appropriate since typical calculations must often be performed without detailed knowledge of such factors as water chemistries and flow velocities and the documentation for the code acknowledges limitations of the approximate methodology

SECTION 2
RECENT CHANGES TO THE SRRA MODEL

Table 2-1 lists some of the recent changes in the piping SRRA models and software for piping RI-ISI. First, the initial flaw characteristics for some typical sizes of piping welds were recalculated using the latest version of the Rolls-Royce and Associates computer code PRODIGAL (Chapman 1993). This program uses artificial intelligence rules that are based upon experience to simulate each step in the weld fabrication, including the different types of inspections that are used in the process. The results of these calculations and the preliminary calculations made by the NRC consultants both indicated that the number and depths of the flaws were dependent upon the size of the weld and were not a constant ratio as was assumed in the input to the original SRRA program models.

2.1 INITIAL FLAW CHARACTERISTICS

Figure 2-1 shows the variation in the number of flaws per weld length (pipe circumference) near the inner surface of the pipe with the wall thickness that was calculated by PRODIGAL. Two values are calculated by the program, flaws in the inner region (inner 25% of the wall) and the flaws in the innermost two weld passes, both including any inner surface breaking flaws. As shown in Figure 2-1, for welds that have a final radiographic (RT or X-Ray) inspection, the SRRA piping models select the maximum of the two values. For welds without this X-Ray inspection, the number of flaws is increased by a factor of 12.8 based upon the PRODIGAL results calculated for typical piping welds. Although the simplified SRRA piping models do not include crack initiation by fatigue or stress corrosion cracking, the effect can be conservatively simulated by assuming exactly one flaw exists at the start of life. This one-flaw input option was also added to the latest SRRA models.

All near-surface flaws are assumed to be inner surface breaking flaws. As discussed above, the stress intensity factor for the near-surface flaws (inner 25% of wall or innermost 2 weld passes) are conservatively calculated in the SRRA fracture mechanics models. Furthermore, the flaw density used for the failure probability calculation is not reduced to eliminate the effect of flaws that are not actually surface flaws.

The other initial flaw characteristics that were added to the SRRA models include the log-normal distribution of flaw depth, which varies as a function of weld size (pipe wall thickness) and stainless steel (SS) or ferritic material, but not the final X-Ray inspection. Figure 2-2 shows the calculated variation in the median initial flaw depth and shape factor for the log-normal depth distribution with the pipe wall thickness. These models for flaw density and flaw depth are applicable to welds, not to plate or forged components.

2.2 FAILURE MODES

Several significant changes were also made to the treatment of failure modes in the piping SRRA models. First, a large (system disabling) leak was added as a failure mode because it could have a higher probability than a full break, which required a design limiting event (DLE) with a frequency of occurrence normally much less than one in a given year (0.001 was the default value in the original SRRA model input). Second, the option of taking credit for a

detectable leak before a large leak or break was added to the piping SRRA models. Figure 2-3 graphically shows the logic that was implemented in the latest SRRA models. As shown in this figure, the first time the crack grows through the wall (small leak failure mode), its length is checked to see if it exceeds that for a full break or large leak. If it does, then failure occurs. If not, then the crack length is checked to see if it is detectable. If it is, then the simulation ends without failure. If not, the crack continues to grow until it is checked again for these same failure modes at the end of the next time step.

The reason the probability of break is evaluated in the SRRA models for a design limiting event (DLE) is because its loading is normally significantly higher than that during steady state operation. However, if the new large (system disabling) leak failure mode has a probability higher than that for full break, then the frequency of the DLE would not need to be considered. Since it is not known a priori whether the large leak or full break failure mode would be controlling, all assumptions about the frequency of the DLE have been eliminated from the revised SRRA models. The effect of this change is the same as setting the DLE frequency to 1, which would also cover the possibility of pipe break during steady-state operation.

To calculate the crack length for detectable and large leak rates, a new program, CLVSQ, was developed to calculate the input to the SRRA models. This program first calculates the crack opening displacement as a function of crack length and loading using elastic-plastic fracture mechanics techniques (Kumar et al. 1984). Then the leak rate as a function of crack length is calculated as a function of pressure and pipe wall thickness using a simplified correlation based upon results from the more detailed models in an updated version of pc-PRAISE (see Figure 2-4). The improved leak rate models in pc-PRAISE are similar to those used in the PICEPS computer code developed for EPRI (Norris and Chexal 1984).

Due to the differences in crack morphology, the PICEPS code would predict a larger leak rate for fatigue type cracks than cracks due to stress corrosion cracking (SCC) even if all other conditions were the same. Since most piping susceptible to SCC is also subject to fatigue loading, such as normal heat up and cool down, the leak rate correlation for fatigue type cracks was conservatively assumed for the CLVSQ Program. If the piping is shown to be subject to SCC and not fatigue, then the conservative SRRA over-prediction of SCC leak rate can be corrected by using the PICEPS computer code to calculate an equivalent fatigue crack leak rate corresponding to the desired SCC-only crack leak rate.

In the original piping SRRA models, the pipe wall thinning due to material wastage (e.g. flow assisted corrosion) was conservatively added directly to the crack depth (initial and growth with time). However, the failure probability was always multiplied by the probability of the initial flaw being present, which was potentially nonconservative. To rectify this situation, the SRRA models were revised to now track the changes in crack depth and wall thinning separately. If the thinning grows through the wall first, then no credit is taken for the probability of initial flaw existence. Moreover, the thinning is conservatively assumed to apply to the full pipe circumference so that large leak or full break cannot be precluded. These same failure mode assumptions were also applied to the high-cycle fatigue loading when it exceeds the fatigue crack growth threshold.

2.3 OTHER CHANGES

The assigned levels of vibrational stresses in the original SRRA input for various diameters of piping were based upon limited engineering experience since vibrational stresses are normally not measured nor calculated very accurately. As pointed out during a peer group review by the ASME Research Task Force on Risk-Based Inspection (ASME 1991, 1992), most of the vibration induced failures have occurred in small piping (sizes of 1 inch or smaller). The task force members further suggested that the vibration stresses be reduced for the larger piping sizes (10 inch or greater), where failures were not known to be vibration induced.

In the revised SRRA Software, the high-cycle fatigue stresses due to mechanical vibration are now specified in the SRRA input for a small pipe size of 1 inch and corrected for the input pipe size. The logarithm of the correction factor varies linearly with pipe size from a factor of 1 at 1 inch to a factor of 1/6 at 10 inches. A factor of 1/6 is also used for all pipe sizes above 10 inches. This variation in reduction factor with pipe size is consistent with that suggested by the ASME Research Task Force on Risk-Based Inspection (ASME 1991, 1992). To accommodate this change, the affected simplified input parameter is now the peak-to-peak vibratory stress range in ksi corresponding to a one-inch pipe size. For example, if a 1-ksi stress range is estimated for the 10-inch pipe being evaluated, then an equivalent 6-ksi range for a one-inch pipe size would be input so it would be factored correctly to the desired 1-ksi stress range.

The maximum median residual stress of 20 ksi and a 2-sigma log-normal factor of 2 were selected to bound the maximum tensile residual stresses at the pipe weld I.D. for intermediate (10-20") and large (>20") sized stainless steel pipe. These residual stresses are given in the pc-PRAISE User's Manual (Harris, Dedhia and Lu 1992) and are used to calculate probabilities of small leak due to IGSCC consistent with those that have been observed (see Figure 4-3). However, unlike pc-PRAISE, the residual stress is assumed to be constant through the weld wall and around the weld circumference in the SRRA models. Furthermore, no relaxation of residual stress is assumed for an initial fabrication flaw. Because of these conservatisms, the ASME Research Task Force members recommended that the residual stress calculated by the SRRA computer code be truncated at a maximum value equal to the yield strength regardless of the input values. To accommodate this change, the yield strength of the weld was assumed to be 90% of the flow stress in the modified SRRA code used for RI-ISI.

Table 2-1
SUMMARY OF CHANGES TO SRRA SOFTWARE

1. New Failure Modes and Conditions

   a) Monte-Carlo simulation & importance sampling only

   b) Maximum probability estimate for no failures and accuracy warning for less than 10 failures

   c) Time in years instead of operating cycles

   d) Truncation of residual stress

   e) Eliminated frequency of design limiting event

   f) ASME fatigue crack growth for carbon steel

   g) No flaw density correction for high wastage or vibration

   h) Same leak and break probabilities for high wastage or vibration

   i) New probability of disabling leak or break

   j) Effect of leak detection on break probability

   k) Fatigue growth threshold corrected by R of 0.9 for vibration only (no frequency)

2. New Input Options and Standardized Correlations

   a) More trials and sampling for better accuracy

   b) Calculation of OD and uncertainties with pipe size

   c) Input residual stress and vibration stress range

   d) Size correction for vibration stress range

   e) Correlations for flaw density, depth and uncertainty with wall thickness

   f) One flaw option added for initiation

   g) Weibull distribution in full-menu option

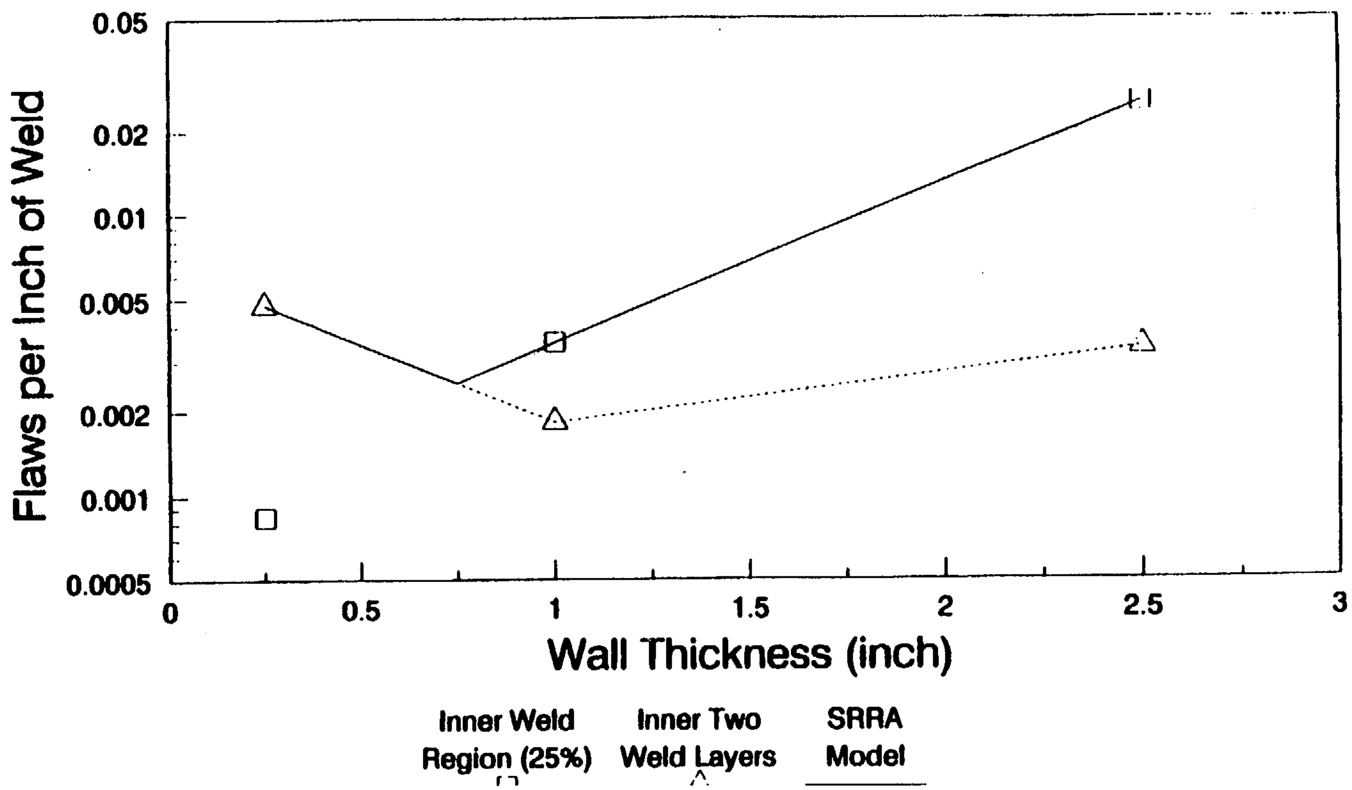


Figure 2-1 Initial Flaw Density for Welds with X-Ray

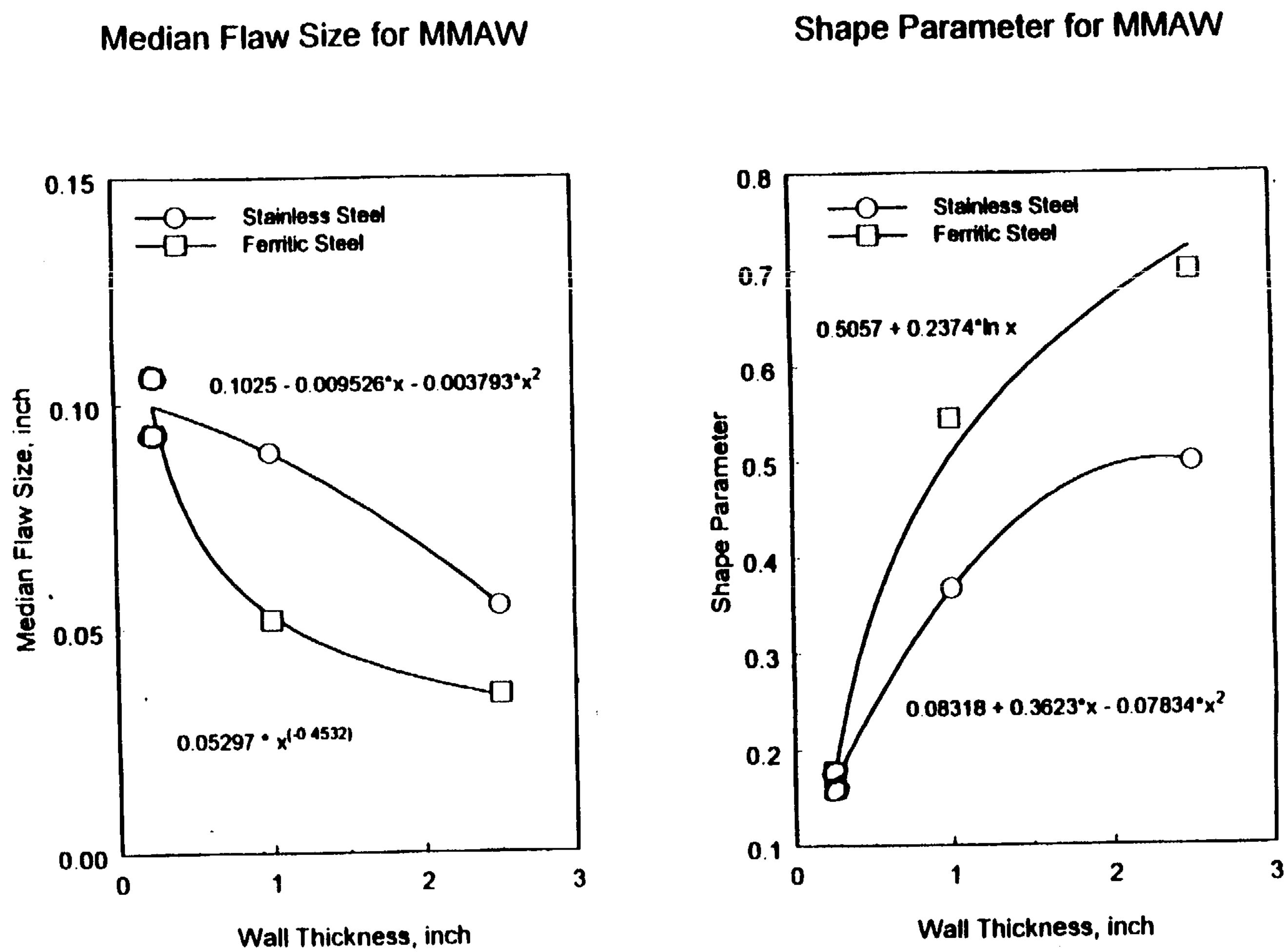


Figure 2-2 Initial Flaw Depth Parameters

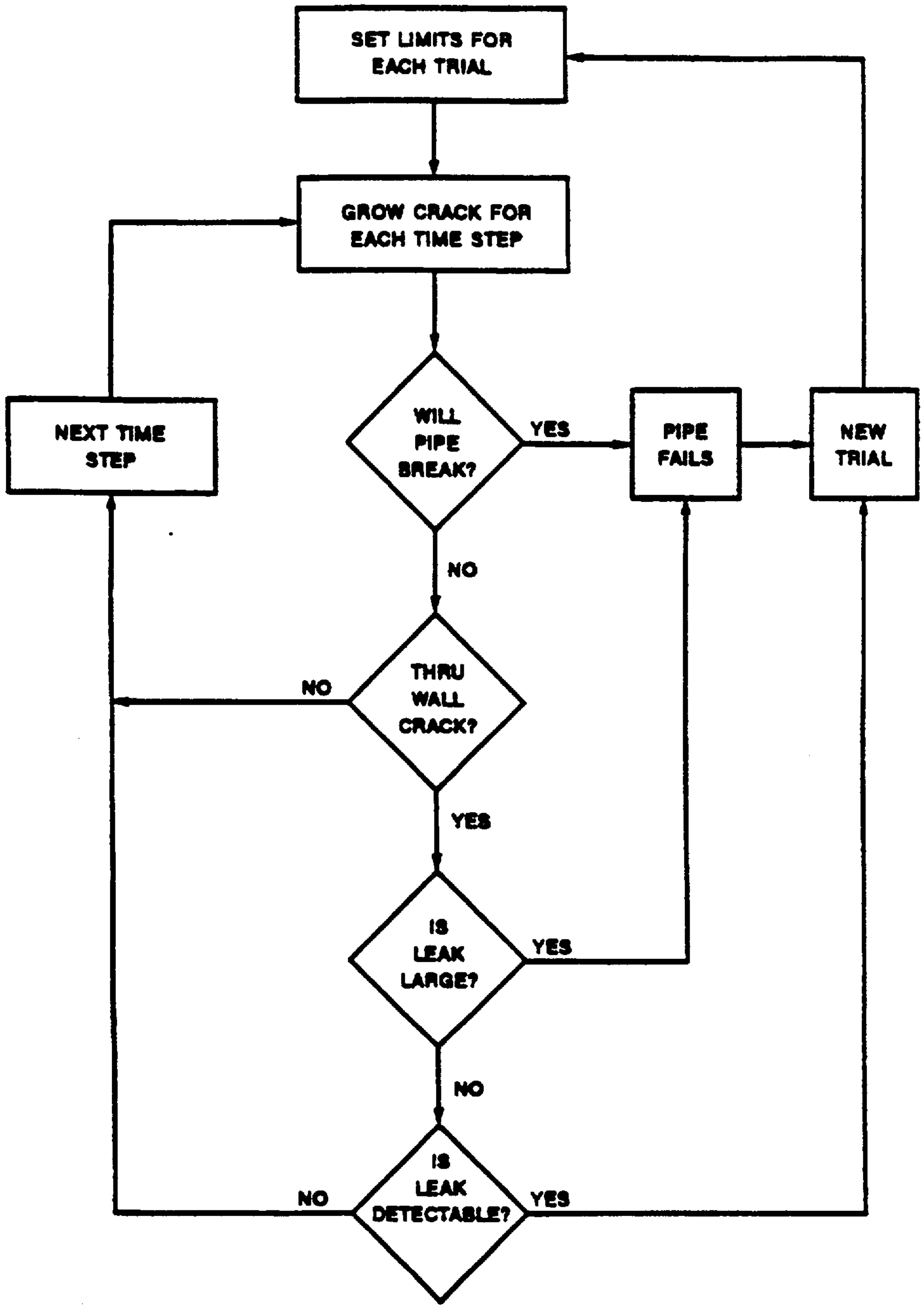


Figure 2-3 Flow Chart for New Piping Failure Modes

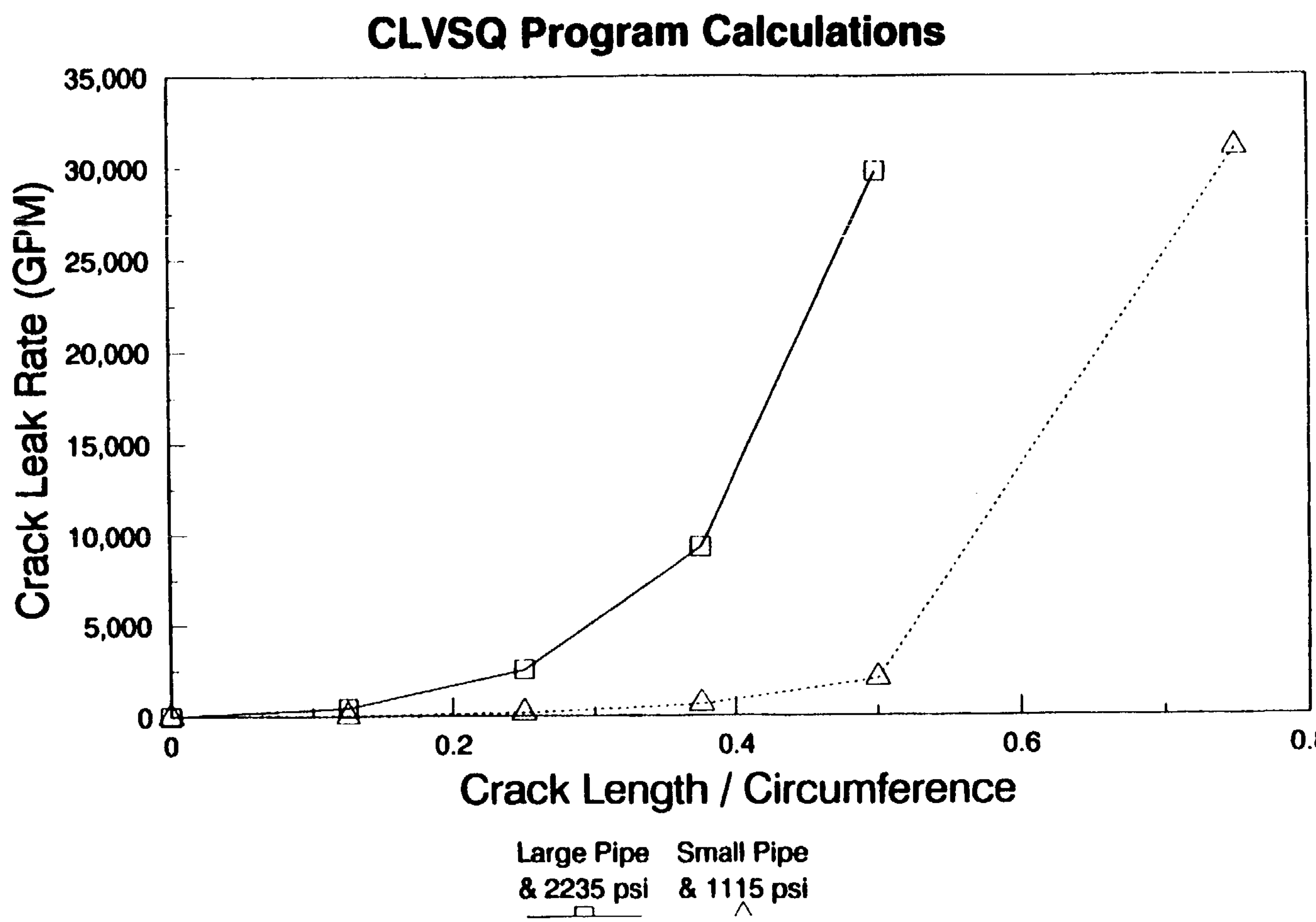


Figure 2-4 Leak Rate Program Calculations

SECTION 3
CURRENT SRRA MODEL AND SOFTWARE

The SRRA software is a set of executable personal computer programs to specify input, calculate and plot failure probability of piping with time for the selected input values of key design, operational, and inspection parameters. The SRRA computer program for structural reliability calculations for piping RI-ISI is LEAKPROF. Instructions on use of the software are provided in Appendix A.

3.1 CAPABILITIES AND LIMITATIONS

The primary capability of this SRRA computer code is to estimate the probability of exceeding the specified limits for a given piping failure mode as a function of time due to the combined effects of the modeled degradation (aging) mechanisms and input uncertainties. The piping failure modes considered are: 1) small leak (through-wall crack), 2) large (system disabling) leak and 3) full break (exceed material flow stress in uncracked section) during a postulated design-limiting event. The piping materials that are considered are type 304 and 316 stainless steel and carbon (ferritic) steel. The degradation mechanisms that are modeled include: 1) low-cycle fatigue crack growth of an existing (fabrication) flaw, 2) high-cycle fatigue stress, such as those due to vibration, exceeding the fatigue crack threshold, 3) stress corrosion crack growth of an existing flaw and 4) wall thinning due to wastage, such as flow assisted corrosion. The effects of flaws initiated by high-cycle fatigue or stress corrosion cracking can also be conservatively estimated. Typical uncertainties that are specified in the SRRA input are: 1) pipe geometry, 2) depth and length of the initial weld flaws, 3) residual stresses and stresses due to the piping loading conditions (pressure, deadweight, thermal, high and low-cycle stress ranges and design limiting stress, such as that due to a safe shutdown earthquake), 4) crack growth rate coefficients (fatigue and stress corrosion) and 5) material wastage rate. The SRRA computer code also has the capability to estimate the effects of inservice inspections as a function of the input values for accuracy and frequency.

The pressure stress, the number of initial flaws in a weld and pipe leak rate are all calculated assuming circular piping geometry with uniform wall thickness and flaws of concern being circumferentially oriented. In the rare situation that a longitudinal flaw in an axial weld or non-standard geometry would need to be evaluated, the failure probability should be estimated by other means (e.g., expert opinion or advanced modeling).

There are two major limitations on the use of the SRRA computer code. First, the SRRA computer code can only calculate probabilities for the failure modes, materials, degradation mechanisms, input variables and uncertainties it was programmed to consider. For example, the SRRA computer code does not analyze laminated piping or failure due to laminated flaws. Second, the SRRA calculated value of probability is the true failure probability of the actual piping if, and only if, all the failure modes and degradation mechanisms are exactly as modeled and all the input variables, including their uncertainties, are correct, which is highly unlikely. The last part of Section 4 discusses the uncertainties on the estimated failure probabilities calculated by the SRRA computer code. Caution should be particularly exercised when evaluating full pipe break probabilities with leak detection.

3.2 SIMPLIFIED AND DETAILED INPUT

In addition to the type of piping material and failure modes, seventeen variable parameters are used in the SRRA simplified input menu program LEAKMENU for piping RI-ISI. These parameters are listed in the input form of Table 3-1. Their range of standard values are provided in Tables 3-2 and 3-3. The selection of these key parameters is based on studies of size effects of Thomas (1981), inservice inspection effects of Woo and Simonen (1984) and transient severity and frequency effects of Chapman, Milner and Baker (1991). The effects observed in the piping failure database (Bush 1992) and correlated by Gamble and Taggart (1991) are also considered. Use of the ratio of the applied stress values to flow stress is from the work of Bishop and others (1985). Since the flow stress is normally related to design stress limits (yield and ultimate strength), experience with piping design stress analyses can also be used to guide the setting of the input values of stress ratio. Finally, the initial flaw conditions and leak rates are included for the recent model revisions. Additional information on how the variables in Tables 3-1 and 3-2 are input is provided in Item 9 of Section B in the input instructions of Appendix A. Tables 3-4 and 3-5 show example input and output screens with the default values for the LEAKMENU Program, which is the simplified piping input preprocessor for the Westinghouse SRRA software.

To calculate failure probability for the simplified input of Tables 3-1 and 3-2, the specified input values are used to set the median values in a more detailed structural reliability model in the LEAKPROF program. The input variables for this model and the correspondence to those for the simplified input are shown in Table 3-6. The order refers to the simplified input variables of Tables 3-2 and 3-3. The type of statistical distribution of each random variable in the detailed model input is also indicated in Table 3-6. For the variables not set by the simplified input and the standard uncertainties for all the variables with statistical distributions in Table 3-6, the input information is obtained from the SRRA reference input files listed in Table 3-7. As shown in Table 3-7, the reference input files consider the combined effects of material, predominant degradation mechanism, failure mode and credit for leak detection (i.e. leak before break).

The following items describe the simplified input variables in Tables 3-1 and 3-2 and any associated assumptions that could be important in assigning their input values. If more than one degradation mechanism is present in a given piping segment, then the limiting input values for each mechanism should be combined so that a limiting failure probability is calculated for risk ranking.

a) The inservice inspection input is optional since it is used to evaluate the benefit of a proposed inspection program. See the second paragraph of Section 3.3 on specifying an appropriate accuracy (probability of detection). Note that the first inspection is assumed to be performed at 1/2 of the input interval. For a normal interval of 10 years, ISI would be assumed at the end of years 5, 15, 25 and 35.

b) All piping material properties, except flow stress (approximate average of yield and tensile strengths), are assumed to be independent of temperature in the simplified SRRA input.

c) LEAKMENU will automatically calculate the outside diameter (O.D.) and its uncertainty for the specified nominal pipe size (NPS). However, the actual pipe wall thickness to O.D. ratio must be used.

d) The welding residual stress is much more important for stress corrosion cracking than for fatigue. The weld fabrication process, especially any post-weld heat treatment, should be considered in estimating its median value. The existing residual stress can also be reduced significantly due to mitigative actions, such as application of induction heating and mechanical stress improvement processes. Its value is always truncated at a minimum value of 0 and at a maximum value of 90% of the flow stress (approximate yield strength) during the piping simulations in the LEAKPROF program.

e) The initial flaw conditions normally refers to whether radiographic (X-Ray, NDE) was performed on the pipe weld, since this affects the flaw density (probability of initial flaw existing). One flaw should be specified when the flaw is assumed to be initiated by high-cycle secondary stresses (e.g. thermal striping) or by stress corrosion cracking. The initial flaw size and its uncertainty are automatically calculated for typical welds using results from PRODIGAL (Chapman 1993) as described in Section 2.1.

f) The normal steady-state operating stress is the sum of the stresses due to operating pressure and deadweight and restraint of thermal expansion (DW & Thermal). All stresses that are specified as a ratio to the flow stress are assumed to be upper bound values from a conservative stress analysis. The uncertainty on these stresses assumes that the input median value is only one-half the upper bound value based on experience in performing stress analyses for nuclear plant piping systems.

If all the following conditions exist,

- DW stresses are calculated using distributed values instead of point loading
- actual support stiffnesses are used instead of assuming perfectly rigid (zero deformation) supports,
- actual operating conditions are used for calculation instead of design conditions
- the DW and thermal stresses are calculated without any ASME Section III stress concentration factors for peak stresses, which are important for fatigue crack initiation but not for crack growth

Then, higher median values and lower uncertainty can be justified and used via the detailed input option.

g) The maximum stress corrosion cracking (SCC) potential of 1.0 is for fully sensitized SS in a BWR primary water environment. For the same potential, the SCC rates per K^2 for 304 SS, 316 SS and carbon steel are 3.59E-8, 3.24E-9, and 3.59E-11 inch/hour, respectively, where K is the stress intensity factor for pressure, DW & Thermal and residual stresses.

h) The maximum material wastage potential of 1.0 is for an industry average flow assisted corrosion rate of 9.5 mills per year. For example, if the plant's existing FAC control program indicated a 6-inch (NPS) schedule 40 carbon steel pipe (0.28" wall) would fully waste away in 120 years, then the average rate is 2.3 mills per year and the associated potential is approximately 0.25. For the same potential, the material wastage rates for 304 and 316 SS are assumed to be only 0.1% of that for carbon steel. When material wastage rates are high enough to proceed through the pipe wall, the probabilities of small leak, large leak and break are all calculated to be the same.

For wastage due to flow assisted corrosion, the FAC module in the CHECWORKS Program System, which was developed for EPRI (Chexal, et al. 1998), can be used, with or without data from the plant's existing FAC control program, to estimate the average wastage rate and corresponding potential. However, if mitigative actions have been taken, such as replacement with a corrosion resistant material, then not taking any credit for it could be grossly conservative. For example, with a wastage potential of 1.0 with no credit taken, assuming the mitigation action is 90% effective should result in a wastage potential of only 0.1 (or 0.01 for 99% effective) with significantly lower and more realistic SRRA calculated failure probabilities.

i) The high-cycle fatigue stresses due to mechanical vibration are specified for a small pipe size of 1 inch and corrected for the input pipe size. The logarithm of the correction factor varies linearly with pipe size from a factor of 1 at 1 inch to a factor of 1/6 at 10 inches. A factor of 1/6 is used for all pipe sizes above 10 inches. Failure occurs when the stress-intensity factor range (dK) exceeds the fatigue crack growth threshold at an R value (Kmin/Kmax) of 0.9.

j) Cyclic fatigue loading includes that due to thermal transients, like normal heat up and cool down or stratification, and that due to periodic seismic loading (e.g. OBE). Typically, the higher the degree of piping restraint, the higher the thermal stress range and the lower the seismic stress range. Both the vibratory and cyclic fatigue stress values should be input as a stress range, which is twice the stress amplitude that is sometimes calculated in the stress analysis. Therefore, the input median stress range would equal the calculated upper bound stress amplitude if the stress report loading were controlling.

k) The crack growth rate for cyclic fatigue loading is based upon an R value (see item i) of 0 for stainless steel and from 0 to 0.25 for carbon steel. If R values significantly different than this are known to exist, then correction of the input stress range is required. For stainless steel, an equivalent stress range can be

calculated by simply dividing the value of the stress range by the square root of (1 - R).

l) The design limiting stress is typically provided for the event that would most likely challenge the structural integrity of the piping, such as an SSE, LOCA, or water hammer. It should be provided to check if full break is more limiting than the large system disabling leak. If the system disabling leak rate is set to 0 (none), only the full break probability is calculated. If the break probability turns out to be limiting, then the probability of the design limiting event occurring should also be factored into the failure probability value used for piping segment risk ranking.

m) If the minimum detectable leak rate is set to 0 (none), no credit is taken for leak before break or for small leak before large leak. Note that the design-limiting stress and the disabling and detectable leak rates are not used to calculate small leak (through-wall crack) probabilities.

n) If snubbers are included in the piping system, then the effects of the snubbers not working properly should also be considered. This could result in an increase in slow cycle fatigue loading (item j) if the snubbers lock up during normal thermal cycling or an increase in seismic loading (item l) if the snubbers do not lock up during unexpected rapid motion. In either of these cases, the SRRA calculated probability would have to be multiplied by the probability that the snubbers do not operate properly (e.g. 0.1 for 10%). The larger failure probabilities for either proper or improper snubber operation would then be used for segment risk ranking.

To ensure that the simplified SRRA input parameters described above are consistently assigned and the SRRA computer code properly executed, the engineering team for SRRA input should be trained and qualified. The following topics should be covered in this training:

- Overall risk-informed ISI process,
- How SRRA calculated probabilities are used in the piping segment risk calculation,
- Expertise and type of information required, including applicable sources (see Table 1-1),
- How potential degradation mechanisms are considered and combined (see Table 1-2),
- The importance of each input parameter on each degradation mechanism and failure mode,
- Example SRRA program use for different degradation mechanisms and failure modes, and
- How detailed SRRA input (e.g. uncertainties in Section 3.4) is developed and used.

3.3 AGING AND FAILURE MODELS

The piping failure modes now considered in the structural reliability models are either exceeding the limiting leak rate during normal operation or exceeding the flow stress in the

remaining uncracked section during some design-limiting event. These failure modes encompass the highest (through wall crack for small leak) to lowest (full break) probabilities typically calculated for piping. One cause of failure is intergranular stress-corrosion cracking (IGSCC) growth or fatigue-crack growth of a small undetected crack due to thermal transients or high-cycle loads, such as flow induced vibration. The second cause of failure that is included in the piping structural reliability (SRRA) model is pipe wall thinning due to material wastage, such as flow assisted corrosion. Also included in the SRRA models are the log-normally distributed depth and length of the initial crack and growth of the crack in both the depth and length directions that are calculated using fracture mechanics analysis methods. The initial flaw depth (variable 4 in Table 3-6) is specified in the SRRA input as a continuous log-normal distribution that could theoretically allow values to approach zero or to be greater than the wall thickness. However, the stress intensity factor (fracture mechanics) calculations in the revised SRRA models automatically limit the flaw depth distribution to a range of values from 0.1% to 99.9% of the wall thickness. The stress intensity factors (K) for a semi-elliptical crack on the inside surface in a uniform stress field and the methods for calculating the effects of inservice inspection in the SRRA models are the same as those in the pc-PRAISE code (Harris, Dedhia and Lu 1992). Furthermore, the default input values for the probability of detection (POD) of ferritic and austenitic pipe are also consistent with the default input values for pc-PRAISE since the SRRA models were to be bench-marked with this software (see Section 4.3). However, the SRRA code user must ensure that the specified input values for POD are appropriate for the type of material, inspection method, component geometry and degradation mechanism being evaluated. Additional NDE reliability data and insights for POD determination are given in the references cited in Section 6.1 of the pc-PRAISE User's Manual (Harris, Dedhia and Lu 1992), Section 2.6.2 of Volume 1 (ASME 1991) and Section 2.7.3 of Volume 2, Part 1 (ASME 1992) of the Risk Based Inspection Guidelines.

It should also be noted that the SRRA models in LEAKPROF do not take credit for eliminating large flaws, which would fail during the pre-service hydrostatic proof test, even though this is allowed as an input option in pc-PRAISE. The SRRA model is only slightly conservative in this regard since the probability of having an initial flaw big enough to leak during the hydrostatic proof test would normally be very small.

The size and number of initial flaws (variables 4 and 5 in Table 3-6) are not related to fatigue usage factors. If crack initiation due to high-cycle fatigue (HCF) is a significant concern, then more detailed models, such as the statistically based correlations of ANL (Keister, Chopra and Shack 1994), should be used to analyze it. If crack initiation due to HCF is a potential concern, then the need for a more detailed analysis can be conservatively evaluated with the revised SRRA model. As suggested in the revised SRRA model documentation, this can be done by conservatively assuming the HCF flaw initiates at beginning of life and the initial size of the HCF flaw is conservatively the same as that for a fabrication defect. Both these assumptions can be implemented by specifying exactly one flaw (100% probability of flaw existence) in the piping SRRA simplified input menu program LEAKMENU.

The IGSCC equation for crack growth rate at a given stress intensity level is modeled as a log-log function with values for variables 15 and 16 in Table 3-6 and the uncertainty bounds for 304 SS given by NUREG-0313 (Hazelton and Koo 1988). The ratio of the growth rates for 316 SS relative to 304 SS is from pc-PRAISE (Harris, Dedhia and Lu 1992). Specifically, the

representation and uncertainty for IGSCC or environmentally-assisted crack (EAC) growth is taken from Figures 1 and 2 from Revision 2 of NUREG-0313 (Hazelton and Koo 1988). Figure 2 of this reference gives the form of the equation and its constants:

$$da/dt = C_0 K^m \tag{3-1}$$

Figure 1 from this reference was used to estimate the uncertainty. The selected form in equation (3-1) is also consistent with that given in equations (4-1) and (4-2) for pc-PRAISE (Harris, Dedhia and Lu 1992), where:

$$\log(C_0) = C_{14} + C_{12}\, C_{15} \log[f_2(\text{env.})] \tag{3-2}$$

$$m = C_{13}\, C_{15} \tag{3-3}$$

and constants C_{12} to C_{15} and function f_2 for the environment are from pc-PRAISE (Harris, Dedhia and Lu 1992).

The SRRA models excluded stress corrosion cracks that may initiate during service because it was believed to be more conservative to assume immediate growth of a fabrication defect, even if the probability of the defect existing was much less than 100%. Furthermore, it was believed that this conservative assumption would bound defects initiated later in time with some additional period of time to grow to the size of the fabrication defect. If crack initiation due to stress corrosion cracking is a potential concern, then the need for a more detailed analysis with pc-PRAISE (Harris, Dedhia and Lu 1992) can be conservatively evaluated by conservatively assuming the SCC flaw initiates at beginning of life and the initial size of the SCC flaw is conservatively the same as that for a fabrication defect. Both these assumptions can be implemented by specifying exactly one flaw (100% probability of flaw existence) in the piping SRRA simplified input menu program LEAKMENU. For example, use of this input assumption would increase the leak probability calculated by SRRA (see benchmarking Figure 4-3) by more than a factor of 30, making it much too conservative relative to the observed data.

The erosion/corrosion model used in the LEAKPROF program assumes a uniform rate of material thickness loss (wastage) starting at beginning of operation (time = 0 years). The median rate of material wastage (variable 17 in Table 3-6) and its uncertainty are based upon a statistical evaluation of the utility data on thinning of pipe walls that was compiled by EPRI (Mattu, et al. 1988) for flow assisted corrosion of carbon steel piping (see benchmarking Figure 4-2). Variables 21 to 23 for the log-log fatigue crack growth equations are taken from the pc-PRAISE code (Harris, Dedhia and Lu 1992) for both stainless steel and carbon (ferritic) steel. The R-ratio and environmental effects on the thresholds for high cycle fatigue crack growth that are used in the SRRA models for stainless steel are based upon the information shown in Figure 6 from the NRC supported work of Woo and Chou (1983). This figure shows the fatigue crack growth rate data in a simulated light water reactor environment for 316 and 304 type stainless steels. This figure also shows the threshold value of 4.6 ksi$\sqrt{\text{in}}$ for a R value of 0. In the revised SRRA model input, the threshold value is corrected for an R (K_{min}/K_{max}) value of 0.9, which is consistent with the value used in pc-PRAISE (Harris, Dedhia and Lu 1992).

The technical basis for the da/dn curve used in the original SRRA models to calculate fatigue crack growth in carbon steels was the previous ASME Section XI log-log linear law for a water environment. The work of Bamford (1979) provided the basis for changing to the current bi-linear log-log correlation in Section XI of the ASME Code. Figure 7 from this work shows how the different correlations compare to the carbon steel data in a simulated PWR water environment. This figure shows that the new correlation provides a much better fit to the data with R (K_{min}/K_{max}) values of 0.7 while not being overly conservative relative to the data with R values of 0.2. The pc-PRAISE (Harris, Dedhia and Lu 1992) computer code also uses the bi-linear log-log correlation that is in Section XI of the ASME Code to calculate fatigue crack growth of carbon steels in a water environment. In order for the SRRA computer code to accurately predict the failure probabilities of carbon steel in the benchmarking study with pc-PRAISE (see Section 4), the fatigue crack growth models and uncertainties were revised to be the same as those in pc-PRAISE.

The value of flow stress (variable 25 in Table 3-6) is required to predict full break failures. It is also used for the simplified input of Table 3-1, where the applied stresses are specified as a ratio to the flow stress (even for leak analysis). For stainless steel, a statistical evaluation of the data for various types of welds by EPRI (1986) is used for the change in mean flow stress with temperature. From the summary of licensee's responses to NRC Bulletin 87-01 (Mattu et al. 1988), the carbon steel material specifications indicated that the flow stress is higher than that for stainless steel at the same temperature (Phillips et al. 1992), as shown in Table 3-3.

3.4 UNCERTAINTIES

The standard uncertainties (type of statistical distribution and the parameter to specify its magnitude, such as the standard deviation for a normal distribution) and their technical basis used in the SRRA reference input files of Table 3-7 are summarized in Table 3-8. The uncertainties that are shown in bold in Table 3-8 were recommended by members of the ASME Research Task Force on Risk-Based Inspection (ASME 1991, 1992). When not enough data was available to justify a statistically significant value, engineering judgment was used. For example, many of the stress values that come from ASME Code stress analyses are assumed to be upper bound values with the median (expected) values one-half those values (see last item of Table 1-2). The technical basis for this 0.5 reduction factor on seismic stress is Figure 13 from the NRC study of failures in the reactor coolant loop piping of Westinghouse PWR Plants (Woo, Mensing and Benda 1984). This factor is applied to the stress values from seismic calculations to obtain the median value for a log-normal distribution. These values are used for input to the SRRA calculations both for the low-cycle fatigue loading due to an operating basis earthquake and the design limiting stress due to a safe-shutdown earthquake. These types of seismic loads are the same types that are used to grow cracks in pc-PRAISE (Harris, Dedhia and Lu 1992). Figure 13 from this study shows that the seismic stresses calculated using response spectrum method and reported in the stress report required by Section III of the ASME Code are at least two times the corresponding stresses using the more complicated, but more accurate, time history method. Therefore, the time-history calculated stresses are approximated as a median value by applying the 0.5 reduction factor to the response-spectrum calculated seismic stresses. As shown in Table 3-8, the response-spectrum calculated values are still used as an upper 2-sigma bound (twice the median value). The log-normal distribution is used because the

uncertainty is expressed as a factor instead of a difference (standard deviation in a normal distribution).

If there is sufficient information available in documents or databases, then the uncertainties for any SRRA input variable can be easily changed by using the detailed input menu preprocessor program, PROFMENU. The standard distributions that are available to specify the uncertainty include: normal, log-normal, uniform, log-uniform and Weibull. The deviation D for the normal distribution in the SRRA input/output is defined as follows:

$$D = V_{84} - V_{50} \tag{3-4}$$

The deviation factor F for the log-normal distribution in the SRRA output is defined as follows:

$$F = V_{84} / V_{50} \tag{3-5}$$

Where: V_{84} = +1-Sigma value at a cumulative probability of 84.1%

V_{50} = Median value at a cumulative probability of 50.0%

Because of the input options and format for the detailed SRRA input menu program PROFMENU, an equivalent deviation defined per equation (3-4) is also used to input the uncertainty for a log-normal distribution. The relationship between the SRRA output factor F and PROFMENU input deviation D for a log-normal distribution is:

$$\text{Log}(F) = \text{Log}(V_{50} + D) - \text{Log}(V_{50}) \tag{3-6}$$

These statistical definitions and the fact that the median value is also equal to the mean (average) value for the symmetric normal distribution are also included in the instructions for the LEAKPROF Program in Appendix A.

3.5 FAILURE PROBABILITY WITH TIME

The probability of failure of the piping as a function of operating time is calculated directly for each set of input values using Monte-Carlo simulation with importance sampling. This variance reduction technique, as described by Witt (1984), is used to greatly reduce the number of trials required for calculating small failure probabilities. In importance sampling, the important random values are selected from the more severe high or low regions of their distributions so as to promote failure. However, when failure is calculated, the count is corrected to account for the lower probability of simultaneously obtaining all the more severe random values.

Initially, a maximum of 5,000 Monte-Carlo simulations was specified for use with importance sampling based upon the work of Witt (1984) on pressurized thermal shock of embrittled reactor pressure vessels. Figure 4 from this work shows that this number of simulations with importance sampling gave comparable results as 100,000 and 500,000 simulations without importance sampling. However, in order for the SRRA computer code to more accurately predict the low failure probabilities in the benchmarking study with pc-PRAISE (see Section 4),

the standard number of simulations was increased. The last column of Table 3-7 gives the standard values that are now specified in the revised SRRA input. The uncertainties and confidence levels on the calculated probabilities are discussed in detail in Section 4.

To apply this simulation method to the latest piping SRRA models, the Westinghouse PROF (probability of failure) Software System (object library) is used to generate the executable program LEAKPROF.EXE for calculation of piping failure probability with time. This library has been verified and benchmarked in a number of ways as described in Section 4. The flow chart for the LEAKPROF Program, which is used for piping RI-ISI, is shown in Figure 3-1. Variables 1 to 6 in Table 3-6 are used to *initialize parameters* or set values that do not vary with time in Subroutine SET. Variables 7 to 11 are needed to calculate the *effects of ISI* in Subroutine ISI, 12 to 17 for *steady-state changes* in Subroutine SSC and 18 to 23 for *transient changes* in Subroutine TRC. Finally, variables 24 to 28 are used to *check if failure occurs* in Subroutine FMD.

The failure probability is always calculated with the SRRA code LEAKPROF for the typical 40 year licensed life instead of a calculated life based upon the known or assumed rate of degradation. This is because the time for a given failure mode, such as small leak or full break, varies significantly due to the uncertainties in the SRRA input variables (Table 3-8). If 10 million (10^7) monte-carlo simulations of the time to failure were performed without importance sampling by the SRRA code, the distribution of failure times might look something like that shown in Figure 3-2. The corresponding cumulative number of failures for each year of operation is shown in Figure 3-3. Note that the median failure time (at 5 million cumulative failures in 10^7 simulations) is significantly greater than 40 years. In fact, the SRRA computer code simulation is truncated at 40 years for computational efficiency that avoids additional calculations that are not needed. If all the calculations were all run to a median failure time, the time would be significantly greater than 40 years and vary from location to location but the probability would always be the same.

There are a number of steps involved in calculating the failure probability of a pipe weld during a 40 year period with no inspections. The SRRA computer code LEAKPROF is the primary tool used for piping RI-ISI. The time to failure for a given failure mode, such as large leak, is calculated using one set of values of all the SRRA input variables in Table 3-6. If the failure time is less than or equal to 40 years it is noted, otherwise a new calculation is started with a different set of values for the input variables. The value of some variables in each simulation (trial) are randomly selected from the statistical distributions specified in the input. Table 3-8 identifies the random variables and their distributions that are used in the standard SRRA input. The other input variables in Table 3-6 are constants that do not vary from trial to trial.

As described previously, Figure 3-2 provides an example histogram of failure times that might be generated by 10 million simulations with the SRRA computer code without importance sampling. Note that in any one year, the number of failures varies from 0 to 40 with a generally increasing number with time. This increase is due to the effects of the degradation (aging) mechanisms, such as fatigue crack growth. Figure 3-3 shows the corresponding cumulative number of calculated failures for each year of operation. Note that by year 20, there have been slightly less than 100 failures and by year 40, slightly more than 400 failures. If the cumulative number of failures is divided by the number of trials (10^7), then the result is the estimated failure probability with time for 40 years of operation without any benefit of inservice inspection. As shown in Figure 3-4, the probability at 20 years is approximately 1E-05 ($\sim 100/10^7$) and at 40 years approximately 4E-05 ($\sim 400/10^7$). For calculational efficiency, the SRRA computer code uses a variance reduction technique called importance sampling (Witt 1984). This technique allows low values of failure probability to be accurately calculated with a maximum of 60,000 simulations instead of 10 million simulations.

3.6 SAMPLE OUTPUT

Table 3-9 provides sample output from the LEAKPROF Program for the default values of the simplified input variables in Tables 3-1 and 3-4. Likewise, Appendix B provides the LEAKPROF output files for each of the reference input files of Table 3-7. The first part of each output file describes the input that is used for the calculations, including the simplified input if the LEAKMENU program was used. The "MEDIAN VALUE" column in the SRRA output print files is the value at 50% probability (half above and half below this value); it is also the mean (average) value for symmetric distributions, like the normal (bell-shaped curve) distribution. The "SHIFT MV/SD" column indicates how many standard deviations (SD) the median value (MV) is shifted for importance sampling (Witt 1984). The second part of the LEAKPROF program output provides the change in failure probability per operating cycle (year) and the cumulative probability. The deviation on the cumulative total that is output is the deviation due to the Monte-Carlo simulation only. Figure 3-5 shows the plot generated by the SRRAPLOT post-processor program. It compares the calculated piping failure probabilities with and without the effects of inservice inspection for leak of carbon steel piping.

3.7 EFFECT OF CHANGES

As required by the ASME risk-based inspection guidelines for nuclear plant components (ASME 1991), any significant design changes, systems backfits and even the good or bad results of an inspection would be evaluated to see if the new failure probability and/or consequences would result in any changes to the piping segment's safety significance. For example, the SRRA software could be used to evaluate the effects of repaired pipes and weld overlays by using the same methods as those for unrepaired pipes. However, the input to the SRRA models would be modified to reflect the changes due to the repairs, such as an increased wall thickness, reduced tensile residual stresses and reduced susceptibility to stress corrosion cracking for weld overlays. Two SRRA analyses would be performed, one with the repairs and one without them, for the licensed life of 40 years. For an example implementation of the repairs at after 20 years of operation, an upper bound estimate of the probability at 40 years would be:

$$P_U(40) = P_O(20) + P_R(40) - P_R(20) \qquad (3\text{-}7)$$

where $P_O(t)$ = original probability without repairs after t years

and $PR(t)$ = probability with repairs after t years.

The lower bound estimate on the probability at 40 years would be:

$$P_L(40) = P_O(20) + P_R(20) - P_R(0) \qquad (3\text{-}8)$$

The upper bound approach was used previously by Westinghouse to estimate the effects of mid-life changes on stress corrosion cracking of stainless steel piping in a boiling water reactor before this capability was added to pc-PRAISE (Harris, Dedhia and Lu 1992). This work and example results are described in the section entitled *Evaluation of Corrective Actions Using SRRA* (pp 93 & 96) in the ASME Risk-Based Inspection Guidelines for Nuclear Power Plant Components (ASME 1992).

Table 3-1
SIMPLIFIED INPUT FOR PIPING STRUCTURAL RELIABILITY EVALUATION

No.	Input Parameter Description	Underline Input Choice (for Table 2-2 Value)			Set Value *
1	Type of Piping Steel Material	304 St.	316 St.	Carbon	---
2	Crack Inspection Interval (Optional)	Low (6)	Medium (10)	High (14)	
3	Crack Inspection Accuracy (Optional)	High (.16)	Medium (.24)	Low (.32)	
4	Temperature at Pipe Weld	Low (150)	Medium (350)	High (550)	
5	Nominal Pipe Size	Small (2)	Medium (5)	Large (16)	
6	Thickness to O.D. Ratio	Thin (.05)	Normal (.13)	Thick (.21)	
7	Normal Operating Pressure	Low (0.5)	Medium (1.3)	High (2.1)	
8	Residual Stress Level	None (0.0)	Moderate (10)	Maximum (20)	
9	Initial Flaw Conditions	One Flaw	X-Ray NDE	No X-Ray	
10	DW & Thermal Stress Level	Low (.05)	Medium (.11)	High (.17)	
11	Stress Corrosion Potential	None (0.0)	Moderate (0.5)	Maximum (1.0)	
12	Material Wastage Potential	None (0.0)	Moderate (0.5)	Maximum (1.0)	
13	Vibratory Stress Range	None (0.0)	Moderate (1.5)	Maximum (3.0)	
14	Fatigue Stress Range	Low (.30)	Medium (.50)	High (.70)	
15	Low Cycle Fatigue Frequency	Low (10)	Medium (20)	High (30)	
16	Design-Limiting Stress (LL/Break Only)	Low (.10)	Medium (.26)	High (.42)	
17	System Disabling Leak (Large Leak Only)	None (0)	Medium (300)	High (600)	
18	Min. Detectable Leak (LL/Break Only)	None (0)	Medium (5)	High (10)	

* For optional numeric input, standard values (and associated units) are given in Table 3-2.

Table 3-2 RANGE OF STANDARD NUMERIC VALUES FOR SIMPLIFIED INPUT TO PIPING STRUCTURAL RELIABILITY MODELS			
No.	**Parameter Description**	**Range**	**Step Size**
2	Years Between Inspections	4 - 16	2
3	Wall Fraction for 50% Detection	0.12 - 0.36	0.02
4	Degrees (F) at Pipe Weld	50 - 650	50
5	Nominal Pipe Size (NPS, inch)	1 - 20	0.5, $D \leq 5$ 2.0, $D \geq 6$
6	Thickness / Outside Diameter	0.01 - 0.25	0.01
7	Operating Pressure (ksi)	0.1 - 2.5	0.20
8	Uniform Residual Stress (ksi)	0.0 - 20.0	2.0
9	Flaw Factor (<0 for 1 Flaw)	1.0 or 12.8	11.8
10	DW & Thermal Stress / Flow Stress *	0.02 - 0.20	0.03
11	SCC Rate / Rate for BWR Sensitized SS	0.0 - 1.0	0.05
12	Wastage Rate / 0.095 in. per yr.	0.0 - 1.0	0.05
13	P-P Vib. Stress (ksi for NPS of 1)	0.0 - 3.0	0.5
14	Cyclic Stress Range / Flow Stress *	0.20 - 0.80	0.05
15	Fatigue Cycles per Year	5 - 35	5
16	Design-Limit Stress / Flow Stress *	0.02 - 0.50	0.04
17	System Disabling Leak Rate (GPM)	0 - 600	50
18	Minimum Detectable leak Rate (GPM)	0 - 10	1
* The stress ratio is the value of the applied stress to the weld flow stress for the specified temperature and the type of material. See Table 3-3 for weld flow stresses.			

Table 3-3 VALUE OF WELD FLOW STRESS (KSI) USED FOR SIMPLIFIED PIPING STRUCTURAL RELIABILITY INPUT		
Temperature (°F)	**304 & 316 SS**	**Carbon Steel**
50	74.32	80.92
100	72.23	78.83
150	70.14	76.74
200	68.05	74.65
250	65.96	72.56
300	63.87	70.47
350	61.78	68.38
400	59.69	66.29
450	57.60	64.20
500	55.51	62.11
550	53.42	60.02
600	51.33	57.93
650	49.24	55.84

Table 3-4
SAMPLE INPUT SCREEN FOR THE LEAKMENU PROGRAM

Westinghouse	**Program LEAKMENU**	**ESBU-NSD**
	Type of LEAKMENU Program Option	Set Input
	Type of Piping Steel Material	Carbon
	Pipe Weld Failure Mode	Small Leak
	Crack Inspection Interval	Medium
	Crack Inspection Accuracy	Medium
	Temperature at Pipe Weld	Medium
	Nominal Pipe Size	Medium
	Thickness to O.D. Ratio	Thin
	Normal Operating Pressure	Medium
	Residual Stress Level	None
	Initial Flaw Conditions	X-Ray NDE
	DW & Thermal Stress Level	Medium
	Stress Corrosion Potential	None
	Material Wastage Potential	None
	Vibratory Stress Range	None
	Fatigue Stress Range	Medium
	Fatigue Stress Frequency	Medium
	Design-Limit Stress Level	Medium
	System Disabling Leak	None
	Minimum Detectable Leak	None
Messages and Input	Use Up, Down, Right or Left Arrows, End, Esc, Enter or Insert Keys to Select Options\Values	

Table 3-5 SAMPLE OUTPUT SCREEN FOR THE LEAKMENU PROGRAM		
WestinghouseProgram	**Program LEAKMENU**	**ESBU-NSD**

Type of LEAKMENU Program Option	Run PROF
Type of Piping Steel Material	Carbon
Pipe Weld Failure Mode	Small Leak
Operating Cycles Between Inspections	10.0
Wall Fraction for 50% Detection	0.240
Degrees (F) at Pipe Weld	350.0
Nominal Pipe Size (NPS, inch)	5.0
Thickness / Outside Diameter	0.0500
Operating Pressure (ksi)	1.30
Uniform Residual Stress (ksi)	0.0
Flaw Factor (<0 for 1 Flaw)	1.00
DW & Thermal Stress / Flow Stress	0.11
SCC Rate / Rate for BWR Sens. SS	0.00
Factor on Wastage of .0095 in/yr	0.00
P-P Vib. Stress (ksi for NPS of 1)	0.0
Cyclic Stress Range / Flow Stress	0.500
Fatigue Cycles per Year	20.0
Design-Limit Stress / Flow Stress	0.260
System Disabling Leak Rate (GPM)	0.0
Minimum Detectable Leak Rate (GPM)	0.0

Messages	These input values are used for Current Case 1
and Input	Enter Pipe Segment Number(s): ____________

Table 3-6
VARIABLES FOR PIPING STRUCTURAL RELIABILITY MODELS IN LEAKPROF

Order	No.	Name	Description Of Model Variable	Distribution
5th	1	PIPE-ODIA	PIPE OUTSIDE DIAMETER (INCH)	Normal
6th	2	WALL/ODIA	PIPE WALL TO DIAMETER RATIO	Normal
8th	3	SRESIDUAL	WELD I.D. RESIDUAL STRESS (KSI)	Log-Normal
	4	INT%DEPTH	INITIAL CRACK DEPTH (% OF WALL)	Log-Normal
	5	L/D-RATIO	INITIAL CRACK LENGTH TO DEPTH RATIO	Log-Normal
9th	6	FLAWS/IN	FLAWS PER INCH OF WELD (1 FLAW IF < 0)	Constant
2nd	7	FIRST-ISI	YEAR NUMBER FOR FIRST INSPECTION (ISI)	Constant
2nd	8	FREQ-ISI	FREQUENCY FOR SUBSEQUENT ISI'S (YEARS)	Constant
	9	EPST-PND	MINIMUM ISI PROB. OF NONDETECTION (PND)	Constant
3rd	10	ASTAR-PND	DEPTH FOR 50% PROB. OF NONDETECTION	Constant
	11	ANUU-PND	PND EXPONENTIAL SLOPE WITH CRACK DEPTH	Constant
	12	HOURS/YR	EFFECTIVE HOURS PER YEAR OF OPERATION	Log-Normal
7th	13	PRESSURE	NORMAL OPERATING PRESSURE (KSI)	Log-Normal
10th	14	SIG-DW&TH	DEADWEIGHT AND THERMAL STRESS (KSI)	Log-Normal
11th	15	SCC-COEFF	STRESS-CORROSION COEFFICIENT (IN/HR)	Log-Normal
	16	SCC-EXPNT	SCC EXPONENT FOR STRESS INTENSITY	Constant
12th	17	WASTAGE	MATERIAL WASTAGE RATE (IN/HR)	Log-Normal
13th	18	DSIG-VIBR	HIGH CYCLE VIBRATION STRESS RANGE (KSI)	Log-Normal
15th	19	CYCLES/YR	NUMBER OF FATIGUE CYCLES PER YEAR	Constant
14th	20	DSIG-FATG	CYCLIC FATIGUE STRESS RANGE (KSI)	Log-Normal
1st	21	FCG-COEFF	FATIGUE CRACKING COEFFICIENT (IN/CYCLE)	Log-Normal
1st	22	FCG-EXPNT	FATIGUE CRACK GROWTH EXPONENT	Constant
1st	23	FCG-THOLD	FCG THRESHOLD IN KSI-SQRT(INCH)	Constant
	24	LDEPTH-SL	LIMIT CRACK DEPTH FOR SMALL LEAK (IN)	Normal
4th	25	SIG-FLOW	FLOW STRESS FOR FULL PIPE BREAK (KSI)	Normal
16th	26	STRESS-DL	DESIGN LIMITING AXIAL STRESS (KSI)	Log-Normal
17th	27	B-SDLEAK	LENGTH FOR SYSTEM DISABLING LEAK (IN)	Constant
18th	28	B-MDLEAK	LENGTH FOR MINIMUM DETECTABLE LEAK (IN)	Constant

Table 3-7
REFERENCE FILES USED BY THE SRRA MENU PROGRAMS

Reference File	Type Steel Material	Failure Mode	Primary Mechanism	Leak Credit	Number of Trials
CSPROFSL	Carbon	Small Leak	Fatigue	No	40,000
CSPROFLL	Carbon	Large Leak	Fatigue	No	50,000
CSPROFDL	Carbon	Large Leak	Fatigue	Yes	60,000
CSPROFBL	Carbon	Leak or Break	Wastage	No	10,000
S4PROFSL	304 St.	Small Leak	Fatigue	No	40,000
S4PROFSS	304 St.	Small Leak	SSC	No	10,000
S4PROFLL	304 St.	Large Leak	Fatigue	No	50,000
S4PROFDL	304 St.	Large Leak	Fatigue	Yes	60,000
S4PROFLS	304 St.	Large Leak	SSC	No	20,000
S4PROFDS	304 St.	Large Leak	SSC	Yes	30,000
S4PROFDB	304 St.	Full Break	Fatigue	Yes	60,000
S6PROFSL	316 St.	Small Leak	Fatigue	No	40,000
S6PROFSS	316 St.	Small Leak	SSC	No	10,000
S6PROFLL	316 St.	Large Leak	Fatigue	No	50,000
S6PROFDL	316 St.	Large Leak	Fatigue	Yes	60,000
S6PROFLS	316 St.	Large Leak	SSC	No	20,000
S6PROFDS	316 St.	Large Leak	SSC	Yes	30,000
S6PROFDB	316 St.	Full Break	Fatigue	Yes	60,000

Table 3-8 BASIS FOR STANDARD UNCERTAINTIES USED IN SRRA INPUT		
Parameter	**Distribution**	**Basis for Uncertainty**
PIPE-ODIA	Normal	Tolerance = $\pm 2\sigma$ for ASTM A-106, A-355 & A-376
WALL/ODIA	Normal	12% = $\pm 2\sigma$ for ASTM A-106, A-355 & A-376
SRESIDUAL	Log-Normal	2σ factor = 2 for benchmarking with leak data
INT%DEPTH	Log-Normal	Calculated using latest models for flaw depth (Figure 2-2)
L/D-RATIO	Log-Normal	pc-PRAISE [4] FCG example used a 1σ factor of 1.3077
HOURS/CY	Log-Normal	$\pm 3\sigma$ range based upon a capacity factor from 70 to 100%
PRESSURE	Log-Normal	**3σ value = 10% of median value**
SIG-DW&TH	Log-Normal	3σ factor = 2 by engineering judgment
SSC-COEFF	Log-Normal	$\pm 2\sigma$ range = 31.6 factor in NUREG-0313, Rev. 2 [16]
WASTAGE	Log-Normal	Consistent with 99.5% bound (2.575σ) factor of 9.24 for data on wall thinning in EPRI NP-6066 [18]
DSIG-VIBR	Log-Normal	**Upper 99% bound is a factor of 2**
DSIG-FATG	Log-Normal	2σ factor = 2 by engineering judgment
FCG-COEFF	Log-Normal	Consistent with 90% bound (1.282σ) factor of 3.83 in pc-PRAISE [4]
SIG-FLOW	Normal	Statistical fit of weld data in EPRI NP-4768 [21]
STRESS-DL	Log-Normal	2σ factor = 2 by engineering judgment

Table 3-9
EXAMPLE LEAKPROF OUTPUT FILE

Output Print File CSPROFSL.P01 Opened at 11:28 on 08-28-1997

Type of Piping Steel Material	Carbon
Pipe Weld Failure Mode	Small Leak
Years Between Inspections	10.0
Wall Fraction for 50% Detection	0.240
Degrees (F) at Pipe Weld	350.0
Nominal Pipe Size (NPS, inch)	5.0
Thickness / Outside Diameter	0.0500
Operating Pressure (ksi)	1.30
Uniform Residual Stress (ksi)	0.0
Flaw Factor (<0 for 1 Flaw)	1.00
DW & Thermal Stress / Flow Stress	0.11
SCC Rate / Rate for BWR Sens. SS	0.00
Factor on Wastage of .0095 in/yr	0.00
P-P Vib. Stress (ksi for NPS of 1)	0.0
Cyclic Stress Range / Flow Stress	0.500
Fatigue Cycles per Year	20.0
Design-Limit Stress / Flow Stress	0.260
System Disabling Leak Rate (GPM)	0.0
Minimum Detectable Leak Rate (GPM)	0.0
Value of Weld Metal Flow Stress in Ksi	68.35

STRUCTURAL RELIABILITY AND RISK ASSESSMENT (SRRA)

WESTINGHOUSE PROBABILITY OF FAILURE PROGRAM LEAKPROF ESBU-NSD

==

INPUT VARIABLES FOR CASE 1: Carbon Steel Pipe Segment Default Values

NCYCLE =	40	NFAILS =	400	NTRIAL =	40000
NOVARS =	28	NUMSET =	6	NUMISI =	5
NUMSSC =	6	NUMTRC =	6	NUMFMD =	5

VARIABLE NO.	NAME	DISTRIBUTION TYPE	LOG	MEDIAN VALUE	DEVIATION OR FACTOR	SHIFT MV/SD	USAGE NO.	SUB
1	PIPE-ODIA	NORMAL	NO	5.5630D+00	2.4000D-02	00	1	SET
2	WALL/ODIA	NORMAL	NO	5.0000D-02	1.5500D-03	00	2	SET
3	SRESIDUAL	NORMAL	YES	1.0000D-03	1.4142D+00		3	SET
4	INT%DEPTH	NORMAL	YES	3.4010D+01	1.2238D+00	2.00	4	SET
5	L/D-RATIO	NORMAL	YES	6.0000D+00	1.7126D+00	1.00	5	SET
6	FLAWS/IN	- CONSTANT -		4.5820D-03			6	SET
7	FIRST-ISI	- CONSTANT -		5.0000D+00			1	ISI
8	FREQ-ISI	- CONSTANT -		1.0000D+01			2	ISI
9	EPST-PND	- CONSTANT -		5.0000D-03			3	ISI
10	ASTAR-PND	- CONSTANT -		-2.4000D-01			4	ISI
11	ANUU-PND	- CONSTANT -		3.0000D+00			5	ISI
12	HOURS/YR	NORMAL	YES	7.4473D+03	1.0500D+00	.00	1	SSC
13	PRESSURE	NORMAL	YES	1.3000D+00	1.0323D+00	.00	2	SSC
14	SIG-DW&TH	NORMAL	YES	7.5184D+00	1.2599D+00	.00	3	SSC
15	SCC-COEFF	NORMAL	YES	3.5900D-14	2.3714D+00	.00	4	SSC
16	SCC-EXPNT	- CONSTANT -		2.1610D+00			5	SSC
17	WASTAGE	NORMAL	YES	1.2740D-09	2.3714D+00	.00	6	SSC
18	DSIG-VIBR	NORMAL	YES	4.5098D-04	1.3465D+00	.00	1	TRC
19	CYCLES/YR	- CONSTANT -		2.0000D+01			2	TRC
20	DSIG-FATG	NORMAL	YES	3.4174D+01	1.4142D+00	.00	3	TRC
21	FCG-COEFF	NORMAL	YES	6.7931D-13	1.7194D+00	1.00	4	TRC
22	FCG-EXPNT	- CONSTANT -		5.9500D+00			5	TRC
23	FCG-THOLD	- CONSTANT -		1.9000D+01			6	TRC
24	LDEPTH-SL	- CONSTANT -		-9.9900D-01			1	FMD
25	SIG-FLOW	NORMAL	NO	6.8349D+01	3.2000D+00	.00	2	FMD

Table 3-9 (cont.)
EXAMPLE LEAKPROF OUTPUT FILE

```
26  STRESS-DL   - CONSTANT -     0.0000D+00                          3  FMD
27  B-SDLEAK    - CONSTANT -     0.0000D+00                          4  FMD
28  B-MDLEAK    - CONSTANT -     0.0000D+00                          5  FMD

  PROBABILITIES OF FAILURE MODE: THROUGH-WALL CRACK DEPTH FOR SMALL LEAK

            NUMBER FAILED =  400            NUMBER OF TRIALS =    722
```

END OF CYCLE	FAILURE PROBABILITY WITHOUT FOR PERIOD	CUM. TOTAL	AND WITH INSERVICE FOR PERIOD	INSPECTIONS CUM. TOTAL
1.0	1.37881D-07	1.37881D-07	1.37881D-07	1.37881D-07
2.0	7.45127D-07	8.83008D-07	7.45127D-07	8.83008D-07
3.0	8.20420D-07	1.70343D-06	8.20420D-07	1.70343D-06
4.0	3.93908D-07	2.09734D-06	3.93908D-07	2.09734D-06
5.0	9.42928D-06	1.15266D-05	9.42928D-06	1.15266D-05
6.0	9.00953D-06	2.05361D-05	4.50477D-08	1.15717D-05
7.0	2.34973D-05	4.40334D-05	1.17556D-07	1.16892D-05
8.0	1.50147D-05	5.90481D-05	7.50889D-08	1.17643D-05
9.0	1.33606D-05	7.24086D-05	6.70906D-08	1.18314D-05
10.0	6.41567D-06	7.88243D-05	3.20872D-08	1.18635D-05
11.0	2.73199D-05	1.06144D-04	1.45457D-07	1.20089D-05
12.0	2.42208D-05	1.30365D-04	1.23119D-07	1.21321D-05
13.0	1.47560D-05	1.45121D-04	7.39312D-08	1.22060D-05
14.0	3.10075D-05	1.76128D-04	1.56302D-07	1.23623D-05
15.0	4.41547D-05	2.20283D-04	2.28309D-07	1.25906D-05
16.0	3.60986D-05	2.56382D-04	9.40532D-10	1.25915D-05
17.0	7.73729D-05	3.33755D-04	2.17693D-09	1.25937D-05
18.0	5.92704D-05	3.93025D-04	1.53255D-09	1.25953D-05
19.0	8.98505D-05	4.82876D-04	2.72908D-09	1.25980D-05
20.0	1.07077D-04	5.89953D-04	3.10947D-09	1.26011D-05
21.0	3.56465D-05	6.25599D-04	1.04884D-09	1.26021D-05
22.0	1.71710D-05	6.42770D-04	5.05338D-10	1.26026D-05
23.0	2.22646D-05	6.65035D-04	7.04659D-10	1.26033D-05
24.0	1.09065D-04	7.74100D-04	3.76907D-09	1.26071D-05
25.0	9.64765D-05	8.70576D-04	5.03026D-09	1.26121D-05
26.0	1.06691D-04	9.77267D-04	1.68908D-11	1.26122D-05
27.0	1.08467D-04	1.08573D-03	2.38146D-11	1.26122D-05
28.0	8.62784D-05	1.17201D-03	3.80953D-11	1.26122D-05
29.0	3.35300D-04	1.50731D-03	1.81096D-10	1.26124D-05
30.0	2.48039D-04	1.75535D-03	4.44751D-11	1.26125D-05
31.0	2.60044D-04	2.01539D-03	1.74551D-10	1.26126D-05
32.0	8.06245D-05	2.09602D-03	5.74635D-11	1.26127D-05
33.0	1.73367D-04	2.26939D-03	3.83326D-10	1.26131D-05
34.0	1.53817D-04	2.42320D-03	4.73538D-11	1.26131D-05
35.0	2.70263D-05	2.45023D-03	5.93620D-12	1.26131D-05
36.0	1.23268D-04	2.57350D-03	1.14817D-13	1.26131D-05
37.0	6.85987D-06	2.58036D-03	4.38247D-15	1.26131D-05
38.0	7.70360D-05	2.65739D-03	6.14035D-14	1.26131D-05
39.0	1.50678D-04	2.80807D-03	3.68045D-13	1.26131D-05
40.0	1.15180D-04	2.92325D-03	1.51192D-12	1.26131D-05
DEVIATION ON CUMULATIVE TOTALS =			9.76779D-05	9.59612D-06

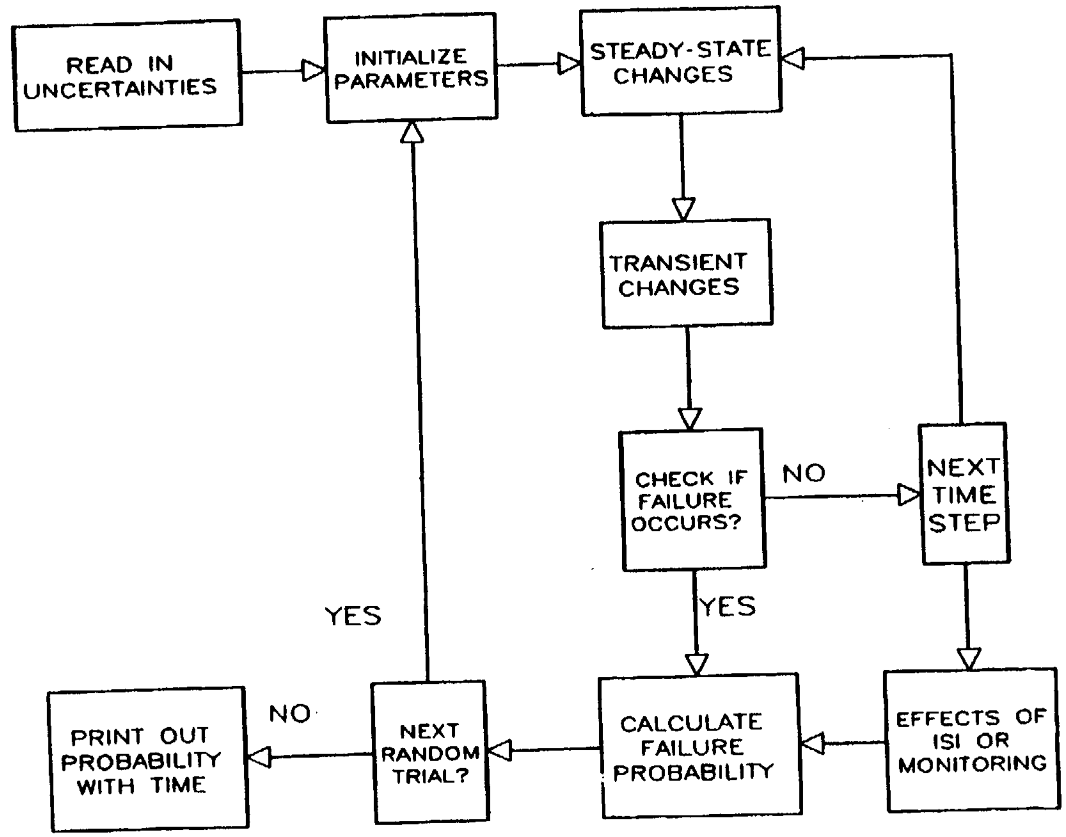


Figure 3-1 Flow Chart for LEAKPROF Piping SRRA Program

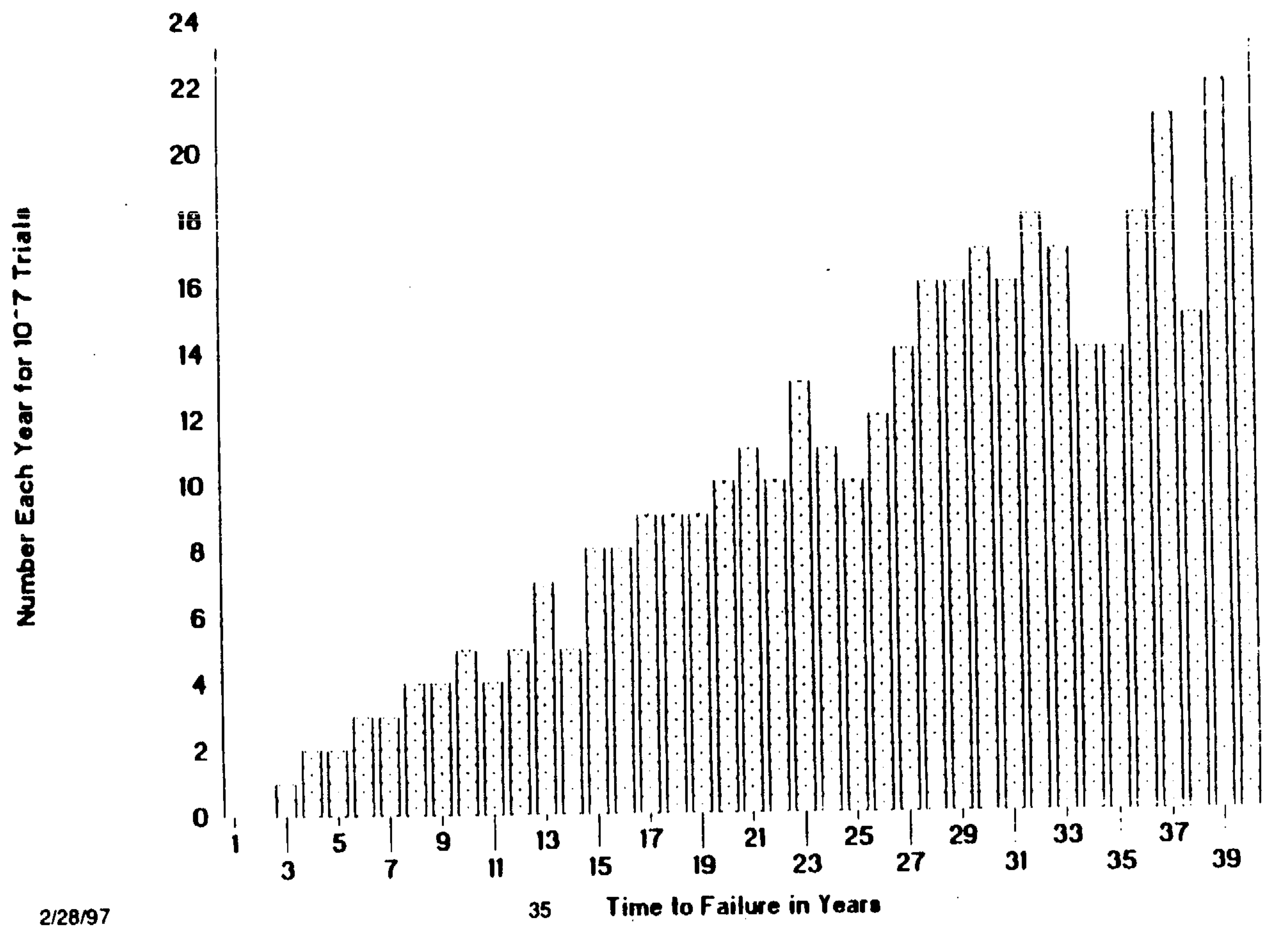


Figure 3-2 Example Histogram from SRRA

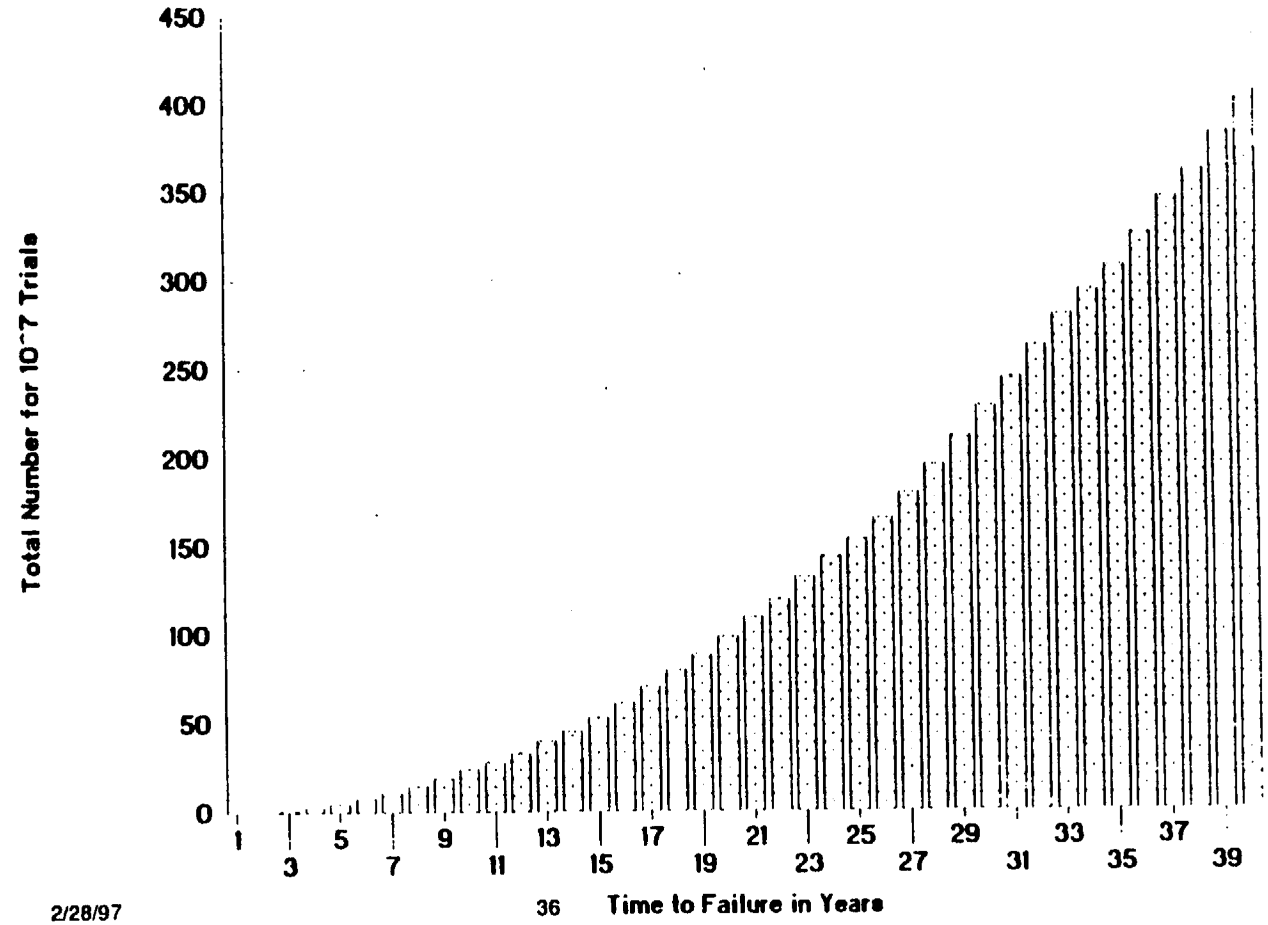


Figure 3-3 Example Cumulative Histogram from SRRA

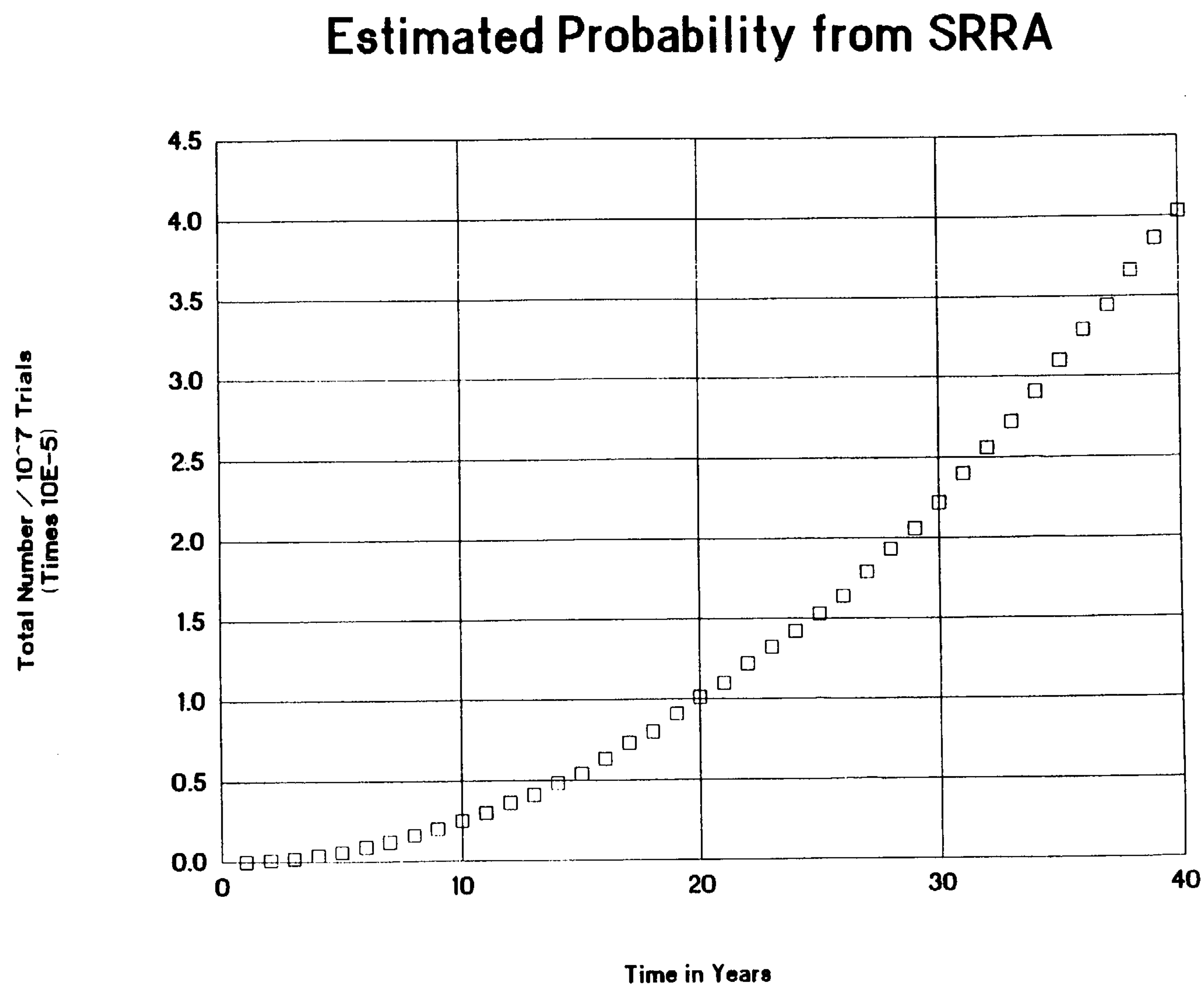


Figure 3-4 Example Estimated Probability from SRRA

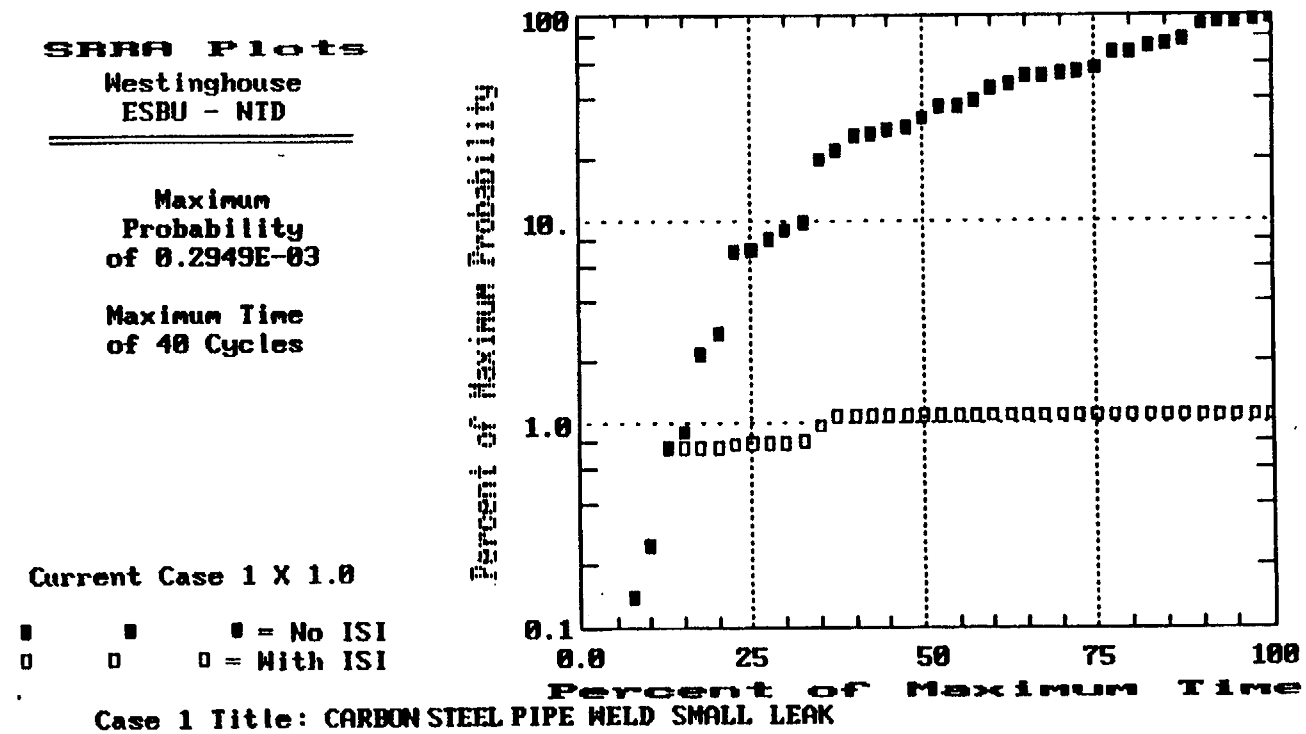


Figure 3-5 SRRA Plot of Example LEAKPROF Output

SECTION 4
SRRA BENCHMARKING AND UNCERTAINTIES

The probability of failure of the carbon and stainless steel piping as a function of operating time is calculated directly for each set of input values using Monte-Carlo simulation with importance sampling. The simulation does not force the calculated output probability distribution to be of a fixed type (e.g. Weibull, Log-normal or Extreme Value). The actual output distribution is calculated based upon the distributions of the uncertainties in the key structural reliability model parameters and plant specific input parameters.

4.1 ALTERNATIVE CALCULATIONS

To apply the simulation method, the existing Westinghouse PROF (probability of failure) Software System (object library) was combined with the piping structural reliability models described in Section 3. The PROF library provides standard input and output, including plotting, and probabilistic analysis capabilities (e.g. random number generation, importance sampling). The Westinghouse PROF Software Library, which was used to generate the LEAKPROF program used for piping RI-ISI, has been verified and benchmarked in a number of ways. Table 4-1 provides a comparison of probabilities from hand calculation for simple crack growth models, where the only random variables are the initial and limiting crack depths. The crack growth due to two independent mechanisms is deterministic (variables are constant). As can be seen in Table 4-1, the W-PROF calculated values agree very well (less than 4% error) for a number of different distributions and with the effects of importance sampling.

The calculation of failure probability using the W-PROF methods and importance sampling was also compared to that calculated by an alternative methods for more complex models. The more complex crack growth model included the uncertainties in growth rate, which were also a function of the crack depth. The alternative method was the @RISK add-in for Lotus 1-2-3 spreadsheets (Palisade Corporation 1992). As seen in Figure 4-1, the comparison of calculated probabilities is excellent at the low probability values, where importance sampling is normally used.

4.2 COMPARISON WITH DATA

The Westinghouse SRRA methodology has also been verified for two degradation mechanisms where there is sufficiently well defined failure data to make a meaningful comparison. Figure 4-2 shows the comparison of the SRRA model predictions (W-PROF CALCULATED) and industry plant data (ASME MIN. WALL DATA). This figure specifically compares the probability of violating the minimum wall thickness criteria with the cumulative industry ratio of the number of pipes replaced for this reason to the number of pipes inspected for potential wall thinning (flow assisted corrosion wastage). While not exact, the comparison is relatively good, considering the uncertainty in the input to the industry database compiled by EPRI (Mattu, 1988) (e. g. operating time and time of failure).

A comparison of the Westinghouse SRRA model predictions with the observed leak data due to intragranular stress corrosion cracking (IGSCC) is provided in Figure 4-3. This figure compares the data with predictions from more detailed pc-PRAISE (Harris, Dedhia and Lu 1992) models

for both initiation and growth with different residual stress factors (RSFs), from the SRRA models and from a Westinghouse modified version of PRAISE. This Westinghouse study and example results are described in the section entitled Evaluation of Corrective Actions Using SRRA (pp 93 & 96) in the ASME Risk-Based Inspection Guidelines for Nuclear Power Plant Components (ASME 1992).

In the verification of the simplified piping fracture mechanic (SPFM) structural reliability (SRRA) programs for risk based inspection (Bishop 1993, Bishop and Phillips 1993), the calculated small leak probabilities for thermal transient induced fatigue crack growth were compared with results from the pc-PRAISE program (Harris, Dedhia and Lu 1992). This program, which was developed by Lawrence Livermore National Laboratory for the NRC, is the benchmark standard for calculating the structural reliability of piping. As can be seen in Table 4-2, the comparison of calculated leak probabilities with the number of operating cycles (years), with and without the effects of inspection, was found to be excellent. Therefore, it was concluded that the Westinghouse SRRA methods employed in calculating piping leak probabilities with SPFMPROF were sufficiently verified and benchmarked for application to a piping risk based inspection program.

4.3 BENCHMARKING WITH PRAISE

The latest revised version of the piping SRRA software was also extensively benchmarked when sufficient failure data was not available, such as pipe breaks due to seismic induced loading of a fatigue crack. This benchmarking was achieved by comparison of the SRRA results with independent calculations. Table 4-3 describes the parameters that were used to benchmark some of the revised piping SRRA model results with pc-PRAISE (Harris, Dedhia and Lu 1992). As shown in Table 4-4, the variations in the parameters of Table 4-3 resulted in 23 cases being analyzed in the benchmarking study with the probability of three failure modes being calculated for each case: 1) small leak (through-wall crack), 2) large (system disabling) leak and 3) full break (unstable fracture). Deterministic analyses and comparisons of fatigue crack growth rates with time were also made and found to be similar for several of the cases. Table 4-5 and Figure 4-4 show the comparison of the calculated probabilities by the LEAKPROF and pc-PRAISE programs after 40 years of operation. As can be seen, the calculated values from the probabilistic fracture mechanics analyses for 40 years of operation agree very well. No changes in the SRRA models were required to obtain such good agreement with pc-PRAISE. More trials (Monte-Carlo simulations) and greater importance sampling were used for better accuracy in calculating the very low values of failure probability.

4.4 UNCERTAINTY IN CALCULATED PROBABILITY

Even with this benchmarking, there are questions about the uncertainty in the SRRA probability calculations for those cases where failure data is not available for comparison. There are three different types of uncertainties in the pipe failure probabilities that are estimated using the SRRA models and software. First, there is the inherent randomness in the material properties, flaw size distributions and pipe loading. These uncertainties, which are summarized in Table 3-8, are used to simulate a distribution in the times to failure from which the failure probability with time is estimated.

The second uncertainty is how well the probability can be modeled and calculated. Figures 4-2 and 4-3 provide comparisons of observed failure data with the calculated probabilities for flow assisted corrosion and stress corrosion cracking, respectively. Table 4-5 and Figure 4-4 provide the results of a benchmarking study where the same input is used to calculate failure probabilities using two different analysis codes (LEAKPROF and pc-PRAISE). The differences due to the uncertainties in this category are typically from ± a factor of 2 to ± one order of magnitude (maximum to minimum factor from 4 to 100).

The third type of uncertainty is that due to the lack of knowledge about what is the true behavior at the piping location being analyzed. This is the biggest uncertainty and represents the difference in the best-estimate failure probability prediction and the true failure probability. This difference is zero if, and only if, all the failure modes and degradation mechanisms are exactly as modeled and all the input variables, including their uncertainties, are correct, which is highly unlikely. Figure 2 from a Paper by Akiba (1994) shows almost four orders of magnitude difference in calculated leak probability for six different assumptions on the initial flaw depth distributions. Likewise, Figure 2-29 from the ASME Risk-Based Inspection Guidelines for Nuclear Power Plant Components (ASME 1992) shows a factor of 300 on break probability with leak detection for just two different initial flaw depth distributions.

This last type of uncertainty, which bounds all the other uncertainties, is also the most difficult to predict because the true state of the one piping location being analyzed is not really known. It can only be inferred from available data on similar piping material samples that have been measured or tested. In some cases, only engineering judgement has been used to estimate the median stress values and their uncertainties in the SRRA input. To provide an estimate of the 5% and 95% bounds on the SRRA calculated best-estimate probabilities (median 50% value assumed), the minimum and maximum values of probability from an expert panel elicitation for the Surry Unit 1 auxiliary feedwater system piping can be used. Figure 2-29 from the ASME Risk-Based Inspection Guidelines for Nuclear Power Plant Components (ASME 1992) shows a range from 2 to 5 orders of magnitude on the estimated failure frequency (probability per year). This uncertainty range is assumed to bound the uncertainty range on the SRRA calculated failure probabilities. Thus the 90% uncertainty bounds (5% lower and 95% upper) is estimated to be 2 to 5 orders of magnitude around the best-estimate value of failure probability.

A sensitivity study using pc-PRAISE (Harris, Dedhia and Lu 1992) on the effect of uncertainties was recently completed by ASME Research Task Force member Fred Simonen and Moe Khaleel of Battelle Pacific Northwest Laboratory. Figure 4-5, taken from this study, shows that the 99% uncertainty bounds on a typical pc-PRAISE (Harris, Dedhia and Lu 1992) calculation of leak probability decreases as the value of leak probability increases. These uncertainty bounds should be higher than the corresponding uncertainty bounds on a typical leak probability calculated with the revised SRRA program LEAKPROF. This is because many of the uncertainties not directly evaluated by pc-PRAISE, such as that on cyclic stress range, are already included in the standard SRRA software input (see Table 3-8).

Table 4-1
SIMPLE VERIFICATION OF RESULTS FOR WESTINGHOUSE PROF METHODS

Type of Distribution on Crack Depths (1)	Import. Sampling Shift (2)	Hand Calculated Prob. (3)	W-PROF Calculated Probability	Percent Error
Normal	0.0	0.1003	0.10004	-0.26
Normal	± 1.0	0.1003	0.09889	-1.41
Log-Normal	0.0	0.1003	0.09880	-1.50
Log-Normal	± 1.0	0.1003	0.09652	-3.77
Uniform	0.0	0.1003	0.10393	+3.62
Log-Uniform	0.0	0.1003	0.10018	-0.12
Weibull	0.0	0.0950	0.0934	-1.68

(1) Same type of distribution on random values of initial and limiting crack depths.

(2) Median value of initial depth shifted +1 standard deviation and median value of limiting depth shifted -1 standard deviation when importance sampling is used with less than half the number of trials.

(3) Calculated using stress-strength overlap techniques on crack depth.

Table 4-2 COMPARISON OF SMALL LEAK FAILURE PROBABILITIES				
Number of Cycles	No Inservice Inspection		With Inservice Inspection	
	pc-PRAISE	SPFMPROF	pc-PRAISE	SPFMPROF
8	4.55E-4	4.17E-4	4.55E-4	4.18E-4
16	6.28E-4	5.74E-4	5.07E-4	4.58E-4
24	8.09E-4	7.28E-4	5.14E-4	4.85E-4
32	9.54E-4	1.02E-3	5.15E-4	5.05E-4
40	1.05E-3	1.19E-3	5.15E-4	5.14E-4

Table 4-3 PARAMETERS USED FOR THE BENCHMARKING STUDY		
Type of Parameter	**Low Value**	**High Value**
Pipe Material	Ferritic	Stainless Steel
Pipe Size	6.625" O.D. 0.562" Wall	29.0" O.D. 2.5" Wall
Failure Modes	Small Leak, Through-Wall Crack	Full Break, Unstable Fracture
Last Pass Weld Inspection	No X-Ray	Radiographic
Pressure Loading	1000 psi	2235 psi
Low-Cycle Loading	25 ksi Range 10 cycles/year	50 ksi Range 20 cycles/year
High-Cycle* Loading	1 ksi Range 0.1 cycles/min.	20 ksi Range 1.0 cycles/sec.
Design Limiting Stress	15 ksi	30 ksi
Disabling Leak Rate	50 gpm	500 gpm
Detectable Leak Rate	None	3 gpm

* Notes:

Mechanical Vibration (low stress range and high frequency) for small pipe

Thermal Fatigue (high stress range and low frequency) for large pipe

Table 4-4

VALUE OF PARAMETERS FOR THE BENCHMARKING CASES

Case Number	Pipe Material	Pipe Size(1)	Slow(2) Transients	Fast(2) Transients	Design Stress	Detect Leaks?
1	Stainless	High	Low	None	Low	Yes
2	Stainless	High	High	None	Low	Yes
3	Ferritic	High	Low	None	Low	Yes
4	Ferritic	High	High	None	Low	Yes
5	Stainless	High	Low	None	Low	No
6	Stainless	High	High	None	Low	No
7	Stainless	High	Low	None	High	Yes
8	Stainless	High	High	None	High	Yes
9	Stainless	High	Low	None	High	No
10	Stainless	High	High	None	High	No
11	Stainless	High	None	Low	Low	Yes
12	Stainless	High	None	High	Low	Yes
13	Stainless	Low	Low	None	Low	Yes
14	Stainless	Low	High	None	Low	Yes
15	Stainless	Low	Low	None	Low	No
16	Stainless	Low	High	None	Low	No
17	Stainless	Low	Low	None	High	Yes
18	Stainless	Low	High	None	High	Yes
19	Stainless	Low	Low	None	High	No
20	Stainless	Low	High	None	High	No
21	Stainless	Low	None	Low	Low	No
22	Stainless	Low	None	High	High	No
23	Stainless	Low	Low	High	High	No

(1) Also indicates respective values of Inspection, Pressure and Disabling Leak Rate
(2) Indicates values of both Stress Range and Frequency

Table 4-5
COMPARISON OF CALCULATED PROBABILITIES AT 40 YEARS

Benchmark Case No.	Small Leak		Large Leak		Full Break	
	pc-PRAISE	LEAK PROF	pc-PRAISE	LEAK PROF	pc-PRAISE	LEAK PROF
1	1.4E-10	3.4E-09	2.9E-11	3.0E-10	2.4E-14	2.1E-16
2	6.5E-04	2.2E-04	1.9E-04	1.8E-04	5.7E-14	1.5E-13
3	1.6E-08	7.0E-08	2.5E-09	6.8E-08	4.6E-13	9.1E-13
4	2.7E-06	1.5E-05	8.7E-07	3.1E-06	7.4E-13	9.1E-13
5	3.5E-10	3.4E-09	3.5E-10	2.0E-09	1.4E-10	1.2E-09
6	6.1E-04	2.2E-04	6.1E-04	2.1E-04	6.0E-04	1.8E-04
7	4.9E-09	6.0E-08	3.6E-09	3.0E-08	1.6E-13	1.8E-14
8	3.1E-03	8.5E-04	3.1E-03	8.5E-04	2.0E-12	3.7E-14
9	6.5E-09	6.0E-08	6.5E-09	5.9E-08	4.3E-09	4.3E-08
10	9.1E-03	7.2E-04	3.1E-03	7.2E-04	3.1E-03	6.8E-04
11	1.6E-01	6.7E-02	-	-	-	-
12	9.9E-01	8.2E-01	-	-	-	-
13	1.6E-07	3.8E-07	2.8E-08	5.7E-08	7.2E-12	1.2E-13
14	5.1E-03	4.6E-03	1.7E-03	3.1E-03	2.9E-10	2.4E-12
15	8.9E-08	3.8E-07	7.0E-08	2.9E-07	1.6E-08	1.1E-07
16	4.7E-03	4.6E-03	4.7E-03	4.6E-03	4.1E-03	2.9E-03
17	7.3E-06	9.0E-06	7.6E-07	3.7E-06	6.7E-10	1.1E-11
18	1.4E-02	1.2E-02	1.3E-02	1.1E-02	1.8E-08	3.8E-09
19	7.3E-06	9.0E-06	3.7E-06	8.2E-06	3.5E-06	3.9E-06
20	1.4E-02	1.2E-02	1.4E-02	1.1E-02	1.2E-02	9.4E-03
21	1.9E-07	2.5E-07	-	-	-	-
22 & 23	7.1E-1	5.8E-01	-	-	-	-

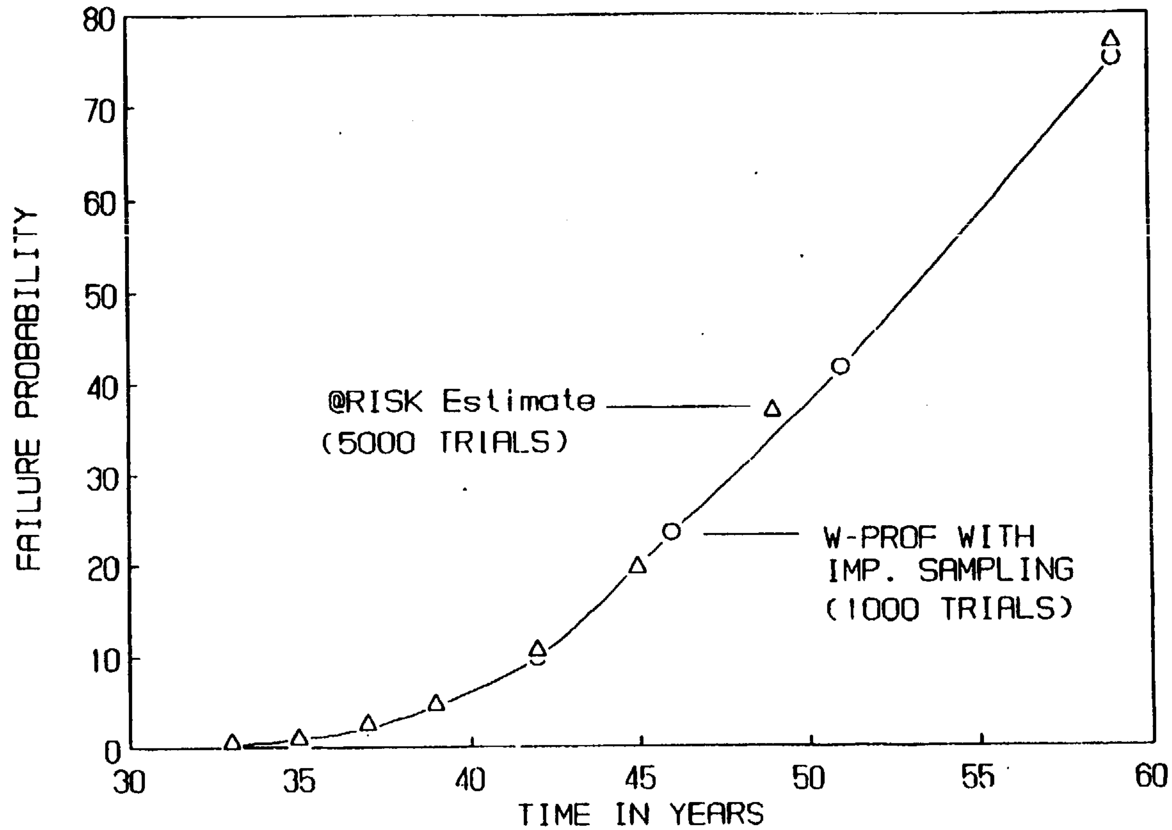


Figure 4-1 Importance Sampling Check of Westinghouse PROF Methods

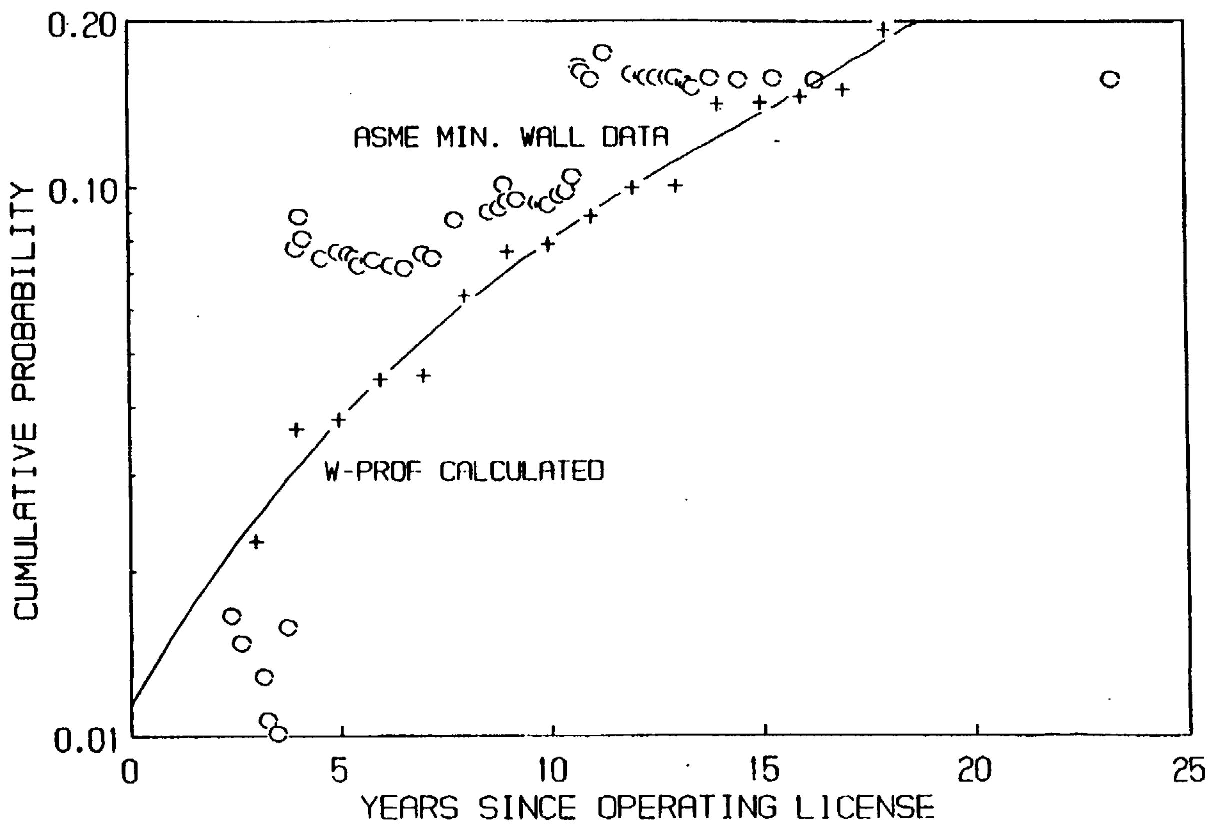
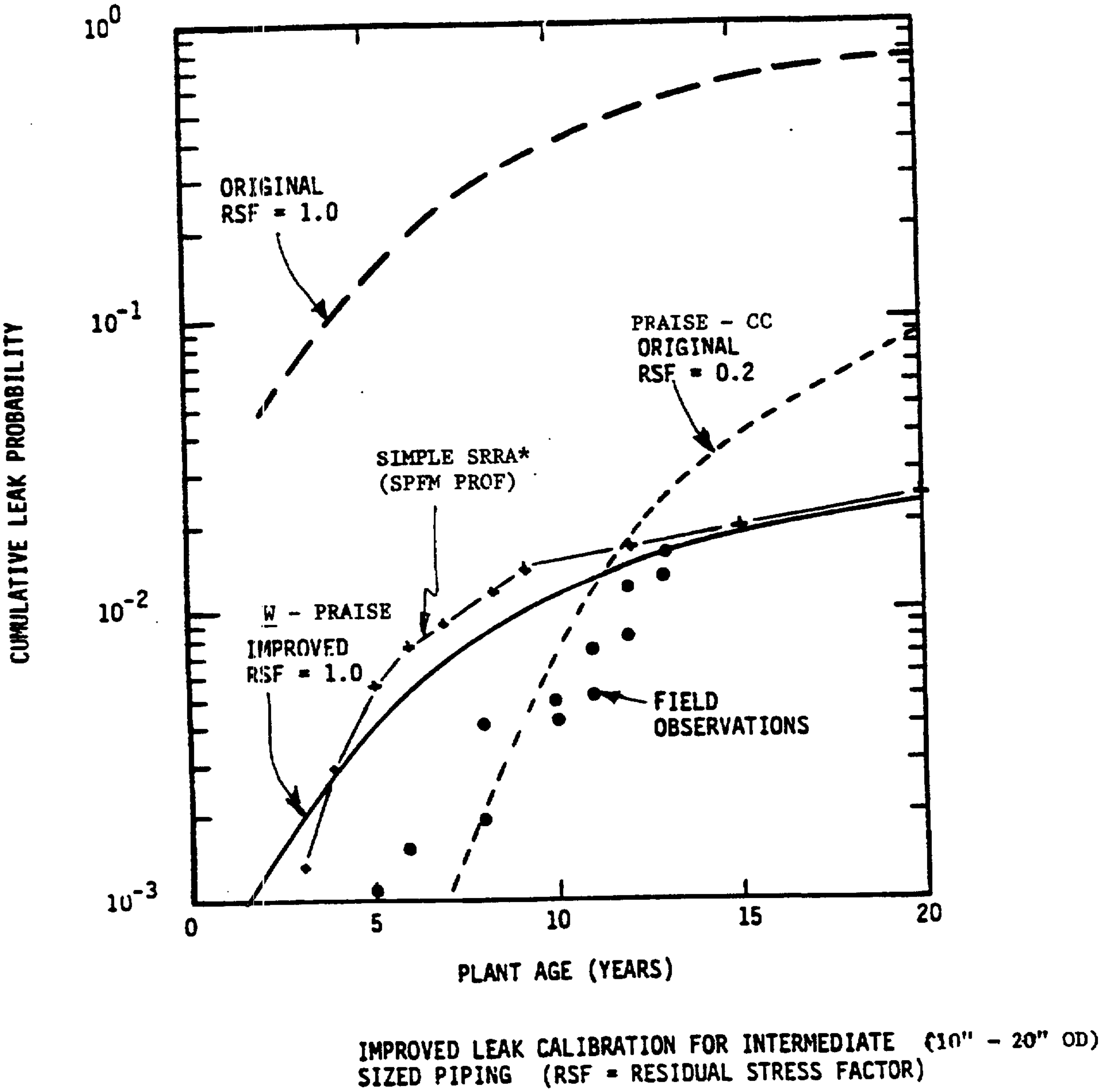


Figure 4-2 Comparison of SRRA Model With Flow Assisted Corrosion Data



*304SS leak with 15" OD, Max. IGSCC, Min. Inif Crack Depth (5% of wall) and residual stress of 9.3 ksi (same as Praise CC), no crack initiation and prob of crack existing = $10^{-4}/in^3$ of volume.

Figure 4-3 Comparison of SRRA Model With Stress Corrosion Cracking Data

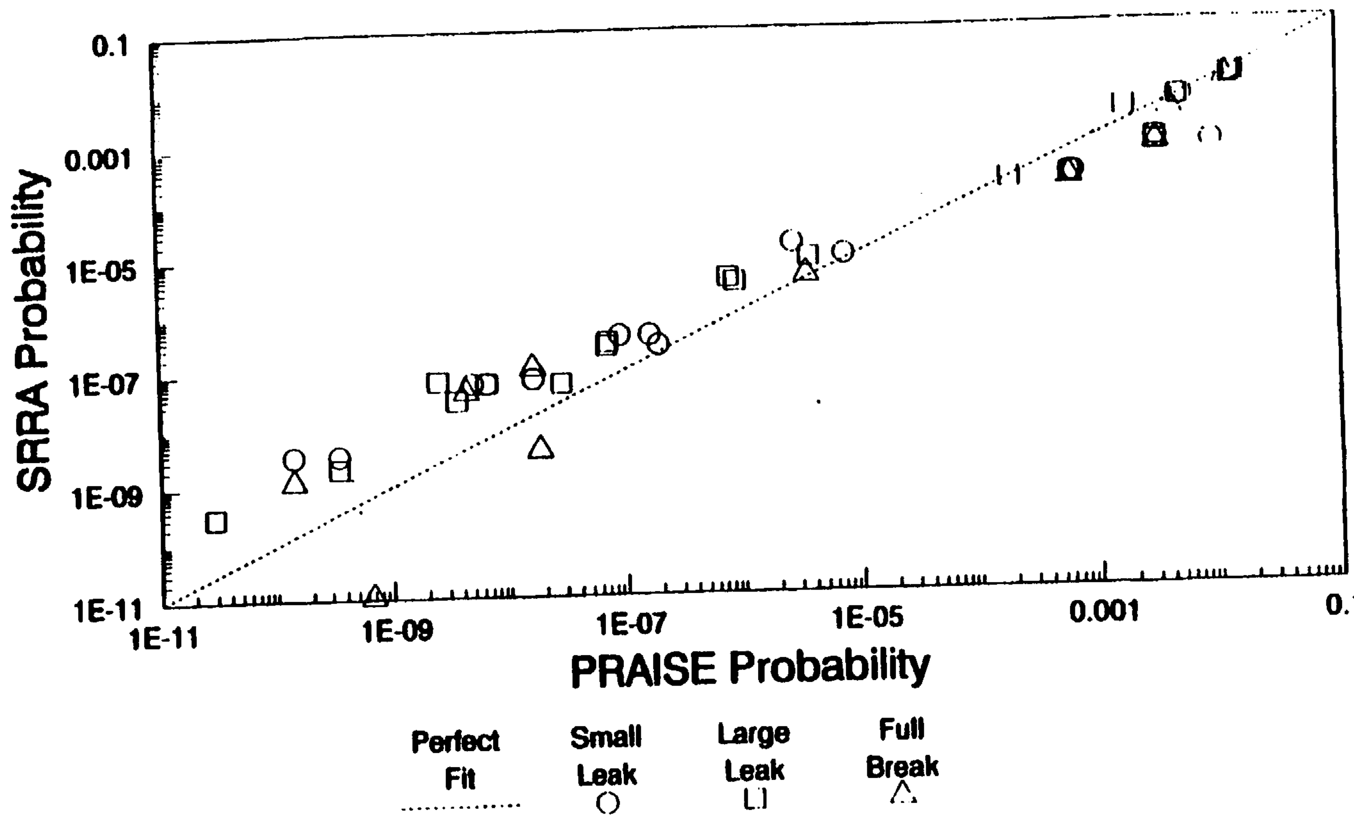


Figure 4-4 Results of the SRRA Benchmarking Study With pc-PRAISE

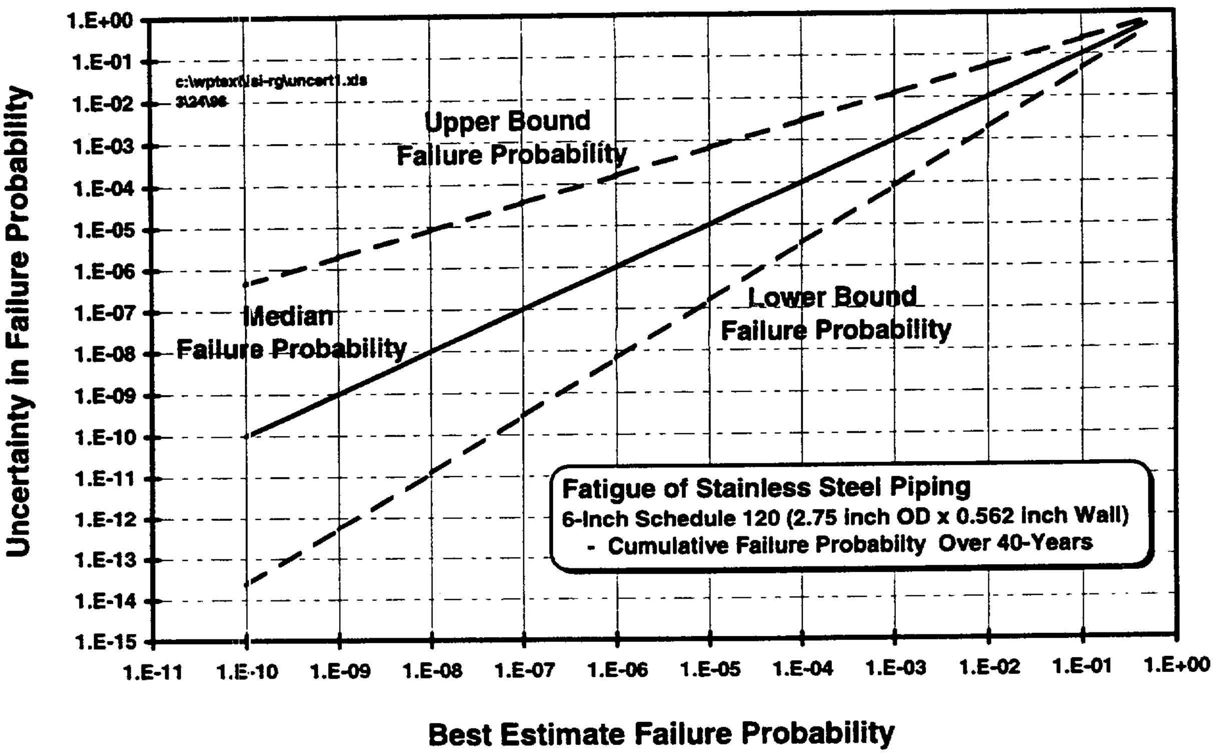


Figure 4-5 Uncertainties in Leak Probabilities for Stainless Steel Fatigue Calculated by PC-PRAISE (Khaleel and Simonen 1998)

SECTION 5
SUMMARY AND CONCLUSIONS

As described in Section 2, all model changes requested by the NRC reviewers and recommended by the ASME Research Task Force on Risk Based Inspection, including the new failure mode for a large leak and the optional credit for leak detection, have been incorporated into the latest piping SRRA models.

Input and output changes suggested by the utility users at the Millstone Unit 3 and Surry Unit 1 nuclear power plants have also been incorporated into the latest piping SRRA software, which is described in Section 3. The input and calculations for the new models and features, such as comparing the effects of leak detection and inspection on large leak probability, are still easy do with the latest SRRA software.

Comparisons with both available failure data and independent calculations were made to benchmark the SRRA calculated probabilities, as described in Section 4. A range of input parameters was used to successfully benchmark the small leak, large leak and full break probabilities from the latest SRRA models with those from pc-PRAISE for fatigue crack growth of an initial flaw.

The overall conclusion is that the latest piping structural reliability (SRRA) models for the WOG sponsored risk informed inservice inspection programs are technically robust and the SRRA software is still easy to use at the plant site.

SECTION 6
REFERENCES

Akiba, H., et al., "Probabilistic Fracture Mechanics Analyses of LWR's Pressure Vessels and Piping: A Sensitivity Study on Initial Crack Size," *Fatigue, Flaw Evaluation and Leak-Before-Break Assessments*, ASME PVP-Vol. 280, 1994.

American Society of Mechanical Engineers, "Risk-Based Inspection - Development of Guidelines, Volume 1, General Document," CRTD-Vol. 20-1, ASME Research Task Force on Risk-Based Inspection Guidelines, Washington, D.C., 1991.

American Society of Mechanical Engineers, "Risk-Based Inspection - Development of Guidelines, Volume 2 - Part 1, Light Water Reactor (LWR) Nuclear Power Plant Components," CRTD-Vol. 20-2, ASME Research Task Force on Risk-Based Inspection Guidelines, Washington, D.C., 1992.

Balkey, K. R., et al, "Westinghouse Owners Group - Application of Risk-Based Methods to Piping Inservice Inspection - Topical Report," Westinghouse Energy Systems Report WCAP-14572, Revision 0, 1996 (NON-PROPRIETARY).

Bamford, W. H., "Application of Corrosion Fatigue Crack Growth Rate Data to Integrity Analysis of Nuclear Reactor Vessels," pp 182-190, *Transactions of the ASME, Journal of Engineering Materials and Technology*, Vol. 101, 1979.

Bishop, B. A., Lapay, W.S., and Chay, S. C., "Reserve Strength as a Measure of Fragility," *Proceedings of the Workshop on Seismic and Dynamic Fragility of Nuclear Plant Components*, Brookhaven National Laboratory, U. S. NRC Report NUREG/CP-0070, 1985.

Bishop, B. A., "Final Report Documenting the Development of Piping Simplified Probabilistic Fracture Mechanics (SPFM) Models for EG&G Idaho, Inc.," Westinghouse Energy Systems, October, 1993

Bishop, B.A., and Phillips, J.H., "Prioritizing Aged Piping For Inspection Using a Simple Probabilistic Structural Analysis Model," *Reliability and Risk in Pressure Vessels and Piping*, ASME PVP-Vol. 251, 1993.

Bush, S. H., "Failure Rates in Nuclear Plant Piping Systems," *ASME Journal of Pressure Vessel Technology*, Vol. 114, 1992.

Chapman, O.J.V., "Simulation of Defects in Weld Construction," *Reliability and Risk in Pressure Vessels and Piping*, ASME PVP-Vol.251, 1993.

Chapman, O.J.V., Milner, R.T., and Baker, A.E., "Probability of Failure and Fatigue Life Monitoring for Life Extension," *Fatigue, Fracture and Risk*, - 1991, ASME PVP-Vol. 215, 1991.

Chexal, B. et al., "CHECWORKS Flow Accelerated Corrosion, Version 1.0F, User Guide," Final Report TR-103198-P1, Electric Power Research Institute, June, 1998.

Electric Power Research Institute, "Toughness of Austenitic Stainless Steel Pipe Welds, Report NP-4768, 1986.

Gamble, R. M., and Tagart, S. W. Jr., "A Method to Assign Failure Rates for Piping Reliability Assessments," *Fatigue, Fracture and Risk - 1991*, ASME PVP-Vol. 215, 1991.

Harris, D.O., Dedhia, D.D., and Lu, S.C., "Theoretical and User's Manual for pc-PRAISE, A Probabilistic Fracture Mechanics Computer Code for Piping Reliability Analysis," Lawrence Livermore National Laboratory, U.S. NRC Report NUREG/CR-5864, 1992.

Hazelton, W. S., and Koo, W.H., "Technical Report on Material Selection and Processing Guidelines for BWR Coolant Pressure Boundary Piping, U. S. NRC Report NUREG-0313, Rev. 2, 1988.

Keister, J., Chopra, O. K., and Shack, W.J., "Statistical Analysis of Fatigue Strain-Life Data for Carbon and Low Alloy Steels, U. S. NRC Report NUREG/CR-6237 (ANL-94/21), 1994.

Khaleel, M.A. and Simonen, F.A., "Uncertainty Analysis of Probabilistic Fracture Mechanics Calculations of Piping Failure Probabilities," pp. 2040-2045, *Probabilistic Safety Assessment and Management*, Volume 3, September 1998.

Kumar, V. et al., "Advances in Elastic-Plastic Fracture Analysis," Report NP-3607, Electric Power Research Institute, 1984.

Mattu, R. K., et al., "Utility Response to NRC Bulletin 87-01, Thinning of Pipe Walls in Nuclear Power Plants," Report NP-6066, Electric Power Research Institute, 1988.

Norris, D.M., and Chexal, B., "PICEP: Pipe Crack Evaluation Program," Report NP-3596-SR, Electric Power Research Institute, 1984.

Palisade Corporation, "@RISK, Risk Analysis and Simulation add-In for Lotus 1-2-3, Version 2.01 Users Guide," Newfield, NY, February 6, 1992.

Phillips, J. H., et al., "Investigation of the Risk Significance of Passive Components Using PRA Techniques," *Fatigue, Fracture and Risk - 1992*, ASME PVP-Vol. 241, 1992.

Thomas, H. M., "Pipe and Vessel Failure Probability," *Reliability Engineering*, Vol. 2, 1981.

Witt, F. J., "Development and Applications of Probabilistic Fracture Mechanics for Critical Nuclear Reactor Components," *Advances in Probabilistic Fracture Mechanics*, ASME PVP-Vol. 92, 1984.

Woo, H. H., and Chou, C. K., "Piping Reliability Model Validation and Potential Use for Licensing Regulation Development - Piping Reliability Project," U. S. NRC Report NUREG/CR-2801, 1983.

Woo, H. H., and Simonen, F. A., "The Impact of Inservice Inspection on the Reliability of Nuclear Piping," *Advances in Probabilistic Fracture Mechanics*, ASME PVP-Vol. 92, 1984.

Woo, H. H., Mensing, R. W., and Benda, B. J., "Probability of Pipe Failure in Reactor Coolant Loops of Westinghouse PWR Plants, Volume 2: Pipe Failure Induced by Crack Growth," U. S. NRC Report NUREG/CR-3660, Vol. 2, 1984.

and recommends other methods for use as needed.

A.21 Fatigue Crack Growth Rates

The equations used by the Westinghouse SRRA code to predict fatigue crack growth rates in both stainless and ferritic steels are the same equations used by the pc-PRAISE code. These equations represent the best available correlations for the statistical distributions of mean crack growth rates and for crack growth. On the basis of this review, the staff concludes that the SRRA code has an acceptable basis for simulating fatigue crack growth rates.

A.22 IGSCC Crack Growth Rates

The equations used in SRRA to relate crack tip stress intensity factors to growth rates for stress corrosion cracks are consistent with NRC staff evaluations of BWR piping performed in the 1980s. These equations provide an acceptable approach to predict bounding growth rates for sensitized stainless steel welds in BWR water environments.

The equations implemented in the SRRA code do not provide a mechanistic basis to address stress corrosion cracking under less aggressive conditions. Limitations of the equations are acknowledged in the code documentation provided in WCAP-14572, Revision 1, Supplement 1. A code user is guided to apply knowledge of the materials/welding variables and of the plant operating conditions in combination with engineering judgement to estimate crack growth rates relative to the bounding rates incorporated into the SRRA code. The user is also guided in this difficult task with the option to assign a high, medium, or low category for the crack growth rates. With this option the code internally assigns the numerical parameter which is applied as a multiplying factor to the bounding crack growth rates.

A.23 Wall Thinning Rates

The Westinghouse SRRA code estimates wall thinning rates using a statistical correlation (mean of 0.0095 inch per year and standard deviation of 0.893 inch per year) of field measurements of thinning rates from piping subject to flow-assisted corrosion. These measured rates were from selected piping locations which had sufficient wall thinning to violate minimum wall thickness requirements and thus result in replacement of the piping.

The user of the code must apply knowledge of the piping materials, operating conditions, and (if possible) plant-specific measurements of thinning rates to assign each pipe location to the categories of high, medium, and low thinning rates. The high category corresponds to the statistical data correlation contained in the code, with the other categories corresponding to internally assigned multiples of this reference thinning rate.

Plant technical staff will typically have data available from existing programs for augmented inspection and the management of wall thinning for piping systems at their plants. In these cases, the user can override the parameters corresponding to the three standard categories,

and directly assign input to describe the best estimate and uncertainty in the thinning rates. These assignments can be based on location specific wall thickness measurements, predictions of thinning rates such as by the CHECKWORKS code, or can be based on other sources of knowledge and/or engineering judgement.

With proper inputs, the code provides a useful tool to assist in estimating piping failure probabilities attributable to wall thinning. Before issuing this SER, the staff had identified an open item that Westinghouse should expand the code documentation to provide additional guidance for selecting the input for the calculation. In the public meeting on September 22, 1998 [item 15(b), Ref. 8], Westinghouse stated that the next Revision of WCAP-14572, Supplement 1, will provide detailed guidelines for simplified input variables and any associated assumptions that could be important in assigning the input values for the SRRA code. WCAP-14572 will also state that if more than one degradation mechanism is present in a given segment, the limiting input values for each mechanism should be combined so that a limiting failure probability is calculated for risk ranking. The staff finds the guidance in item 15(b), Ref. 8 to be acceptable because it provides sufficient guidance for the code user for selecting input parameters. The staff's approval is conditioned upon Westinghouse making the change to WCAP-14572 described above.

A.24 Material Property Variability

Variability and uncertainties in certain material properties have a large influence on calculated failure probabilities. Nonetheless it is appropriate for probabilistic structural mechanics codes to treat some material properties as deterministic, while the variability and uncertainty in other properties must be simulated in the probabilistic model. Experience has shown that it is critical to treat the material input parameters associated with crack growth rates, fracture toughness, and strength levels as random variables.

The SRRA code treats probabilistically the important parameters which describe material properties. The staff finds that the code provides an acceptable basis to account for uncertainties in material-related characteristics since the code documentation clearly indicates which material properties are treated in a probabilistic manner and which parameters are treated as deterministic inputs.

A.25 SUMMARY AND CONCLUSIONS

This review concludes that the Westinghouse SRRA code provides an acceptable method that can be used, in combination with trends from data bases and insights from plant operating experience, for estimating piping failure probabilities. The underlying deterministic models used by the code are based on sound engineering principles and make use of inputs which are within the knowledge base of experts that will apply the code. Effects of variability and uncertainties in code inputs are simulated in a reasonable manner. The documentation for the SRRA computer code shows examples where the code has been benchmarked against other computer codes and validated with service experience.

While the SRRA code can be applied as a useful tool for estimating piping failure probabilities,

the present review has identified a number of limitations in the types of calculations that can be performed by the code. Some of the concerns which users of the code must be aware include:

- The quality and usefulness of results from the SRRA code are very dependent on the quality of inputs provided to the code. It is important that users of SRRA be adequately trained in the features and limitations of the code, and have the access to detailed information of the plant specific piping systems being modeled.

- The results of SRRA calculations should always be reviewed to ensure that they are reasonable and consistent with plant operating experience. Data from plant operation should be used to review and refine inputs to calculations. In all cases, greater confidence should be placed in relative values of calculate failure probabilities than on absolute values of these probabilities.

- The stresses used for plant specific applications should be based on actual plant experience and operational practices (including thermal and vibrational fatigue stresses), which may differ from the stresses used for purposes of the original design of the plant.

- The present review describes some numerical difficulties and issues encountered in comparing break probabilities for the fatigue of stainless steel piping when leak detection was included in the calculations. Nevertheless, the present review agrees with the overall conclusion as stated by Westinghouse, that the calculations did successfully benchmark the calculations for the small leak, large leak, and full break probabilities.

- The simplified nature of the SRRA code has resulted in a number of conservative assumptions and inputs being used in applications of the code. It is therefore recommended that sensitivity calculations be performed to ensure that excessive conservatism does not unrealistically impact the categorization and selection of piping locations to be inspected.

- The model of piping fatigue and stress corrosion cracking by the SRRA code addresses only failures due to the growth of preexisting fabrication flaws and does not address service induced initiation of cracks. Given plant operating experience which shows that piping failures by fatigue and IGSCC are very often due to initiated cracks, the prediction of failure probabilities for these degradation mechanisms will often be better addressed by other methods and/or other computer codes, such as pc-PRAISE

- The SRRA model for flow assisted corrosion and wastage only addresses the variability in wall thinning rates, and assumes that the user has a basis for assigning values for expected or nominal thinning rates. Application of the SRRA model should be made within the context of existing plant programs for the inspection and management of wall thinning of piping systems. The SRRA code can be applied most effectively if there are means to estimate the thinning rates, based, for example, on data collected from wall thinning measurements or from predictions of computer codes such as the EPRI developed code CHECKWORKS.

- The pilot applications of the SRRA code to risk-informed ISI as described in WCAP-14572 represent a new and evolving application of the probabilistic structural mechanics technology. Lessons learned from the pilot applications and consideration of the code limitations as identified in the present review should be used to guide the future development and

enhancement the SRRA code.

A.26 REFERENCES for APPENDIX A

Bishop. B.A., "An Updated Structural Reliability Model for Piping Risk-informed ISI," ASME PVP Vol. 346, pp. 245-252, *Fatigue and Fracture - Volume 2, 1997.*

Chexal, B, et al., "*CHECWORKS Computer Program User Guide*, Report TR-103496, EPRI, December 1993.

Harris, D.O., and D. Dedhia, "*Theoretical and Users Manual for pc-PRAISE, a Probabilistic Fracture Mechanics Computer Code for Piping Reliability Analysis*," NUREG/CR-5864, U.S. Nuclear Regulatory Commission, Washington, D.C., 1991.

Hazelton, W.S., and W.H. Koo, "*Technical Report on Material Selection and Processing Guidelines for BWR Coolant Pressure Boundary Piping*," NUREG-0313, Revision 2, U.S. Nuclear Regulatory Commission Report, 1988.

Khaleel, M.A., and F. A. Simonen, "Effects of Through-Wall Bending Stresses on Piping Failure Probabilities," ASME PVP, Vol. 346, pp. 217-224, *Fatigue and Fracture - Volume 2*, 1997.

EXECUTIVE SUMMARY

The structural reliability and risk assessment (SRRA) models and software that are used for the evaluation of piping risk-informed inservice inspection (RI-ISI) have been developed to allow traditional engineering information to be converted into a probability of failure with time, including any effects of inservice inspection (ISI). This supplement to revision 1 of WCAP-14572 describes these SRRA models and associated software and how they were developed.

All model changes requested by the NRC reviewers and recommended by the ASME Research Task Force on Risk-Based Inspection, including the new failure mode for a large leak and the optional credit for leak detection, have been incorporated into the latest piping SRRA models.

Input and output changes suggested by the utility users at the Millstone Unit 3 and Surry Unit 1 nuclear power plants have also been incorporated into the latest piping SRRA software. Example input and calculations shows that the latest SRRA software is still easy to use, even with all the new models and features.

Comparisons with both available failure data and independent calculations were made to benchmark the SRRA calculated probabilities. A range of input parameters was used to successfully benchmark the small leak, large leak and full break probabilities from the SRRA models with those from pc-PRAISE for fatigue crack growth of an initial flaw.

The overall conclusion is that the latest piping SRRA models for the Westinghouse Owners Group sponsored risk informed inservice inspection programs are technically robust and the SRRA software is still easy to use at the plant site.

ACKNOWLEDGEMENTS

In addition to the SRRA expert panel members at the Millstone Unit 3 and Surry Unit 1 nuclear power plants and the members of the ASME Research Task Force on Risk-Based Inspection, who are acknowledged in WCAP-14572, the author wishes to thank C. Y. Yang, T. P. O'Donnell and T. S. Senkewitz for their assistance in preparing and verifying this supplement and the supporting calculations.

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SECTION 1
BACKGROUND AND INTRODUCTION

The structural reliability and risk assessment (SRRA) models that are used for the evaluation of piping risk-informed inservice inspection (RI-ISI) have been developed to allow traditional engineering information to be consistently converted into a probability of failure with time, including any effects of inservice inspection (ISI). Tables 1-1 and 1-2 provide guidance on the expertise and information needed to generate the SRRA input for the limiting location in a given piping segment. A segment is defined in the RI-ISI process supported by the Westinghouse Owners Group (WOG) as the length of piping where a failure would result in essentially the same consequences. This report supplement describes these SRRA models and associated software and how they were developed.

1.1 ORIGINAL MODELS

The original simplified structural reliability models (Bishop 1993, Bishop and Phillips 1993) were developed for prioritizing the inspection of aged piping in nuclear power plants. The philosophy used for the development of these simplified SRRA models was as follows:

1. The primary purpose is to allow deterministic engineering inputs, including insights from plant/industry failure data, to be consistently converted to probability with time.

2. Only the predominant material failure modes (fatigue, stress corrosion cracking and wastage) need to be considered. Others can be evaluated by special purpose tools or expert engineering judgment.

3. When failure would be of concern, calculated probabilities must agree with expected results (e.g. data for flow assisted corrosion, pc-PRAISE for fatigue). Accuracy below 1E-08 should not be required.

4. Software must allow easy input changes and run fast so that questions about the input can be resolved by trying different values (i.e., sensitivity studies).

5. Any simplifying assumptions must err on the conservative side, especially when the detailed alternative would be more difficult to justify.

6. Software and its documentation is to be publicly available and be compatible with the expected users at the utility office or plant site.

7. Use experience and results from previous probabilistic fracture mechanics analyses to define default input unfamiliar to the expected users (e.g. uncertainties, importance sampling).

8. Also provide capability to change standard input uncertainties if required statistical information is available.

9. To avoid misuse of calculated results, especially large failure probabilities, they need to be reduced by the probability of flaw existence, and the break probability needs to be reduced by the probability of the design limiting event.

1.2 USE OF ORIGINAL MODELS

Some of these original SRRA models were used at a WOG sponsored reference plant application of risk-informed piping inspection. The reference plant, Northeast Utilities Millstone Unit 3 nuclear power plant (NPP), used the simplified input but not the simplified output portion of these SRRA models. Only the normal SRRA calculational methods, Monte-Carlo simulation with importance sampling, were used. This limited use was because the simplified SRRA probability estimation techniques provided limited results when there were no predominant failure mechanisms and the calculated probabilities approach zero. The reference plant application at Millstone 3 was documented (Balkey et al. 1996) and submitted to the U.S. Nuclear Regulatory Commission (NRC) for information to assist them in their preparation of a standard review plan and regulatory guide on implementation of an acceptable risk-informed inservice inspection program. Based upon their experience using the SRRA software, Northeast Utilities prepared a list of suggested changes to improve the software and requested that a bounding probability value be estimated when there were no failures during the Monte-Carlo simulations. These changes were made and the modified SRRA software and training in its use were provided to the staff at Virginia Power, including NRC observers, for use in a WOG-sponsored validation and verification (V&V) pilot plant application for RI-ISI of piping at the earlier vintage Surry Unit 1 NPP.

1.3 MODEL CHANGES

Shortly after the Surry-1 V&V Program started, NRC's subcontractors reported differences in some of the values of failure probabilities calculated by the SRRA software versus results from pc-PRAISE (Harris, Dedhia and Lu 1992). The primary sources of the disagreement were traced to different inputs for the postulated initial flaw density and size distribution and to the credit being applied for leak detection prior to break. The SRRA models had not incorporated the new information on the distribution of flaws in welds and had conservatively taken no credit for leak detection. As a result of these findings, the Surry-1 V&V Program was delayed until an independent review of the SRRA methods was completed by the ASME Research Task Force that had developed the guidelines (ASME 1991) for risk-based inspection and the application guide for NPP components (ASME 1992). As a result of this review, a number of changes have been made to the SRRA models and software in three different categories:

1. New failure modes and conditions in the models,
2. New input options and standardized correlations and
3. More flexibility and simplification of the input

1.4 REPORT CONTENTS

These changes and their bases are summarized in Section 2. The latest SRRA models, the default input data sets and the corresponding failure probability calculations with time are

described in Section 3 and Appendix B. Section 4 summarizes the results of the extensive benchmarking with available failure data and pc-PRAISE (Harris, Dedhia and Lu 1992) for all the existing and new options in the SRRA software for piping RI-ISI, which is available upon request. Finally, in Section 5 it is concluded that the latest piping SRRA models for the WOG sponsored RI-ISI programs are technically robust and the SRRA software is still easy to use at the plant site.

Table 1-1
GUIDELINES ON INFORMATION REQUIRED TO SELECT LIMITING LOCATIONS AND ESTIMATE FAILURE PROBABILITIES

THERMAL-FLUIDS SYSTEM ANALYSIS

- Potential sources and locations of thermal striping or stratification
- Areas of high flow velocity or turning losses for vibration/wastage
- Stagnant flow zones and coolant chemistry for wastage/corrosion
- Location of high transient pressures or loads (e.g. water hammer)
- Steady-state and transient temperatures and gradients

DESIGN STRESS ANALYSIS

- Location of discontinuities, like snubbers, anchors, support lugs and dissimilar metal joints for high operating or cyclic stresses
- Location of any field welds or cold springing (residual stress)
- Areas of high thermal stress (low cycle fatigue)
- Locations with high transient loads (seismic)
- Sensitized material locations for potential stress corrosion

INSERVICE INSPECTION

- Locations with poor pre-service inspection (undetected flaws)
- Inspection locations now required by ASME Code, Section XI
- History of any indications in this or similar configurations
- Results of applicable Section XI flaw evaluations
- Accuracy of potential inservice inspection

OPERATIONS AND MAINTENANCE

- Any problems observed during fabrication, installation or hot functional testing of system
- History of any leaks or repairs in this or similar configurations
- Any observed failures or areas of high vibration
- History of snubber retesting or other support problems
- Any other maintenance problems of concern (valves, bellows, etc.)

Table 1-2
GUIDELINES TO SELECT LIMITING LOCATIONS AND ESTIMATE FAILURE PROBABILITIES

GENERAL CONSIDERATIONS

- The purpose of the piping inspection is to detect a small flaw before it becomes big enough to be a potential problem during a postulated design-limiting event, such as a safe-shutdown earthquake or loss of coolant accident.
- Locations to be considered are not only those where a small flaw might occur (mechanistic), but also where you would want to know about it (break potential) if one did occur for an unexpected reason.
- Also consider the effects of adjacent components not working properly on both the mechanistic approach (eg. snubber lockup or a leaking valve) and the break potential (eg. snubber not engaging).
- Since the initial flaw size is a fraction (11%) of the wall thickness, which is a specified fraction of the pipe size, larger and thicker pipes should have higher failure probabilities, all other factors being equal.

MECHANISTIC APPROACH

- For poor fabrication and pre-service inspection quality (initial flaws), look for field vs. shop welds and configurations that would be hard to maintain fabrication tolerances or to inspect. Lack of stress relief or cold springing could also lead to residual stresses for stress-corrosion cracking.
- For stress-corrosion cracking, high stresses (residual, steady-state, pressure), sensitized material (304 SS) and high coolant conductivity are all required.
- For material wastage, look for locations of relative support motion (wear), high pressure drop or turning losses (erosion-corrosion) or areas of stagnant coolant (microbiological attack) if the piping materials, especially at crevices, are susceptible to any of these wastage mechanisms.
- For high cycle fatigue, look for configurations susceptible to flow induced vibration and flow striping or for vibratory resonance with rotating equipment (pump) frequencies.
- For low cycle fatigue, look for areas with high loads due to thermal expansion (equipment nozzles and other anchor points, near snubbers, dissimilar metal joints) for heat-up and cool-down thermal cycling.

Table 1-2 (cont.)
GUIDELINES TO SELECT LIMITING LOCATIONS AND ESTIMATE FAILURE PROBABILITIES

BREAK POTENTIAL APPROACH

- Identify source of potentially limiting loads (eg. seismic, water hammer) and then the location of maximum loading if the source was to occur.
- If some new unexpected loading were to occur, what is the weakest point in the segment that would be inspected/checked for failure?
- Look at locations identified in the mechanistic approach to see if potential source loadings would still be high enough to be of concern.

REQUIRED INPUT DETAIL

- In general, the level of input detail should be commensurate with the importance associated with how the probability estimates are used.
- Qualitative values (high, medium or low) should be sufficient for ranking piping systems or segments.
- Standard numerical input values should still be sufficient for ranking of potential inspection locations in risk-significant piping segments
- Full menu input of median values or uncertainties should only be required for evaluating different inspection strategies or other mitigators for the most risk-significant locations.
- Calculated stresses from design analyses (per ASME Code) are assumed to be upper bound values with the median (expected) values one-half those values.

APPENDIX A

INSTRUCTIONS FOR THE

WESTINGHOUSE SRRA SOFTWARE

A - INSTRUCTIONS FOR RUNNING THE LEAKPROF PROGRAMS

The easiest way to start execution of the SRRA programs is to simply enter "RII in the hard disk subdirectory to which the files have been copied. The steps for running the LEAKPROF programs would be as follows:

1. Press Y for yes or N for no to review the input instructions. Use the page down keys to review the instructions then press "X" or "Esc" to end the review. The instructions can also be printed, if desired. Press Y for yes to (or N to not) install the MOUSEKEY program that allows a mouse to be used for input to the LEAKMENU Program. Next press Y for yes to (or N to not) install the DOS GRAPHICS program that allows the plots of failure probability to be printed. If this option is selected, then press Y(es) or N(o) for the LASERJETII type of printer. If this procedure is not acceptable, then use the TEDIT program or another text editing program to modify the supplied RII.BAT file.

2. The simplified input generation program LEAKMENU is then run for your plant specific piping segments using the instructions provided in Section B. After the input is completed, LEAKMENU optionally calls the PROFMENU program for more detailed input changes (see Section C). Either program automatically calls program LEAKPROF to calculate the probabilities and program SRRAPLOT to plot them with time (see Section D). When finished, all the generated output files can be reviewed (and printed) as described in Section E. The format of the input files is described in Section F.

B - INPUT INSTRUCTIONS FOR THE LEAKMENU PROGRAM

Input instructions are briefly summarized in the (yellow) message box at the bottom of the screen. The equivalent keys when using a mouse with the MOUSEKEY Program are indicated in the opening screen. You may also follow the detailed instructions in the steps below:

1. Press N to start with a new input set, Y to continue making cumulative changes to the previous input set or Q to quit the LEAKMENU Program.

2. The top line is the action option line. Use the right or left arrow keys to move from "Set Input" option to "Full Menu" or "Run PROF" options. The required actions for each option are include in the message box at the bottom of the screen.

3. To specify the input, which is the main purpose of the program, press the Enter or down arrow key at the "Set Input" option.

4. Use the right and left arrow keys to select the desired choice of three piping materials. Press the Enter or down arrow key to move to the next input parameter.

5. Use the right and left arrow keys to select the small or large leak (or break) failure modes. Press the Enter or down arrow keys to move on to the input parameters with numerical equivalents below.

6. Each of the numerical input parameters has three general values like "low", "medium" or "high" and an option to "Set Value". Use the right and left arrow keys for the desired choice and press the Enter or up or down arrow keys to move to the next desired input parameter. If the "Set Value" option is selected by an arrow key instead of the Enter key, a beep is sounded as a reminder that you might want to go back and change the numerical value of the previous input parameter.

7. If the "Set Value" option was selected in step 6, use the right and left arrow keys to select the desired numerical value, then press the Enter or up or down arrow keys to move to the next desired input parameter. If it is desired to return to the non-numeric general values of the current input parameter, simply press the Esc key.

8. If the choices of numerical values in the "Set Value" option of step 7 are not acceptable, pressing the Insert key will allow the desired numerical value to be entered directly. If the input is a stress ratio and the stress in ksi is between 1.5 and 100, its value may be entered directly. The program will then automatically calculate the ratio of the input stress value in ksi to the flow stress.

9. The simplified input parameters are translated into detailed input parameters for the LEAKPROF program using certain assumptions. If there is information available to support changing the detailed input, then it can be done using the "Full Menu" option (PROFMENU program of Section C). The following items describe the simplified input variables and any associated assumptions that could be important in assigning their input values. If more than one degradation mechanism is present in a given piping segment, then the limiting input values for each mechanism should be combined so that a limiting failure probability is calculated for risk ranking.

   a) The in-service inspection input is optional since it is used to evaluate the benefit of a proposed inspection program. See WCAP-14572 Supplement on specifying an appropriate accuracy (probability of detection). Note that the first inspection is assumed to be performed at 1/2 of the input interval. For a normal interval of 10 years, ISI would be assumed at the end of years 5, 15, 25 and 35.

   b) All piping material properties, except flow stress (approximate average of yield and tensile strengths), are assumed to be independent of temperature in the simplified SRRA input.

   c) LEAKMENU will automatically calculate the outside diameter (O.D.) and its uncertainty for the specified nominal pipe size (NPS). However, the actual pipe wall thickness to O.D. ratio must be used. A chart is available from Westinghouse for standard piping sizes and schedules.

   d) The welding residual stress is much more important for stress corrosion cracking the fatigue. The weld fabrication process, especially any post-weld heat treatment, should be considered in estimating its median value. The existing residual stress can also be reduced significantly due to mitigative actions, such as application of induction heating and mechanical stress improvement processes. Its value is always

truncated at a minimum value of 0 and at a maximum value of 90% of the flow stress (approximate yield strength) during the piping simulations in the LEAKPROF program.

e) The initial flaw conditions normally refers to whether radiographic (X-Ray NDE) was performed on the pipe weld, since this affects the flaw density (probability of initial flaw existing). One flaw should be specified when the flaw is assumed to be initiated by high-cycle secondary stresses (e.g. thermal striping) or by stress corrosion cracking. The initial flaw size and its uncertainty are automatically calculated for typical welds using results from PRODIGAL by Chapman.

f) The normal steady-state operating stress is the sum of the stresses due to operating pressure and deadweight and restraint of thermal expansion (DW & Thermal). All stresses that are specified as a ratio to the flow stress are assumed to be upper bound values from a conservative stress analysis. The uncertainty on these stresses assumes that the input median value is only one-half the upper bound value based on experience in performing stress analyses for nuclear plant piping systems. If all of the following conditions exist: the DW stresses are calculated using distributed values instead of point loading; actual support stiffnesses are used instead of assuming perfectly rigid (zero deformation) supports; actual operating conditions are used for calculation instead of design conditions; the DW and thermal stresses are calculated without any ASME Section III stress concentration factors for peak stresses, which are important for fatigue crack initiation but not for crack growth, then higher median values and lower uncertainty can be justified and used via the detailed input option.

g) The maximum stress corrosion cracking (SCC) potential of 1.0 is for fully sensitized SS in a BWR primary water environment. For the same potential, the SCC rates per K^2 for 304 SS, 316 SS and carbon steel are 3.59E-8, 3.24E-9, and 3.59E-11 inch/hour, respectively, where K is the stress intensity factor for pressure, DW & Thermal and residual stresses.

h) The maximum material wastage potential of 1.0 is for an industry average flow assisted corrosion rate of 9.5 mills per year. For example, if the plant's existing FAC control program indicated a 6-inch (NPS) schedule 40 carbon steel pipe (0.28" wall) would fully waste away in 120 years, then the average rate is 2.3 mills per year and the associated potential is approximately 0.25. For the same potential, the material wastage rates for 304 and 316 SS are assumed to be only 0.1% of that for carbon steel. When material wastage rates are high enough to proceed through the pipe wall, the probabilities of small leak, large leak and break are all calculated to be the same. For wastage due to flow assisted corrosion, the FAC module in the CHECWORKS Program System, which was developed for EPRI (TR-103198-P1, June 1998), can be used, with or without data from the plant's existing FAC control program, to estimate the average wastage rate and corresponding potential. However, if mitigative actions have been taken, such as replacement with a corrosion resistant material, then not taking any credit for it could be grossly conservative. For example, with a wastage potential of 1.0 with no credit taken, assuming the

mitigation action is 90% effective should result in a wastage potential of only 0.1 (or 0.01 for 99% effective) with significantly lower and more realistic SRRA calculated failure probabilities.

i) The high-cycle fatigue stresses due to mechanical vibration are specified for a small pipe size of 1 inch and corrected for the input pipe size. The logarithm of the correction factor varies linearly with pipe size from a factor of 1 at 1 inch to a factor of 1/6 at 10 inches. A factor of 1/6 is used for all pipe sizes above 10 inches. Failure occurs when the stress-intensity factor range (dK) exceeds the fatigue crack growth threshold at an R value (Kmin/Kmax) of 0.9.

j) Cyclic fatigue loading includes that due to thermal transients, like normal heat up and cool down or stratification, and that due to periodic seismic loading (e.g. OBE). Typically, the higher the degree of piping restraint, the higher the thermal stress range and the lower the seismic stress range. Both the vibratory and cyclic fatigue stress values should be input as a stress range, which is twice the stress amplitude that is sometimes calculated in the stress analysis. Therefore, the input median stress range would equal the calculated upper bound stress amplitude if the stress report loading were controlling.

k) The crack growth rate for cyclic fatigue loading is based upon an R value (see item i) of 0 for stainless steel and from 0 to 0.25 for carbon steel. If R values significantly different than this are known to exist, then correction of the input stress range is required. For stainless steel, an equivalent stress range can be calculated by simply dividing the value of the stress range by the square root of (1 - R).

l) The design limiting stress is typically provided for the event that would most likely challenge the structural integrity of the piping, such as an SSE, LOCA, or water hammer. It should be provided to check if full break is more limiting than the large system disabling leak. If the system disabling leak rate is set to 0 (none), only the full break probability is calculated. If the break probability turns out to be limiting, then the probability of the design limiting event occurring should also be factored into the failure probability value used for piping segment risk ranking.

m) If the minimum detectable leak rate is set to 0 (none), no credit is taken for leak before break or for small leak before large leak. Note that the design-limiting stress and the disabling and detectable leak rates are not used to calculate small leak (through-wall crack) probabilities.

n) If snubbers are included in the piping system, then the effects of the snubbers not working properly should also be considered. This could result in an increase in slow cycle fatigue loading (item j) if the snubbers lock up during normal thermal cycling or an increase in seismic loading (item l) if the snubbers do not lock up during unexpected rapid motion. In either of these cases, the SRRA calculated probability would have to be multiplied by the probability that the snubbers do not operate properly (e.g. 0.1 for 10%). The larger failure probabilities for either proper or improper snubber operation would then be used for segment risk ranking.

10. When all desired input parameters have been changed to their desired values, use the up or down arrow keys to return to the top option line. As an alternative, pressing the End key will move directly to the top option line.

11. Use the right or left arrow keys and then the Enter key to go directly to the LEAKPROF program or to go to PROFMENU for more detailed input changes first (follow instructions of Section C for PROFMENU). After a beep with all numeric input values shown on the screen, enter the segment identification for the indicated case number or press the Enter key for the default title. To avoid overwriting previous output files, the case number should not be allowed to exceed 99.

C - INPUT INSTRUCTIONS FOR THE PROFMENU PROGRAM

1. Enter C for color or M for monochrome monitor. From this point on in the PROFMENU program, input instructions are given in the yellow dialogue box at the bottom of the screen. To maximize the program's compatibility on all computers, it is recommended that all single-letter input to the PROFMENU Program be upper case.

2. Enter 1 to change title, 2 to 6 to change input to subroutines SET, ISI, SSC, TRC or FMD, respectively, or 7 to run the LEAKPROF program.

3. If 1 is entered, simply enter the new run title in the spaces indicated.

4. If 2 to 6 is entered in step 2, enter the variable number to change or press the Enter key to return to the main menu (step 2).

5. Once the selected variable is highlighted, enter M for median value, T for type of distribution and optionally (if not a constant) D for deviation or R for range.

6. If T is selected, enter C for constant, N for Normal, U for uniform or W for Weibull type of distribution. If asked, enter Y for yes if distribution is logarithmic or N if not.

7. If M, D or R is selected in step 5, enter D to double value, H to halve value, Z to set value to zero or enter any new value desired. To input new uncertainty values, the deviation (D in step 5) is defined as the difference between the (1-sigma) value at 84.1% probability and the median value (50% probability). The range (R in step 5) is defined as the difference between the maximum value at 100% probability and the median value.

8. When finished making changes on the selected variable, press the Enter key to return to the variable menu of step 4.

9. When all changes to the variables of the selected subroutine are completed, press the Enter key to return to the main menu.

10. When finished making changes to the input variables of the various subroutines, press the Enter key (or 7) to run the LEAKPROF program with the current set of input values.

D - INSTRUCTIONS FOR RUNNING LEAKPROF AND SRRAPLOT PROGRAMS

1. At the (yellow) prompt on the screen, press the Enter key one or more times to review the values the LEAKPPROF program is using for input. Note that the median value is the value for 50% cumulative probability and the uncertainty is normally specified as the equivalent deviation (difference between values at 84.1% and 50% probabilities). For a uniform distribution, the equivalent deviation is the difference between values at 100% and 50% probabilities. If the distribution is logarithmic, then the corresponding 1-sigma factor is ten raised to the power of the equivalent deviation.

2. Watch the number of failures and trails increase until the required number is obtained. Press the Enter key as prompted to review the calculated probabilities with time (cycles). Note that the first probability value on a given line is the probability that the pipe will fail during that cycle. The second value is the cumulative probability that the pipe will fail by the end of the indicated cycle; it is the summation of the probabilities that it will fail during this cycle and all the previous cycles. The third and fourth values of probability are like the first and second values, but include the effects of any inservice inspections.

3. Press any key when finished viewing the plot of cumulative failure probability with the number of operating cycles. If the DOS GRAPHICS command was loaded, pressing the Print-Screen key will print a copy of the plot shown on the screen.

E - INSTRUCTIONS FOR REVIEWING THE LEAKPROF OUTPUT

This set of instructions provides the opportunity to review, print and plot the output files from the current LEAKPROF program runs.

1. Press the page down key to review each output print file whose name is indicated on the highlighted line at the top of the screen. The coding for the file name is ??PROF??.Pnn, where, nn indicates the case number. Note that the previous set of output print files is automatically saved as ??PROF??.Snn. Each file contains both the numerical input for the LEAKMENU Program as well as the output from the corresponding LEAKPROF Program run. After each file is reviewed, press the "Esc" key to review the next print file. Pressing "X" will end the review of all output print files.

2. Press Y to (or N to not) print all the output files. If selected, enter the printer port (e.g. LPT2) or press the Enter key for the default (PRN).

3. Press Y for yes to (or N to not) run SRRAPLOT for additional plots.

4. If plotting is selected, enter the plot file name and optionally, a reference file name. The coding for the plot file name is ??PROF??.0nn, where nn indicates the case number. For example, entering "CSPROFLL.012,CSPROFSL.011" would plot case 12 for carbon steel

pipe large leak (or break) as the current case and case 11 for carbon steel pipe small leak as the reference case. The plot title can also be changed, if desired.

5. If the DOS GRAPHICS command was loaded, pressing the Print-Screen key will print a copy of the plot shown on the screen.

6. Press any key to end the current plot. New plot file names can then be entered when requested. Pressing the Enter key without any file names will end SRRAPLOT.

F- INSTRUCTIONS FOR CHANGING INPUT DATA FILES

While the LEAKMENU or PROFMENU program automatically specify the median values and distribution for many of the input variables to the LEAKPROF Program, it does not specify the other input variables that may need to be changed. To assist in changing the input data files, program TEDIT.COM is provided for this purpose. To use it, simply enter:

    >TEDIT FILENAME

where FILENAME is of the form ??PROF??.REF or ??PROF??.IN

To save the changed file and a backup (*.BAK) copy of the original file, simply press the F7 key when finished editing the file. The use of the other function keys is described on the line at the bottom of the screen. The letter of at the end of the line indicates whether the program is in Insert or Overstrike mode. The format of the PROF and MENU input files by line is:

1. NOCASE is the case number (should be left at 1 for MENU input)

2. NCYCLE is the number of cycles for calculation and output (a cycle may be more than one year, but the times for inspection must be specified by cycle no., not years)

3. NFAILS is the required number of failures for importance sampling

4. NTRIAL is the maximum number of Monte-Carlo simulation trials (overrides NFAILS)

5. NOVARS is the total number of subroutine input variables (40 maximum)

6+ NUM??? is the number of input variables for subroutines (??? =) SET, ISI, SSC, TRC and FMD, respectively (8 maximum, limit of 7 for MENU input)

11. Title of run and output file name (location of file name must not be changed since fixed format input is used for character variables)

12. Description of failure mode and output plot file name (same note as 11)

13+ VNAME, NO, ITYPE, ISUB, NSUB and DESCR for each variable, where

VNAME = 8 character variable name

NO = variable number (negative if not used or set to zero)

ITYPE = type of distribution (-2 is log-uniform, -1 is uniform,

0 is constant, 1 is normal, 2 is log-normal, 3 is Weibull)

ISUB = order of variable in subroutine (ITYPE of 0 if negative)

NSUB = subroutine number, in order of line 6+

14+ PARAM1, PARAM2, PARAM3 for each variable, where

PARAM1 = mean value or log (base 10) of median value if ITYPE +/-2

PARAM2 = deviation or half-range values (or logs if ITYPE +/-2)

PARAM3 = number of standard deviations the mean (median) value is shifted for Importance Sampling of (log)normal distribution

(CAUTION - use PARAM3 only on variables that contribute to failure)

APPENDIX B

SRRA OUTPUT FILES FOR

THE REFERENCE INPUT FILES

Output Print File for Input From CSPROFSL.REF

STRUCTURAL RELIABILITY AND RISK ASSESSMENT (SRRA)
WESTINGHOUSE PROBABILITY OF FAILURE PROGRAM LEAKPROF ESBU-NSD

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INPUT VARIABLES FOR CASE 1: CARBON STEEL PIPE WELD SMALL LEAK

NCYCLE =	40	NFAILS =	400	NTRIAL =	40000
NOVARS =	28	NUMSET =	6	NUMISI =	5
NUMSSC =	6	NUMTRC =	6	NUMFMD =	5

VARIABLE NO.	NAME	DISTRIBUTION TYPE	LOG	MEDIAN VALUE	DEVIATION OR FACTOR	SHIFT MV/SD	USAGE NO.	SUB
1	PIPE-ODIA	NORMAL	NO	5.5630D+00	2.4000D-02	.00	1	SET
2	WALL/ODIA	NORMAL	NO	5.0000D-02	1.5500D-03	.00	2	SET
3	SRESIDUAL	NORMAL	YES	1.0000D-03	1.4142D+00	.00	3	SET
4	INT%DEPTH	NORMAL	YES	3.4010D+01	1.2238D+00	2.00	4	SET
5	L/D-RATIO	NORMAL	YES	6.0000D+00	1.7126D+00	1.00	5	SET
6	FLAWS/IN	- CONSTANT -		4.5820D-03			6	SET
7	FIRST-ISI	- CONSTANT -		5.0000D+00			1	ISI
8	FREQ-ISI	- CONSTANT -		1.0000D+01			2	ISI
9	EPST-PND	- CONSTANT -		5.0000D-03			3	ISI
10	ASTAR-PND	- CONSTANT -		-2.4000D-01			4	ISI
11	ANUU-PND	- CONSTANT -		3.0000D+00			5	ISI
12	HOURS/YR	NORMAL	YES	7.4473D+03	1.0500D+00	.00	1	SSC
13	PRESSURE	NORMAL	YES	1.3000D+00	1.0323D+00	.00	2	SSC
14	SIG-DW&TH	NORMAL	YES	7.5184D+00	1.2599D+00	.00	3	SSC
15	SCC-COEFF	NORMAL	YES	3.5900D-14	2.3714D+00	.00	4	SSC
16	SCC-EXPNT	- CONSTANT -		2.1610D+00			5	SSC
17	WASTAGE	NORMAL	YES	1.2740D-09	2.3714D+00	.00	6	SSC
18	DSIG-VIBR	NORMAL	YES	4.5098D-04	1.3465D+00	.00	1	TRC
19	CYCLES/YR	- CONSTANT -		2.0000D+01			2	TRC
20	DSIG-FATG	NORMAL	YES	3.4174D+01	1.4142D+00	.00	3	TRC
21	FCG-COEFF	NORMAL	YES	6.7931D-13	1.7194D+00	1.00	4	TRC
22	FCG-EXPNT	- CONSTANT -		5.9500D+00			5	TRC
23	FCG-THOLD	- CONSTANT -		1.9000D+01			6	TRC
24	LDEPTH-SL	- CONSTANT -		-9.9900D-01			1	FMD
25	SIG-FLOW	NORMAL	NO	6.8349D+01	3.2000D+00	.00	2	FMD
26	STRESS-DL	- CONSTANT -		0.0000D+00			3	FMD
27	B-SDLEAK	- CONSTANT -		0.0000D+00			4	FMD
28	B-MDLEAK	- CONSTANT -		0.0000D+00			5	FMD

PROBABILITIES OF FAILURE MODE: THROUGH-WALL CRACK DEPTH FOR SMALL LEAK

NUMBER FAILED = 400 NUMBER OF TRIALS = 722

END OF CYCLE	FAILURE PROBABILITY WITHOUT FOR PERIOD	WITHOUT CUM. TOTAL	WITH INSERVICE INSPECTIONS FOR PERIOD	WITH INSERVICE INSPECTIONS CUM. TOTAL
1.0	1.37882D-07	1.37882D-07	1.37882D-07	1.37882D-07
2.0	7.45128D-07	8.83009D-07	7.45128D-07	8.83009D-07
3.0	8.20420D-07	1.70343D-06	8.20420D-07	1.70343D-06
4.0	3.93908D-07	2.09734D-06	3.93908D-07	2.09734D-06
5.0	9.42928D-06	1.15266D-05	9.42928D-06	1.15266D-05
6.0	9.00954D-06	2.05362D-05	4.50477D-08	1.15717D-05
7.0	2.34973D-05	4.40334D-05	1.17556D-07	1.16892D-05
8.0	1.50147D-05	5.90481D-05	7.50889D-08	1.17643D-05
9.0	1.33606D-05	7.24087D-05	6.70906D-08	1.18314D-05
10.0	6.41568D-06	7.88244D-05	3.20872D-08	1.18635D-05
11.0	2.73199D-05	1.06144D-04	1.45457D-07	1.20089D-05
12.0	2.42209D-05	1.30365D-04	1.23119D-07	1.21321D-05
13.0	1.47560D-05	1.45121D-04	7.39313D-08	1.22060D-05
14.0	3.10075D-05	1.76129D-04	1.56302D-07	1.23623D-05
15.0	4.41548D-05	2.20283D-04	2.28309D-07	1.25906D-05
16.0	3.60986D-05	2.56382D-04	9.40533D-10	1.25915D-05
17.0	7.73730D-05	3.33755D-04	2.17693D-09	1.25937D-05
18.0	5.92705D-05	3.93025D-04	1.53255D-09	1.25953D-05
19.0	8.98506D-05	4.82876D-04	2.72908D-09	1.25980D-05
20.0	1.07077D-04	5.89953D-04	3.10948D-09	1.26011D-05
21.0	3.56465D-05	6.25600D-04	1.04884D-09	1.26021D-05
22.0	1.71710D-05	6.42771D-04	5.05338D-10	1.26027D-05
23.0	2.22647D-05	6.65035D-04	7.04660D-10	1.26034D-05
24.0	1.09065D-04	7.74100D-04	3.76908D-09	1.26071D-05
25.0	9.64766D-05	8.70577D-04	5.03026D-09	1.26122D-05
26.0	1.06691D-04	9.77268D-04	1.68908D-11	1.26122D-05
27.0	1.08467D-04	1.08573D-03	2.38147D-11	1.26122D-05
28.0	8.62784D-05	1.17201D-03	3.80953D-11	1.26122D-05
29.0	3.35300D-04	1.50731D-03	1.81096D-10	1.26124D-05
30.0	2.48039D-04	1.75535D-03	4.44751D-11	1.26125D-05
31.0	2.60044D-04	2.01540D-03	1.74551D-10	1.26126D-05
32.0	8.06245D-05	2.09602D-03	5.74636D-11	1.26127D-05
33.0	1.73367D-04	2.26939D-03	3.83326D-10	1.26131D-05
34.0	1.53818D-04	2.42320D-03	4.73539D-11	1.26131D-05
35.0	2.70263D-05	2.45023D-03	5.93621D-12	1.26131D-05
36.0	1.23269D-04	2.57350D-03	1.14817D-13	1.26131D-05
37.0	6.85987D-06	2.58036D-03	4.38247D-15	1.26131D-05
38.0	7.70361D-05	2.65740D-03	6.14036D-14	1.26131D-05
39.0	1.50678D-04	2.80807D-03	3.68046D-13	1.26131D-05
40.0	1.15180D-04	2.92325D-03	1.51192D-12	1.26131D-05

DEVIATION ON CUMULATIVE TOTALS = 9.76780D-05 9.59613D-06

Output Print File for Input From CSPROFLL.REF

STRUCTURAL RELIABILITY AND RISK ASSESSMENT (SRRA)

WESTINGHOUSE PROBABILITY OF FAILURE PROGRAM LEAKPROF ESBU-NSD

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INPUT VARIABLES FOR CASE 1: CARBON STEEL PIPE WELD LARGE LEAK

NCYCLE =	40	NFAILS =	400	NTRIAL =	50000
NOVARS =	28	NUMSET =	6	NUMISI =	5
NUMSSC =	6	NUMTRC =	6	NUMFMD =	5

VARIABLE NO.	NAME	DISTRIBUTION TYPE	LOG	MEDIAN VALUE	DEVIATION OR FACTOR	SHIFT MV/SD	USAGE NO.	SUB
1	PIPE-ODIA	NORMAL	NO	5.5630D+00	2.4000D-02	.00	1	SET
2	WALL/ODIA	NORMAL	NO	5.0000D-02	1.5500D-03	.00	2	SET
3	SRESIDUAL	NORMAL	YES	1.0000D-03	1.4142D+00	.00	3	SET
4	INT%DEPTH	NORMAL	YES	3.4010D+01	1.2238D+00	2.00	4	SET
5	L/D-RATIO	NORMAL	YES	6.0000D+00	1.7126D+00	2.00	5	SET
6	FLAWS/IN	- CONSTANT -		4.5820D-03			6	SET
7	FIRST-ISI	- CONSTANT -		5.0000D+00			1	ISI
8	FREQ-ISI	- CONSTANT -		1.0000D+01			2	ISI
9	EPST-PND	- CONSTANT -		5.0000D-03			3	ISI
10	ASTAR-PND	- CONSTANT -		-2.4000D-01			4	ISI
11	ANUU-PND	- CONSTANT -		3.0000D+00			5	ISI
12	HOURS/YR	NORMAL	YES	7.4473D+03	1.0500D+00	.00	1	SSC
13	PRESSURE	NORMAL	YES	1.3000D+00	1.0323D+00	.00	2	SSC
14	SIG-DW&TH	NORMAL	YES	7.5184D+00	1.2599D+00	.00	3	SSC
15	SCC-COEFF	NORMAL	YES	3.5900D-14	2.3714D+00	.00	4	SSC
16	SCC-EXPNT	- CONSTANT -		2.1610D+00			5	SSC
17	WASTAGE	NORMAL	YES	1.2740D-09	2.3714D+00	.00	6	SSC
18	DSIG-VIBR	NORMAL	YES	4.5098D-04	1.3465D+00	.00	1	TRC
19	CYCLES/YR	- CONSTANT -		2.0000D+01			2	TRC
20	DSIG-FATG	NORMAL	YES	3.4174D+01	1.4142D+00	.00	3	TRC
21	FCG-COEFF	NORMAL	YES	6.7931D-13	1.7194D+00	1.00	4	TRC
22	FCG-EXPNT	- CONSTANT -		5.9500D+00			5	TRC
23	FCG-THOLD	- CONSTANT -		1.9000D+01			6	TRC
24	LDEPTH-SL	- CONSTANT -		0.0000D+00			1	FMD
25	SIG-FLOW	NORMAL	NO	6.8349D+01	3.2000D+00	.00	2	FMD
26	STRESS-DL	NORMAL	YES	1.7771D+01	1.4142D+00	.00	3	FMD
27	B-SDLEAK	- CONSTANT -		6.5731D+00			4	FMD
28	B-MDLEAK	- CONSTANT -		1.7477D+01			5	FMD

PROBABILITIES OF FAILURE MODE: EXCEED DISABLING LEAK RATE OR BREAK

NUMBER FAILED = 400 NUMBER OF TRIALS = 2314

END OF CYCLE	FAILURE PROBABILITY WITHOUT FOR PERIOD	CUM. TOTAL	AND WITH INSERVICE FOR PERIOD	INSPECTIONS CUM. TOTAL
1.0	3.18855D-10	3.18855D-10	3.18855D-10	3.18855D-10
2.0	3.28581D-11	3.51713D-10	3.28581D-11	3.51713D-10
3.0	2.53295D-08	2.56812D-08	2.53295D-08	2.56812D-08
4.0	2.65630D-09	2.83375D-08	2.65630D-09	2.83375D-08
5.0	3.50145D-09	3.18389D-08	3.50145D-09	3.18389D-08
6.0	4.16158D-09	3.60005D-08	2.08079D-11	3.18598D-08
7.0	2.49008D-08	6.09014D-08	1.24505D-10	3.19843D-08
8.0	2.73360D-07	3.34261D-07	1.36680D-09	3.33511D-08
9.0	5.53714D-08	3.89632D-07	2.76858D-10	3.36279D-08
10.0	1.79740D-08	4.07606D-07	8.98998D-11	3.37178D-08
11.0	3.22891D-07	7.30497D-07	1.61468D-09	3.53325D-08
12.0	3.05058D-08	7.61003D-07	1.60407D-10	3.54929D-08
13.0	1.13077D-07	8.74080D-07	5.65429D-10	3.60583D-08
14.0	1.05618D-07	9.79698D-07	5.42030D-10	3.66004D-08
15.0	8.30140D-08	1.06271D-06	4.23684D-10	3.70240D-08
16.0	3.46008D-07	1.40872D-06	8.68729D-12	3.70327D-08
17.0	1.28023D-07	1.53674D-06	3.20564D-12	3.70359D-08
18.0	6.77055D-07	2.21380D-06	1.69268D-11	3.70529D-08
19.0	2.20976D-07	2.43477D-06	5.53100D-12	3.70584D-08
20.0	2.32823D-07	2.66760D-06	5.86804D-12	3.70643D-08
21.0	9.91878D-07	3.65947D-06	2.48071D-11	3.70891D-08
22.0	8.18880D-07	4.47835D-06	2.05060D-11	3.71096D-08
23.0	1.04730D-07	4.58308D-06	2.66387D-12	3.71122D-08
24.0	7.09680D-07	5.29276D-06	1.77619D-11	3.71300D-08
25.0	8.09341D-07	6.10210D-06	6.02011D-11	3.71902D-08
26.0	8.08041D-07	6.91015D-06	1.09397D-13	3.71903D-08
27.0	1.68233D-06	8.59248D-06	2.11016D-13	3.71905D-08
28.0	4.42269D-06	1.30152D-05	5.54391D-13	3.71911D-08
29.0	3.52407D-07	1.33676D-05	4.45653D-14	3.71911D-08
30.0	2.33909D-06	1.57067D-05	3.03608D-13	3.71914D-08
31.0	1.31323D-06	1.70199D-05	1.64565D-13	3.71916D-08
32.0	6.30221D-07	1.76501D-05	7.95484D-14	3.71917D-08
33.0	2.04134D-07	1.78543D-05	2.58521D-14	3.71917D-08
34.0	3.12925D-06	2.09835D-05	4.34948D-13	3.71921D-08
35.0	5.06530D-07	2.14900D-05	6.34301D-14	3.71922D-08
36.0	1.73492D-06	2.32250D-05	1.17204D-15	3.71922D-08
37.0	6.07981D-06	2.93048D-05	3.87116D-15	3.71922D-08
38.0	5.33000D-06	3.46348D-05	3.60838D-15	3.71922D-08
39.0	3.05037D-06	3.76851D-05	1.94009D-15	3.71922D-08
40.0	1.47224D-05	5.24075D-05	9.42184D-15	3.71922D-08

DEVIATION ON CUMULATIVE TOTALS = 2.38367D-06 6.98168D-08

Output Print File for Input From CSPROFDL.REF

STRUCTURAL RELIABILITY AND RISK ASSESSMENT (SRRA)

WESTINGHOUSE PROBABILITY OF FAILURE PROGRAM LEAKPROF ESBU-NSD

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INPUT VARIABLES FOR CASE 1: CARBON STEEL PIPE WELD LARGE LEAK

NCYCLE =	40	NFAILS =	400	NTRIAL =	60000
NOVARS =	28	NUMSET =	6	NUMISI =	5
NUMSSC =	6	NUMTRC =	6	NUMFMD =	5

VARIABLE NO.	NAME	DISTRIBUTION TYPE	LOG	MEDIAN VALUE	DEVIATION OR FACTOR	SHIFT MV/SD	USAGE NO.	SUB
1	PIPE-ODIA	NORMAL	NO	5.5630D+00	2.4000D-02	.00	1	SET
2	WALL/ODIA	NORMAL	NO	5.0000D-02	1.5500D-03	.00	2	SET
3	SRESIDUAL	NORMAL	YES	1.0000D-03	1.4142D+00	.00	3	SET
4	INT%DEPTH	NORMAL	YES	3.4010D+01	1.2238D+00	2.00	4	SET
5	L/D-RATIO	NORMAL	YES	6.0000D+00	1.7126D+00	2.00	5	SET
6	FLAWS/IN	- CONSTANT -		4.5820D-03			6	SET
7	FIRST-ISI	- CONSTANT -		5.0000D+00			1	ISI
8	FREQ-ISI	- CONSTANT -		1.0000D+01			2	ISI
9	EPST-PND	- CONSTANT -		5.0000D-03			3	ISI
10	ASTAR-PND	- CONSTANT -		-2.4000D-01			4	ISI
11	ANUU-PND	- CONSTANT -		3.0000D+00			5	ISI
12	HOURS/YR	NORMAL	YES	7.4473D+03	1.0500D+00	.00	1	SSC
13	PRESSURE	NORMAL	YES	1.3000D+00	1.0323D+00	.00	2	SSC
14	SIG-DW&TH	NORMAL	YES	7.5184D+00	1.2599D+00	.00	3	SSC
15	SCC-COEFF	NORMAL	YES	3.5900D-14	2.3714D+00	.00	4	SSC
16	SCC-EXPNT	- CONSTANT -		2.1610D+00			5	SSC
17	WASTAGE	NORMAL	YES	1.2740D-09	2.3714D+00	.00	6	SSC
18	DSIG-VIBR	NORMAL	YES	4.5098D-04	1.3465D+00	.00	1	TRC
19	CYCLES/YR	- CONSTANT -		2.0000D+01			2	TRC
20	DSIG-FATG	NORMAL	YES	3.4174D+01	1.4142D+00	.00	3	TRC
21	FCG-COEFF	NORMAL	YES	6.7931D-13	1.7194D+00	2.00	4	TRC
22	FCG-EXPNT	- CONSTANT -		5.9500D+00			5	TRC
23	FCG-THOLD	- CONSTANT -		1.9000D+01			6	TRC
24	LDEPTH-SL	- CONSTANT -		0.0000D+00			1	FMD
25	SIG-FLOW	NORMAL	NO	6.8349D+01	3.2000D+00	.00	2	FMD
26	STRESS-DL	NORMAL	YES	1.7771D+01	1.4142D+00	.00	3	FMD
27	B-SDLEAK	- CONSTANT -		6.5731D+00			4	FMD
28	B-MDLEAK	- CONSTANT -		3.7257D+00			5	FMD

PROBABILITIES OF FAILURE MODE: EXCEED LARGE LEAK RATE (BREAK) BEFORE DL

NUMBER FAILED = 400 NUMBER OF TRIALS = 7859

END OF CYCLE	FAILURE PROBABILITY WITHOUT FOR PERIOD	AND CUM. TOTAL	WITH INSERVICE INSPECTIONS FOR PERIOD	CUM. TOTAL
1.0	4.60436D-07	4.60436D-07	4.60436D-07	4.60436D-07
2.0	1.09531D-09	4.61531D-07	1.09531D-09	4.61531D-07
3.0	1.91935D-09	4.63451D-07	1.91935D-09	4.63451D-07
4.0	2.54246D-09	4.65993D-07	2.54246D-09	4.65993D-07
5.0	4.07983D-09	4.70073D-07	4.07983D-09	4.70073D-07
6.0	7.36677D-08	5.43741D-07	3.68339D-10	4.70441D-07
7.0	3.19183D-09	5.46932D-07	1.59602D-11	4.70457D-07
8.0	7.80267D-09	5.54735D-07	3.90592D-11	4.70496D-07
9.0	1.22843D-08	5.67019D-07	6.15660D-11	4.70558D-07
10.0	1.43268D-08	5.81346D-07	7.17160D-11	4.70630D-07
11.0	1.74511D-08	5.98797D-07	8.73918D-11	4.70717D-07
12.0	6.47800D-09	6.05275D-07	3.25811D-11	4.70750D-07
13.0	8.18045D-09	6.13456D-07	4.10161D-11	4.70791D-07
14.0	5.38245D-09	6.18838D-07	2.74666D-11	4.70818D-07
15.0	9.17630D-09	6.28015D-07	4.62928D-11	4.70864D-07
16.0	3.10267D-08	6.59041D-07	8.58797D-13	4.70865D-07
17.0	7.34425D-09	6.66386D-07	1.86732D-13	4.70865D-07
18.0	4.59628D-09	6.70982D-07	1.36037D-13	4.70866D-07
19.0	4.55356D-08	7.16517D-07	1.14426D-12	4.70867D-07
20.0	7.75679D-09	7.24274D-07	5.48493D-13	4.70867D-07
21.0	2.12223D-10	7.24486D-07	5.62778D-15	4.70867D-07
22.0	2.70666D-09	7.27193D-07	7.09758D-14	4.70867D-07
23.0	8.73402D-09	7.35927D-07	2.55558D-13	4.70868D-07
24.0	2.28762D-08	7.58803D-07	6.17258D-13	4.70868D-07
25.0	3.34088D-08	7.92212D-07	8.43809D-13	4.70869D-07
26.0	1.39564D-08	8.06168D-07	1.77649D-15	4.70869D-07
27.0	1.97215D-07	1.00338D-06	2.93450D-14	4.70869D-07
28.0	1.15799D-08	1.01496D-06	1.79698D-15	4.70869D-07
29.0	3.61581D-10	1.01532D-06	5.49346D-17	4.70869D-07
30.0	2.49996D-09	1.01782D-06	3.55920D-16	4.70869D-07
31.0	1.53036D-08	1.03313D-06	1.97889D-15	4.70869D-07
32.0	5.55704D-09	1.03869D-06	7.06283D-16	4.70869D-07
33.0	1.62381D-08	1.05492D-06	3.39359D-15	4.70869D-07
34.0	2.58718D-09	1.05751D-06	3.44344D-16	4.70869D-07
35.0	3.06145D-09	1.06057D-06	5.39686D-16	4.70869D-07
36.0	8.35229D-11	1.06066D-06	6.42833D-20	4.70869D-07
37.0	5.41029D-08	1.11476D-06	3.39063D-17	4.70869D-07
39.0	3.73870D-08	1.15215D-06	2.51013D-17	4.70869D-07
40.0	0.00000D+00	1.15215D-06	0.00000D+00	4.70869D-07

DEVIATION ON CUMULATIVE TOTALS = 5.61257D-08 3.64449D-08

Output Print File for Input From CSPROFBL.REF

STRUCTURAL RELIABILITY AND RISK ASSESSMENT (SRRA)

WESTINGHOUSE PROBABILITY OF FAILURE PROGRAM LEAKPROF ESBU-NSD

INPUT VARIABLES FOR CASE 1: CARBON STEEL PIPE WELD LEAK OR BREAK

NCYCLE =	40	NFAILS =	400	NTRIAL =	10000
NOVARS =	28	NUMSET =	6	NUMISI =	5
NUMSSC =	6	NUMTRC =	6	NUMFMD =	5

VARIABLE NO.	NAME	DISTRIBUTION TYPE	LOG	MEDIAN VALUE	DEVIATION OR FACTOR	SHIFT MV/SD	USAGE NO.	SUB
1	PIPE-ODIA	NORMAL	NO	5.5630D+00	2.4000D-02	.00	1	SET
2	WALL/ODIA	NORMAL	NO	5.0000D-02	1.5500D-03	.00	2	SET
3	SRESIDUAL	NORMAL	YES	1.0000D-03	1.4142D+00	.00	3	SET
4	INT%DEPTH	NORMAL	YES	3.4010D+01	1.2238D+00	.00	4	SET
5	L/D-RATIO	NORMAL	YES	6.0000D+00	1.7126D+00	.00	5	SET
6	FLAWS/IN	- CONSTANT -		4.5820D-03			6	SET
7	FIRST-ISI	- CONSTANT -		5.0000D+00			1	ISI
8	FREQ-ISI	- CONSTANT -		1.0000D+01			2	ISI
9	EPST-PND	- CONSTANT -		5.0000D-03			3	ISI
10	ASTAR-PND	- CONSTANT -		-2.5000D-01			4	ISI
11	ANUU-PND	- CONSTANT -		3.0000D+00			5	ISI
12	HOURS/YR	NORMAL	YES	7.4473D+03	1.0500D+00	.00	1	SSC
13	PRESSURE	NORMAL	YES	1.3000D+00	1.0323D+00	.00	2	SSC
14	SIG-DW&TH	NORMAL	YES	7.5184D+00	1.2599D+00	.00	3	SSC
15	SCC-COEFF	NORMAL	YES	3.5900D-14	2.3714D+00	.00	4	SSC
16	SCC-EXPNT	- CONSTANT -		2.1610D+00			5	SSC
17	WASTAGE	NORMAL	YES	6.3700D-07	2.3714D+00	.00	6	SSC
18	DSIG-VIBR	NORMAL	YES	4.5098D-04	1.3465D+00	.00	1	TRC
19	CYCLES/YR	- CONSTANT -		2.0000D+01			2	TRC
20	DSIG-FATG	NORMAL	YES	2.0505D+01	1.4142D+00	.00	3	TRC
21	FCG-COEFF	NORMAL	YES	6.7931D-13	1.7194D+00	.00	4	TRC
22	FCG-EXPNT	- CONSTANT -		5.9500D+00			5	TRC
23	FCG-THOLD	- CONSTANT -		1.9000D+01			6	TRC
24	LDEPTH-SL	- CONSTANT -		-9.9900D-01			1	FMD
25	SIG-FLOW	NORMAL	NO	6.8349D+01	3.2000D+00	.00	2	FMD
26	STRESS-DL	NORMAL	YES	1.7771D+01	1.4142D+00	.00	3	FMD
27	B-SDLEAK	- CONSTANT -		1.7477D+01			4	FMD
28	B-MDLEAK	- CONSTANT -		1.7477D+01			5	FMD

PROBABILITIES OF FAILURE MODE: SMALL OR LARGE LEAK OR BREAK BY WASTAGE

NUMBER FAILED = 400 NUMBER OF TRIALS = 1231

END OF CYCLE	FAILURE PROBABILITY WITHOUT FOR PERIOD	CUM. TOTAL	AND WITH INSERVICE INSPECTIONS FOR PERIOD	CUM. TOTAL
2.0	8.12348D-04	8.12348D-04	8.12348D-04	8.12348D-04
3.0	8.12348D-04	1.62470D-03	8.12348D-04	1.62470D-03
4.0	8.12348D-04	2.43704D-03	8.12348D-04	2.43704D-03
7.0	2.49546D-03	4.93250D-03	1.24796D-05	2.44952D-03
8.0	4.06174D-03	8.99424D-03	2.03828D-05	2.46991D-03
9.0	3.24939D-03	1.22436D-02	1.67943D-05	2.48670D-03
10.0	7.36909D-03	1.96127D-02	4.29972D-05	2.52970D-03
11.0	5.68643D-03	2.52992D-02	4.62092D-05	2.57591D-03
12.0	6.49878D-03	3.17979D-02	8.91811D-04	3.46772D-03
13.0	5.68643D-03	3.74844D-02	1.52388D-04	3.62010D-03
14.0	5.04924D-03	4.25336D-02	6.29082D-04	4.24919D-03
15.0	3.24939D-03	4.57830D-02	6.91542D-04	4.94073D-03
16.0	6.55797D-03	5.23410D-02	1.96039D-05	4.96033D-03
17.0	8.93582D-03	6.12768D-02	2.76267D-05	4.98796D-03
18.0	8.18143D-03	6.94582D-02	1.91863D-05	5.00715D-03
19.0	1.13729D-02	8.08311D-02	1.87531D-05	5.02590D-03
20.0	1.38099D-02	9.46410D-02	4.27389D-05	5.06864D-03
21.0	4.12013D-03	9.87611D-02	1.24036D-05	5.08104D-03
22.0	5.68643D-03	1.04448D-01	2.08501D-05	5.10189D-03
23.0	1.05605D-02	1.15008D-01	3.58616D-05	5.13775D-03
24.0	1.38099D-02	1.28818D-01	4.23433D-05	5.18010D-03
25.0	8.18243D-03	1.37000D-01	2.41409D-05	5.20424D-03
26.0	1.05605D-02	1.47561D-01	1.94114D-07	5.20443D-03
27.0	1.14316D-02	1.58993D-01	1.81302D-07	5.20461D-03
28.0	1.39273D-02	1.72920D-01	2.29308D-07	5.20484D-03
29.0	1.13729D-02	1.84293D-01	2.89589D-07	5.20513D-03
30.0	1.14320D-02	1.95725D-01	3.50681D-07	5.20548D-03
31.0	1.21852D-02	2.07910D-01	1.74500D-07	5.20566D-03
32.0	8.12348D-03	2.16033D-01	1.97474D-07	5.20585D-03
33.0	1.29976D-02	2.29031D-01	4.55332D-07	5.20631D-03
34.0	1.05605D-02	2.39591D-01	2.13143D-06	5.20844D-03
35.0	8.24016D-03	2.47832D-01	4.47966D-07	5.20889D-03
36.0	1.14312D-02	2.59263D-01	5.29282D-09	5.20889D-03
37.0	1.54926D-02	2.74755D-01	2.43643D-08	5.20892D-03
38.0	9.80658D-03	2.84562D-01	2.25543D-08	5.20894D-03
39.0	1.38686D-02	2.98431D-01	8.11923D-09	5.20895D-03
40.0	1.21852D-02	3.10616D-01	3.31961D-08	5.20898D-03

DEVIATION ON CUMULATIVE TOTALS = 1.27656D-02 2.00654D-03

Output Print File for Input From S4PROFSL.REF

STRUCTURAL RELIABILITY AND RISK ASSESSMENT (SRRA)
WESTINGHOUSE PROBABILITY OF FAILURE PROGRAM LEAKPROF ESBU-NSD

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INPUT VARIABLES FOR CASE 1: 304 STAINLESS STEEL PIPE WELD SMALL LEAK

NCYCLE =	40	NFAILS =	400	NTRIAL =	40000
NOVARS =	28	NUMSET =	6	NUMISI =	5
NUMSSC =	6	NUMTRC =	6	NUMFMD =	5

VARIABLE NO.	NAME	DISTRIBUTION TYPE	LOG	MEDIAN VALUE	DEVIATION OR FACTOR	SHIFT MV/SD	USAGE NO.	SUB
1	PIPE-ODIA	NORMAL	NO	5.5630D+00	2.4000D-02	.00	1	SET
2	WALL/ODIA	NORMAL	NO	5.0000D-02	1.5500D-03	.00	2	SET
3	SRESIDUAL	NORMAL	YES	1.0000D-03	1.4142D+00	.00	3	SET
4	INT%DEPTH	NORMAL	YES	3.5792D+01	1.1947D+00	2.00	4	SET
5	L/D-RATIO	NORMAL	YES	6.0000D+00	1.7126D+00	1.00	5	SET
6	FLAWS/IN	- CONSTANT -		4.5820D-03			6	SET
7	FIRST-ISI	- CONSTANT -		5.0000D+00			1	ISI
8	FREQ-ISI	- CONSTANT -		1.0000D+01			2	ISI
9	EPST-PND	- CONSTANT -		1.0000D-03			3	ISI
10	ASTAR-PND	- CONSTANT -		-2.4000D-01			4	ISI
11	ANUU-PND	- CONSTANT -		1.6000D+00			5	ISI
12	HOURS/YR	NORMAL	YES	7.4473D+03	1.0500D+00	.00	1	SSC
13	PRESSURE	NORMAL	YES	1.3000D+00	1.0323D+00	.00	2	SSC
14	SIG-DW&TH	NORMAL	YES	6.7961D+00	1.2599D+00	.00	3	SSC
15	SCC-COEFF	NORMAL	YES	3.5900D-11	2.3714D+00	.00	4	SSC
16	SCC-EXPNT	- CONSTANT -		2.1610D+00			5	SSC
17	WASTAGE	NORMAL	YES	1.2740D-12	2.3714D+00	.00	6	SSC
18	DSIG-VIBR	NORMAL	YES	4.5098D-04	1.3465D+00	.00	1	TRC
19	CYCLES/YR	- CONSTANT -		2.0000D+01			2	TRC
20	DSIG-FATG	NORMAL	YES	3.0891D+01	1.4142D+00	.00	3	TRC
21	FCG-COEFF	NORMAL	YES	9.1401D-12	2.8508D+00	1.00	4	TRC
22	FCG-EXPNT	- CONSTANT -		4.0000D+00			5	TRC
23	FCG-THOLD	- CONSTANT -		1.5000D+00			6	TRC
24	LDEPTH-SL	- CONSTANT -		-9.9900D-01			1	FMD
25	SIG-FLOW	NORMAL	NO	6.1783D+01	3.2000D+00	.00	2	FMD
26	STRESS-DL	- CONSTANT -		0.0000D+00			3	FMD
27	B-SDLEAK	- CONSTANT -		0.0000D+00			4	FMD
28	B-MDLEAK	- CONSTANT -		0.0000D+00			5	FMD

PROBABILITIES OF FAILURE MODE: THROUGH-WALL CRACK DEPTH FOR SMALL LEAK

NUMBER FAILED = 400 NUMBER OF TRIALS = 1601

END OF CYCLE	FAILURE PROBABILITY WITHOUT FOR PERIOD	CUM. TOTAL	AND WITH INSERVICE INSPECTIONS FOR PERIOD	CUM. TOTAL
1.0	3.99468D-07	3.99468D-07	3.99468D-07	3.99468D-07
2.0	8.32296D-07	1.23176D-06	8.32296D-07	1.23176D-06
3.0	5.02504D-06	6.25680D-06	5.02504D-06	6.25680D-06
4.0	6.12566D-06	1.23825D-05	6.12566D-06	1.23825D-05
5.0	7.96774D-06	2.03502D-05	7.96774D-06	2.03502D-05
6.0	1.01911D-05	3.05413D-05	5.24524D-08	2.04027D-05
7.0	7.88398D-06	3.84253D-05	6.77740D-08	2.04704D-05
8.0	6.55855D-06	4.49838D-05	6.95600D-08	2.05400D-05
9.0	2.12106D-05	6.61944D-05	2.25487D-07	2.07655D-05
10.0	5.57313D-06	7.17675D-05	1.15446D-07	2.08809D-05
11.0	9.80225D-06	8.15698D-05	3.02235D-07	2.11832D-05
12.0	5.99638D-06	8.75661D-05	1.33413D-07	2.13166D-05
13.0	3.06405D-05	1.18207D-04	3.22520D-06	2.45418D-05
14.0	2.41519D-05	1.42359D-04	2.06748D-06	2.66092D-05
15.0	1.77848D-05	1.60143D-04	6.60289D-07	2.72695D-05
16.0	2.38259D-06	1.62526D-04	1.70525D-10	2.72697D-05
17.0	3.04949D-06	1.65576D-04	2.66305D-10	2.72700D-05
18.0	1.15387D-05	1.77114D-04	1.10662D-09	2.72711D-05
19.0	4.92510D-05	2.26365D-04	9.13685D-08	2.73624D-05
20.0	3.51578D-06	2.29881D-04	4.59604D-10	2.73629D-05
21.0	1.04358D-06	2.30925D-04	2.55867D-10	2.73632D-05
22.0	4.12611D-06	2.35051D-04	2.46965D-09	2.73656D-05
23.0	8.32481D-06	2.43376D-04	3.35737D-09	2.73690D-05
24.0	1.76581D-05	2.61034D-04	9.04366D-09	2.73780D-05
25.0	1.41298D-05	2.75163D-04	4.54477D-09	2.73826D-05
26.0	1.36867D-05	2.88850D-04	1.94772D-11	2.73826D-05
27.0	1.47186D-05	3.03569D-04	5.35921D-11	2.73826D-05
28.0	1.06934D-04	4.10503D-04	4.61437D-09	2.73873D-05
29.0	3.29003D-05	4.43403D-04	2.59258D-10	2.73875D-05
30.0	4.64403D-05	4.89843D-04	4.50491D-09	2.73920D-05
31.0	3.24831D-06	4.93092D-04	2.56685D-11	2.73920D-05
32.0	1.08925D-05	5.03984D-04	1.42666D-10	2.73922D-05
33.0	4.05087D-06	5.08035D-04	1.56895D-11	2.73922D-05
34.0	1.23177D-05	5.20353D-04	1.60718D-10	2.73924D-05
35.0	9.48940D-06	5.29842D-04	6.17367D-11	2.73924D-05
36.0	4.72361D-06	5.34566D-04	2.61038D-13	2.73924D-05
37.0	2.89674D-05	5.63533D-04	7.15194D-12	2.73924D-05
38.0	5.03742D-06	5.68571D-04	9.01061D-14	2.73924D-05
39.0	2.07785D-04	7.76355D-04	1.26531D-09	2.73937D-05
40.0	8.28800D-06	7.84643D-04	1.07350D-12	2.73937D-05

DEVIATION ON CUMULATIVE TOTALS = 3.39902D-05 7.30070D-06

Output Print File for Input From S4PROFSS.REF

STRUCTURAL RELIABILITY AND RISK ASSESSMENT (SRRA)

WESTINGHOUSE PROBABILITY OF FAILURE PROGRAM LEAKPROF ESBU-NSD

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INPUT VARIABLES FOR CASE 1: 304 ST STEEL PIPE WELD SMALL LEAK BY SCC

NCYCLE =	40	NFAILS =	400	NTRIAL =	10000
NOVARS =	28	NUMSET =	6	NUMISI =	5
NUMSSC =	6	NUMTRC =	6	NUMFMD =	5

VARIABLE NO.	NAME	DISTRIBUTION TYPE	LOG	MEDIAN VALUE	DEVIATION OR FACTOR	SHIFT MV/SD	USAGE NO.	SUB
1	PIPE-ODIA	NORMAL	NO	5.5630D+00	2.4000D-02	.00	1	SET
2	WALL/ODIA	NORMAL	NO	5.0000D-02	1.5500D-03	.00	2	SET
3	SRESIDUAL	NORMAL	YES	1.0000D+01	1.4142D+00	.00	3	SET
4	INT%DEPTH	NORMAL	YES	3.5792D+01	1.1947D+00	1.00	4	SET
5	L/D-RATIO	NORMAL	YES	6.0000D+00	1.7126D+00	.00	5	SET
6	FLAWS/IN	- CONSTANT -		4.5820D-03			6	SET
7	FIRST-ISI	- CONSTANT -		5.0000D+00			1	ISI
8	FREQ-ISI	- CONSTANT -		1.0000D+01			2	ISI
9	EPST-PND	- CONSTANT -		1.0000D-03			3	ISI
10	ASTAR-PND	- CONSTANT -		-2.4000D-01			4	ISI
11	ANUU-PND	- CONSTANT -		1.6000D+00			5	ISI
12	HOURS/YR	NORMAL	YES	7.4473D+03	1.0500D+00	.00	1	SSC
13	PRESSURE	NORMAL	YES	1.3000D+00	1.0323D+00	.00	2	SSC
14	SIG-DW&TH	NORMAL	YES	6.7961D+00	1.2599D+00	.00	3	SSC
15	SCC-COEFF	NORMAL	YES	8.9750D-09	2.3714D+00	.00	4	SSC
16	SCC-EXPNT	- CONSTANT -		2.1610D+00			5	SSC
17	WASTAGE	NORMAL	YES	1.2740D-12	2.3714D+00	.00	6	SSC
18	DSIG-VIBR	NORMAL	YES	4.5098D-04	1.3465D+00	.00	1	TRC
19	CYCLES/YR	- CONSTANT -		2.0000D+01			2	TRC
20	DSIG-FATG	NORMAL	YES	1.8535D+01	1.4142D+00	.00	3	TRC
21	FCG-COEFF	NORMAL	YES	9.1401D-12	2.8508D+00	.00	4	TRC
22	FCG-EXPNT	- CONSTANT -		4.0000D+00			5	TRC
23	FCG-THOLD	- CONSTANT -		1.5000D+00			6	TRC
24	LDEPTH-SL	- CONSTANT -		-9.9900D-01			1	FMD
25	SIG-FLOW	NORMAL	NO	6.1783D+01	3.2000D+00	.00	2	FMD
26	STRESS-DL	- CONSTANT -		0.0000D+00			3	FMD
27	B-SDLEAK	- CONSTANT -		0.0000D+00			4	FMD
28	B-MDLEAK	- CONSTANT -		0.0000D+00			5	FMD

PROBABILITIES OF FAILURE MODE: THROUGH-WALL CRACK DEPTH FOR SMALL LEAK

NUMBER FAILED = 400 NUMBER OF TRIALS = 406

END OF CYCLE	FAILURE PROBABILITY WITHOUT FOR PERIOD	CUM. TOTAL	AND WITH INSERVICE FOR PERIOD	INSPECTIONS CUM. TOTAL
1.0	1.30962D-03	1.30962D-03	1.30962D-03	1.30962D-03
2.0	6.93862D-03	8.24824D-03	6.93862D-03	8.24824D-03
3.0	8.97485D-03	1.72231D-02	8.97485D-03	1.72231D-02
4.0	1.06968D-02	2.79199D-02	1.06968D-02	2.79199D-02
5.0	7.50611D-03	3.54260D-02	7.50611D-03	3.54260D-02
6.0	7.41637D-03	4.28424D-02	4.38019D-05	3.54698D-02
7.0	4.92203D-03	4.77644D-02	1.11930D-04	3.55817D-02
8.0	1.43101D-03	4.91954D-02	1.09815D-04	3.56915D-02
9.0	3.12501D-03	5.23204D-02	4.56495D-04	3.61480D-02
10.0	2.10899D-03	5.44294D-02	4.20146D-04	3.65682D-02
11.0	3.49847D-03	5.79279D-02	4.38178D-04	3.70064D-02
12.0	1.72674D-03	5.96546D-02	2.17480D-04	3.72238D-02
13.0	1.63926D-03	6.12939D-02	4.22802D-04	3.76466D-02
14.0	1.96024D-03	6.32541D-02	7.59214D-04	3.84059D-02
15.0	1.25844D-03	6.45126D-02	5.73773D-04	3.89796D-02
16.0	8.97876D-04	6.54104D-02	6.69933D-07	3.89803D-02
17.0	4.73111D-04	6.58835D-02	8.26439D-08	3.89804D-02
18.0	4.79233D-05	6.59315D-02	1.63059D-07	3.89806D-02
19.0	1.09378D-03	6.70253D-02	7.92088D-05	3.90598D-02
20.0	1.07812D-03	6.81034D-02	4.73886D-05	3.91071D-02
21.0	2.38746D-04	6.83421D-02	2.40356D-06	3.91096D-02
23.0	3.28961D-05	6.83750D-02	1.07766D-06	3.91106D-02
24.0	4.04871D-04	6.87799D-02	1.75394D-04	3.92860D-02
25.0	2.87305D-04	6.90672D-02	1.90370D-05	3.93051D-02
26.0	7.31015D-04	6.97982D-02	2.18067D-07	3.93053D-02
28.0	6.28939D-04	7.04271D-02	1.03847D-07	3.93054D-02
29.0	2.96148D-04	7.07233D-02	1.76235D-07	3.93056D-02
30.0	2.04955D-04	7.09282D-02	4.52455D-06	3.93101D-02
32.0	1.19547D-04	7.10478D-02	4.48126D-06	3.93146D-02
33.0	8.42387D-05	7.11320D-02	5.08544D-08	3.93146D-02
36.0	1.32564D-04	7.12646D-02	1.92155D-09	3.93146D-02
39.0	8.65807D-04	7.21304D-02	1.51907D-06	3.93161D-02
40.0	3.11911D-04	7.24423D-02	4.94236D-07	3.93166D-02
	DEVIATION ON CUMULATIVE TOTALS =		4.40870D-04	1.82243D-03

Output Print File for Input From S4PROFLL.REF

STRUCTURAL RELIABILITY AND RISK ASSESSMENT (SRRA)

WESTINGHOUSE PROBABILITY OF FAILURE PROGRAM LEAKPROF ESBU-NSD

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INPUT VARIABLES FOR CASE 1: 304 ST STEEL PIPE WELD LARGE LEAK

NCYCLE =	40	NFAILS =	400	NTRIAL =	50000
NOVARS =	28	NUMSET =	6	NUMISI =	5
NUMSSC =	6	NUMTRC =	6	NUMFMD =	5

VARIABLE NO.	NAME	DISTRIBUTION TYPE	LOG	MEDIAN VALUE	DEVIATION OR FACTOR	SHIFT MV/SD	USAGE NO.	SUB
1	PIPE-ODIA	NORMAL	NO	5.5630D+00	2.4000D-02	.00	1	SET
2	WALL/ODIA	NORMAL	NO	5.0000D-02	1.5500D-03	.00	2	SET
3	SRESIDUAL	NORMAL	YES	1.0000D-03	1.4142D+00	.00	3	SET
4	INT%DEPTH	NORMAL	YES	3.5792D+01	1.1947D+00	2.00	4	SET
5	L/D-RATIO	NORMAL	YES	6.0000D+00	1.7126D+00	2.00	5	SET
6	FLAWS/IN	- CONSTANT -		4.5820D-03			6	SET
7	FIRST-ISI	- CONSTANT -		5.0000D+00			1	ISI
8	FREQ-ISI	- CONSTANT -		1.0000D+01			2	ISI
9	EPST-PND	- CONSTANT -		1.0000D-03			3	ISI
10	ASTAR-PND	- CONSTANT -		-2.4000D-01			4	ISI
11	ANUU-PND	- CONSTANT -		1.6000D+00			5	ISI
12	HOURS/YR	NORMAL	YES	7.4473D+03	1.0500D+00	.00	1	SSC
13	PRESSURE	NORMAL	YES	1.3000D+00	1.0323D+00	.00	2	SSC
14	SIG-DW&TH	NORMAL	YES	6.7961D+00	1.2599D+00	.00	3	SSC
15	SCC-COEFF	NORMAL	YES	3.5900D-11	2.3714D+00	.00	4	SSC
16	SCC-EXPNT	- CONSTANT -		2.1610D+00			5	SSC
17	WASTAGE	NORMAL	YES	1.2740D-12	2.3714D+00	.00	6	SSC
18	DSIG-VIBR	NORMAL	YES	4.5098D-04	1.3465D+00	.00	1	TRC
19	CYCLES/YR	- CONSTANT -		2.0000D+01			2	TRC
20	DSIG-FATG	NORMAL	YES	3.0891D+01	1.4142D+00	.00	3	TRC
21	FCG-COEFF	NORMAL	YES	9.1401D-12	2.8508D+00	1.00	4	TRC
22	FCG-EXPNT	- CONSTANT -		4.0000D+00			5	TRC
23	FCG-THOLD	- CONSTANT -		1.5000D+00			6	TRC
24	LDEPTH-SL	- CONSTANT -		0.0000D+00			1	FMD
25	SIG-FLOW	NORMAL	NO	6.1783D+01	3.2000D+00	.00	2	FMD
26	STRESS-DL	NORMAL	YES	1.6064D+01	1.4142D+00	.00	3	FMD
27	B-SDLEAK	- CONSTANT -		6.4297D+00			4	FMD
28	B-MDLEAK	- CONSTANT -		1.7477D+01			5	FMD

PROBABILITIES OF FAILURE MODE: EXCEED DISABLING LEAK RATE OR BREAK

NUMBER FAILED = 400 NUMBER OF TRIALS = 1974

END OF CYCLE	FAILURE PROBABILITY WITHOUT FOR PERIOD	CUM. TOTAL	AND WITH INSERVICE INSPECTIONS FOR PERIOD	CUM. TOTAL
1.0	2.16800D-10	2.16800D-10	2.16800D-10	2.16800D-10
2.0	6.38666D-08	6.40834D-08	6.38666D-08	6.40834D-08
3.0	4.88836D-07	5.52919D-07	4.88836D-07	5.52919D-07
4.0	2.97374D-07	8.50293D-07	2.97374D-07	8.50293D-07
5.0	4.71159D-07	1.32145D-06	4.71159D-07	1.32145D-06
6.0	6.90781D-07	2.01223D-06	1.12142D-09	1.32257D-06
7.0	3.03230D-07	2.31546D-06	8.81028D-10	1.32345D-06
8.0	3.60858D-07	2.67632D-06	5.96236D-10	1.32405D-06
9.0	1.86783D-06	4.54415D-06	7.57242D-09	1.33162D-06
10.0	1.89756D-06	6.44171D-06	6.40711D-09	1.33803D-06
11.0	9.06705D-07	7.34841D-06	4.71107D-09	1.34274D-06
12.0	4.40102D-06	1.17494D-05	4.53459D-08	1.38809D-06
13.0	1.08037D-06	1.28298D-05	1.71067D-08	1.40519D-06
14.0	6.70922D-06	1.95390D-05	1.35771D-07	1.54097D-06
15.0	9.09148D-06	2.86305D-05	3.07976D-07	1.84894D-06
16.0	4.17745D-06	3.28079D-05	5.34459D-11	1.84900D-06
17.0	3.27188D-06	3.60798D-05	1.09923D-10	1.84911D-06
18.0	3.32759D-07	3.64126D-05	8.99405D-12	1.84911D-06
19.0	2.03002D-06	3.84426D-05	1.07846D-10	1.84922D-06
20.0	2.18064D-05	6.02491D-05	1.66005D-09	1.85088D-06
21.0	5.09464D-06	6.53437D-05	1.63502D-10	1.85105D-06
22.0	1.38165D-05	7.91602D-05	9.56981D-10	1.85200D-06
23.0	6.16701D-07	7.97769D-05	2.30568D-11	1.85203D-06
24.0	2.14167D-06	8.19186D-05	3.09376D-10	1.85233D-06
25.0	2.35547D-06	8.42741D-05	6.57403D-10	1.85299D-06
26.0	4.98393D-06	8.92580D-05	4.25289D-13	1.85299D-06
27.0	2.70860D-06	9.19666D-05	3.22988D-13	1.85299D-06
28.0	2.26556D-06	9.42322D-05	5.08179D-13	1.85299D-06
29.0	9.50352D-07	9.51825D-05	1.48216D-13	1.85299D-06
30.0	1.67297D-06	9.68555D-05	4.60771D-12	1.85300D-06
31.0	1.14279D-06	9.79983D-05	5.09828D-12	1.85300D-06
32.0	8.55701D-07	9.88540D-05	1.21043D-12	1.85300D-06
33.0	1.22207D-06	1.00076D-04	9.02629D-12	1.85301D-06
34.0	2.39490D-06	1.02471D-04	1.48964D-12	1.85302D-06
35.0	2.07791D-06	1.04549D-04	6.25746D-13	1.85302D-06
36.0	1.79750D-06	1.06346D-04	1.29917D-14	1.85302D-06
37.0	5.04894D-05	1.56836D-04	2.88106D-13	1.85302D-06
38.0	1.23825D-06	1.58074D-04	8.88460D-15	1.85302D-06
39.0	5.42330D-07	1.58616D-04	6.95176D-16	1.85302D-06
40.0	6.14362D-07	1.59231D-04	1.62647D-16	1.85302D-06

DEVIATION ON CUMULATIVE TOTALS = 7.11108D-06 8.58065D-07

Output Print File for Input From S4PROFDL.REF

STRUCTURAL RELIABILITY AND RISK ASSESSMENT (SRRA)

WESTINGHOUSE PROBABILITY OF FAILURE PROGRAM LEAKPROF ESBU-NSD

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INPUT VARIABLES FOR CASE 1: 304 ST STEEL PIPE WELD LARGE LEAK

NCYCLE =	40	NFAILS =	400	NTRIAL =	60000
NOVARS =	28	NUMSET =	6	NUMISI =	5
NUMSSC =	6	NUMTRC =	6	NUMFMD =	5

VARIABLE NO.	NAME	DISTRIBUTION TYPE	LOG	MEDIAN VALUE	DEVIATION OR FACTOR	SHIFT MV/SD	USAGE NO.	SUB
1	PIPE-ODIA	NORMAL	NO	5.5630D+00	2.4000D-02	.00	1	SET
2	WALL/ODIA	NORMAL	NO	5.0000D-02	1.5500D-03	.00	2	SET
3	SRESIDUAL	NORMAL	YES	1.0000D-03	1.4142D+00	.00	3	SET
4	INT%DEPTH	NORMAL	YES	3.5792D+01	1.1947D+00	2.00	4	SET
5	L/D-RATIO	NORMAL	YES	6.0000D+00	1.7126D+00	2.00	5	SET
6	FLAWS/IN	- CONSTANT -		4.5820D-03			6	SET
7	FIRST-ISI	- CONSTANT -		5.0000D+00			1	ISI
8	FREQ-ISI	- CONSTANT -		1.0000D+01			2	ISI
9	EPST-PND	- CONSTANT -		1.0000D-03			3	ISI
10	ASTAR-PND	- CONSTANT -		-2.4000D-01			4	ISI
11	ANUU-PND	- CONSTANT -		1.6000D+00			5	ISI
12	HOURS/YR	NORMAL	YES	7.4473D+03	1.0500D+00	.00	1	SSC
13	PRESSURE	NORMAL	YES	1.3000D+00	1.0323D+00	.00	2	SSC
14	SIG-DW&TH	NORMAL	YES	6.7961D+00	1.2599D+00	.00	3	SSC
15	SCC-COEFF	NORMAL	YES	3.5900D-11	2.3714D+00	.00	4	SSC
16	SCC-EXPNT	- CONSTANT -		2.1610D+00			5	SSC
17	WASTAGE	NORMAL	YES	1.2740D-12	2.3714D+00	.00	6	SSC
18	DSIG-VIBR	NORMAL	YES	4.5098D-04	1.3465D+00	.00	1	TRC
19	CYCLES/YR	- CONSTANT -		2.0000D+01			2	TRC
20	DSIG-FATG	NORMAL	YES	3.0891D+01	1.4142D+00	.00	3	TRC
21	FCG-COEFF	NORMAL	YES	9.1401D-12	2.8508D+00	2.00	4	TRC
22	FCG-EXPNT	- CONSTANT -		4.0000D+00			5	TRC
23	FCG-THOLD	- CONSTANT -		1.5000D+00			6	TRC
24	LDEPTH-SL	- CONSTANT -		0.0000D+00			1	FMD
25	SIG-FLOW	NORMAL	NO	6.1783D+01	3.2000D+00	.00	2	FMD
26	STRESS-DL	NORMAL	YES	1.6064D+01	1.4142D+00	.00	3	FMD
27	B-SDLEAK	- CONSTANT -		6.4297D+00			4	FMD
28	B-MDLEAK	- CONSTANT -		3.9312D+00			5	FMD

PROBABILITIES OF FAILURE MODE: EXCEED LARGE LEAK RATE (BREAK) BEFORE DL

NUMBER FAILED = 400 NUMBER OF TRIALS = 7032

END OF CYCLE	FAILURE PROBABILITY WITHOUT		AND WITH INSERVICE INSPECTIONS	
	FOR PERIOD	CUM. TOTAL	FOR PERIOD	CUM. TOTAL
1.0	4.40302D-07	4.40302D-07	4.40302D-07	4.40302D-07
2.0	5.82483D-08	4.98550D-07	5.82483D-08	4.98550D-07
3.0	3.81878D-08	5.36738D-07	3.81878D-08	5.36738D-07
4.0	2.91947D-07	8.28685D-07	2.91947D-07	8.28685D-07
5.0	1.06617D-06	1.89485D-06	1.06617D-06	1.89485D-06
6.0	7.73298D-08	1.97218D-06	1.54908D-10	1.89501D-06
7.0	1.90614D-07	2.16279D-06	3.93499D-10	1.89540D-06
8.0	3.06743D-06	5.23022D-06	9.17076D-09	1.90457D-06
9.0	2.95267D-09	5.23317D-06	5.27776D-11	1.90462D-06
10.0	1.47002D-07	5.38018D-06	3.97782D-09	1.90860D-06
11.0	4.69048D-05	5.22850D-05	1.55116D-06	3.45976D-06
12.0	9.45832D-09	5.22944D-05	1.88695D-10	3.45995D-06
13.0	1.13322D-08	5.23058D-05	2.17046D-10	3.46016D-06
14.0	4.40193D-06	5.67077D-05	1.09809D-06	4.55825D-06
15.0	1.72425D-08	5.67250D-05	3.57457D-10	4.55861D-06
16.0	6.49844D-10	5.67256D-05	3.07862D-14	4.55861D-06
17.0	5.09117D-09	5.67307D-05	6.98449D-13	4.55861D-06
18.0	2.02567D-09	5.67327D-05	8.32618D-14	4.55861D-06
19.0	1.18039D-06	5.79131D-05	1.65057D-10	4.55877D-06
20.0	1.67240D-08	5.79298D-05	3.04661D-12	4.55878D-06
21.0	1.30770D-06	5.92375D-05	1.16703D-09	4.55994D-06
22.0	2.79075D-09	5.92403D-05	3.25118D-13	4.55995D-06
23.0	2.49535D-08	5.92653D-05	1.10163D-11	4.55996D-06
24.0	3.66478D-09	5.92689D-05	6.46434D-13	4.55996D-06
25.0	1.26049D-09	5.92702D-05	1.77337D-13	4.55996D-06
26.0	3.02086D-08	5.93004D-05	6.44878D-14	4.55996D-06
27.0	3.32502D-07	5.96329D-05	8.64910D-14	4.55996D-06
28.0	1.37218D-10	5.96331D-05	9.01836D-17	4.55996D-06
29.0	5.05240D-08	5.96836D-05	1.86126D-14	4.55996D-06
30.0	1.69970D-08	5.97006D-05	7.55406D-13	4.55996D-06
31.0	2.51895D-09	5.97031D-05	1.18135D-14	4.55996D-06
32.0	1.31925D-08	5.97163D-05	1.22944D-13	4.55996D-06
33.0	8.01646D-08	5.97964D-05	3.76391D-13	4.55996D-06
34.0	4.46169D-08	5.98411D-05	4.08176D-14	4.55996D-06
35.0	3.86058D-10	5.98415D-05	2.55576D-14	4.55996D-06
37.0	2.46355D-08	5.98661D-05	1.21368D-15	4.55996D-06
38.0	1.76366D-05	7.75026D-05	4.75189D-11	4.56001D-06
39.0	3.39211D-10	7.75030D-05	1.12350D-16	4.56001D-06
40.0	9.54311D-10	7.75039D-05	1.52756D-16	4.56001D-06

DEVIATION ON CUMULATIVE TOTALS = 3.76364D-06 9.38464D-07

Output Print File for Input From S4PROFLS.REF

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                         STRUCTURAL RELIABILITY AND RISK ASSESSMENT (SRRA)
WESTINGHOUSE               PROBABILITY OF FAILURE PROGRAM LEAKPROF              ESBU-NSD

==========================================================================================

     INPUT VARIABLES FOR CASE  1: 304 ST STEEL PIPE WELD LARGE LEAK BY SCC

     NCYCLE =     40           NFAILS =    400           NTRIAL = 20000
     NOVARS =     28           NUMSET =      6           NUMISI =     5
     NUMSSC =      6           NUMTRC =      6           NUMFMD =     5
```

VARIABLE NO.	NAME	DISTRIBUTION TYPE	LOG	MEDIAN VALUE	DEVIATION OR FACTOR	SHIFT MV/SD	USAGE NO.	SUB
1	PIPE-ODIA	NORMAL	NO	5.5630D+00	2.4000D-02	.00	1	SET
2	WALL/ODIA	NORMAL	NO	5.0000D-02	1.5500D-03	.00	2	SET
3	SRESIDUAL	NORMAL	YES	1.0000D+01	1.4142D+00	.00	3	SET
4	INT%DEPTH	NORMAL	YES	3.5792D+01	1.1947D+00	1.00	4	SET
5	L/D-RATIO	NORMAL	YES	6.0000D+00	1.7126D+00	1.00	5	SET
6	FLAWS/IN	- CONSTANT -		4.5820D-03			6	SET
7	FIRST-ISI	- CONSTANT -		5.0000D+00			1	ISI
8	FREQ-ISI	- CONSTANT -		1.0000D+01			2	ISI
9	EPST-PND	- CONSTANT -		1.0000D-03			3	ISI
10	ASTAR-PND	- CONSTANT -		-2.4000D-01			4	ISI
11	ANUU-PND	- CONSTANT -		1.6000D+00			5	ISI
12	HOURS/YR	NORMAL	YES	7.4473D+03	1.0500D+00	.00	1	SSC
13	PRESSURE	NORMAL	YES	1.3000D+00	1.0323D+00	.00	2	SSC
14	SIG-DW&TH	NORMAL	YES	6.7961D+00	1.2599D+00	.00	3	SSC
15	SCC-COEFF	NORMAL	YES	3.5900D-11	2.3714D+00	.00	4	SSC
16	SCC-EXPNT	- CONSTANT -		2.1610D+00			5	SSC
17	WASTAGE	NORMAL	YES	1.2740D-12	2.3714D+00	.00	6	SSC
18	DSIG-VIBR	NORMAL	YES	4.5098D-04	1.3465D+00	.00	1	TRC
19	CYCLES/YR	- CONSTANT -		2.0000D+01			2	TRC
20	DSIG-FATG	NORMAL	YES	3.0891D+01	1.4142D+00	.00	3	TRC
21	FCG-COEFF	NORMAL	YES	9.1401D-12	2.8508D+00	.00	4	TRC
22	FCG-EXPNT	- CONSTANT -		4.0000D+00			5	TRC
23	FCG-THOLD	- CONSTANT -		1.5000D+00			6	TRC
24	LDEPTH-SL	- CONSTANT -		0.0000D+00			1	FMD
25	SIG-FLOW	NORMAL	NO	6.1783D+01	3.2000D+00	.00	2	FMD
26	STRESS-DL	NORMAL	YES	1.6064D+01	1.4142D+00	.00	3	FMD
27	B-SDLEAK	- CONSTANT -		6.4297D+00			4	FMD
28	B-MDLEAK	- CONSTANT -		1.7477D+01			5	FMD

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PROBABILITIES OF FAILURE MODE: EXCEED DISABLING LEAK RATE OR BREAK

NUMBER FAILED =  400              NUMBER OF TRIALS = 14218
```

END OF CYCLE	FAILURE PROBABILITY WITHOUT FOR PERIOD	CUM. TOTAL	AND WITH INSERVICE INSPECTIONS FOR PERIOD	CUM. TOTAL
1.0	1.94676D-05	1.94676D-05	1.94676D-05	1.94676D-05
2.0	1.64211D-09	1.94692D-05	1.64211D-09	1.94692D-05
3.0	3.60526D-06	2.30745D-05	3.60526D-06	2.30745D-05
4.0	1.17697D-06	2.42514D-05	1.17697D-06	2.42514D-05
5.0	4.62598D-06	2.88774D-05	4.62598D-06	2.88774D-05
6.0	9.35166D-06	3.82291D-05	1.53633D-08	2.88928D-05
7.0	5.10255D-06	4.33316D-05	8.26683D-09	2.89011D-05
8.0	1.80713D-05	6.14030D-05	3.01254D-08	2.89312D-05
9.0	8.07841D-06	6.94814D-05	1.79270D-08	2.89491D-05
10.0	1.05176D-05	7.99990D-05	1.59504D-07	2.91086D-05
11.0	1.57260D-05	9.57250D-05	9.79233D-08	2.92065D-05
12.0	3.18669D-06	9.89117D-05	9.34184D-09	2.92159D-05
13.0	7.03331D-06	1.05945D-04	2.15705D-07	2.94316D-05
14.0	1.23189D-06	1.07177D-04	4.57748D-08	2.94774D-05
15.0	6.41857D-06	1.13595D-04	1.92347D-07	2.96697D-05
16.0	1.27900D-05	1.26385D-04	3.95685D-09	2.96737D-05
17.0	5.42489D-06	1.31810D-04	2.44645D-10	2.96739D-05
18.0	7.09380D-06	1.38904D-04	5.58758D-10	2.96745D-05
19.0	2.10725D-06	1.41011D-04	5.41811D-11	2.96745D-05
20.0	1.05744D-05	1.51586D-04	1.02739D-09	2.96755D-05
21.0	8.22210D-06	1.59808D-04	5.54646D-10	2.96761D-05
22.0	1.02608D-05	1.70069D-04	7.00225D-10	2.96768D-05
23.0	9.68458D-07	1.71037D-04	6.08965D-11	2.96769D-05
24.0	8.17939D-06	1.79217D-04	4.44185D-08	2.97213D-05
25.0	5.11902D-06	1.84336D-04	1.03302D-09	2.97223D-05
26.0	1.26233D-05	1.96959D-04	3.18938D-11	2.97223D-05
27.0	3.31027D-05	2.30062D-04	3.39515D-10	2.97227D-05
28.0	1.57535D-05	2.45815D-04	3.68996D-11	2.97227D-05
29.0	2.22691D-05	2.68084D-04	4.48439D-11	2.97228D-05
30.0	1.62538D-05	2.84338D-04	5.25594D-11	2.97228D-05
31.0	2.99003D-05	3.14238D-04	9.84339D-09	2.97327D-05
32.0	8.25324D-06	3.22492D-04	6.62475D-12	2.97327D-05
33.0	1.04866D-05	3.32978D-04	7.07280D-11	2.97327D-05
34.0	4.79138D-06	3.37769D-04	1.32302D-11	2.97328D-05
35.0	1.39620D-05	3.51732D-04	5.73414D-11	2.97328D-05
36.0	3.01252D-05	3.81857D-04	1.02399D-12	2.97328D-05
37.0	2.13054D-05	4.03162D-04	6.80547D-11	2.97329D-05
38.0	1.16069D-05	4.14769D-04	3.08759D-13	2.97329D-05
39.0	1.46025D-05	4.29372D-04	1.02946D-12	2.97329D-05
40.0	1.64704D-05	4.45842D-04	6.53235D-12	2.97329D-05

DEVIATION ON CUMULATIVE TOTALS = 2.19771D-05 5.75157D-06

Output Print File for Input From S4PROFDS.REF

STRUCTURAL RELIABILITY AND RISK ASSESSMENT (SRRA)

WESTINGHOUSE PROBABILITY OF FAILURE PROGRAM LEAKPROF ESBU-NSD

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INPUT VARIABLES FOR CASE 1: 304 ST STEEL PIPE WELD LARGE LEAK BY SCC

NCYCLE =	40	NFAILS =	400	NTRIAL =	30000
NOVARS =	28	NUMSET =	6	NUMISI =	5
NUMSSC =	6	NUMTRC =	6	NUMFMD =	5

VARIABLE NO.	NAME	DISTRIBUTION TYPE	LOG	MEDIAN VALUE	DEVIATION OR FACTOR	SHIFT MV/SD	USAGE NO.	SUB
1	PIPE-ODIA	NORMAL	NO	5.5630D+00	2.4000D-02	.00	1	SET
2	WALL/ODIA	NORMAL	NO	5.0000D-02	1.5500D-03	.00	2	SET
3	SRESIDUAL	NORMAL	YES	1.0000D+01	1.4142D+00	.00	3	SET
4	INT%DEPTH	NORMAL	YES	3.5792D+01	1.1947D+00	1.00	4	SET
5	L/D-RATIO	NORMAL	YES	6.0000D+00	1.7126D+00	1.00	5	SET
6	FLAWS/IN	- CONSTANT -		4.5820D-03			6	SET
7	FIRST-ISI	- CONSTANT -		5.0000D+00			1	ISI
8	FREQ-ISI	- CONSTANT -		1.0000D+01			2	ISI
9	EPST-PND	- CONSTANT -		1.0000D-03			3	ISI
10	ASTAR-PND	- CONSTANT -		-2.4000D-01			4	ISI
11	ANUU-PND	- CONSTANT -		1.6000D+00			5	ISI
12	HOURS/YR	NORMAL	YES	7.4473D+03	1.0500D+00	.00	1	SSC
13	PRESSURE	NORMAL	YES	1.3000D+00	1.0323D+00	.00	2	SSC
14	SIG-DW&TH	NORMAL	YES	6.7961D+00	1.2599D+00	.00	3	SSC
15	SCC-COEFF	NORMAL	YES	8.9750D-09	2.3714D+00	.00	4	SSC
16	SCC-EXPNT	- CONSTANT -		2.1610D+00			5	SSC
17	WASTAGE	NORMAL	YES	1.2740D-12	2.3714D+00	.00	6	SSC
18	DSIG-VIBR	NORMAL	YES	4.5098D-04	1.3465D+00	.00	1	TRC
19	CYCLES/YR	- CONSTANT -		2.0000D+01			2	TRC
20	DSIG-FATG	NORMAL	YES	1.8535D+01	1.4142D+00	.00	3	TRC
21	FCG-COEFF	NORMAL	YES	9.1401D-12	2.8508D+00	1.00	4	TRC
22	FCG-EXPNT	- CONSTANT -		4.0000D+00			5	TRC
23	FCG-THOLD	- CONSTANT -		1.5000D+00			6	TRC
24	LDEPTH-SL	- CONSTANT -		0.0000D+00			1	FMD
25	SIG-FLOW	NORMAL	NO	6.1783D+01	3.2000D+00	.00	2	FMD
26	STRESS-DL	NORMAL	YES	1.6064D+01	1.4142D+00	.00	3	FMD
27	B-SDLEAK	- CONSTANT -		6.4297D+00			4	FMD
28	B-MDLEAK	- CONSTANT -		3.9312D+00			5	FMD

PROBABILITIES OF FAILURE MODE: EXCEED LARGE LEAK RATE (BREAK) BEFORE DL

NUMBER FAILED = 400 NUMBER OF TRIALS = 4381

END OF CYCLE	FAILURE PROBABILITY WITHOUT FOR PERIOD	CUM. TOTAL	AND WITH INSERVICE INSPECTIONS FOR PERIOD	CUM. TOTAL
1.0	1.80343D-05	1.80343D-05	1.80343D-05	1.80343D-05
2.0	3.83536D-04	4.01570D-04	3.83536D-04	4.01570D-04
3.0	9.09758D-04	1.31133D-03	9.09758D-04	1.31133D-03
4.0	1.34118D-03	2.65251D-03	1.34118D-03	2.65251D-03
5.0	5.35542D-04	3.18805D-03	5.35542D-04	3.18805D-03
6.0	1.00364D-03	4.19169D-03	1.62658D-06	3.18967D-03
7.0	1.09229D-03	5.28398D-03	1.79275D-06	3.19147D-03
8.0	8.61494D-06	5.29260D-03	8.72295D-08	3.19155D-03
9.0	3.27806D-04	5.62040D-03	1.78381D-06	3.19334D-03
12.0	1.21311D-05	5.63253D-03	4.12413D-06	3.19746D-03
16.0	1.30371D-05	5.64557D-03	3.42855D-09	3.19747D-03
22.0	2.33659D-04	5.87923D-03	3.60385D-05	3.23350D-03
40.0	0.00000D+00	5.87923D-03	0.00000D+00	3.23350D-03

DEVIATION ON CUMULATIVE TOTALS = 2.80252D-04 2.12485D-04

Output Print File for Input From S4PROFDB.REF

STRUCTURAL RELIABILITY AND RISK ASSESSMENT (SRRA)

WESTINGHOUSE PROBABILITY OF FAILURE PROGRAM LEAKPROF ESBU-NSD

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INPUT VARIABLES FOR CASE 1: 304 ST STEEL PIPE WELD FULL BREAK

NCYCLE =	40	NFAILS =	400	NTRIAL =	60000
NOVARS =	28	NUMSET =	6	NUMISI =	5
NUMSSC =	6	NUMTRC =	6	NUMFMD =	5

VARIABLE NO.	NAME	DISTRIBUTION TYPE	LOG	MEDIAN VALUE	DEVIATION OR FACTOR	SHIFT MV/SD	USAGE NO.	SUB
1	PIPE-ODIA	NORMAL	NO	5.5630D+00	2.4000D-02	.00	1	SET
2	WALL/ODIA	NORMAL	NO	5.0000D-02	1.5500D-03	.00	2	SET
3	SRESIDUAL	NORMAL	YES	1.0000D-03	1.4142D+00	.00	3	SET
4	INT%DEPTH	NORMAL	YES	3.5792D+01	1.1947D+00	6.00	4	SET
5	L/D-RATIO	NORMAL	YES	6.0000D+00	1.7126D+00	6.00	5	SET
6	FLAWS/IN	- CONSTANT -		4.5820D-03			6	SET
7	FIRST-ISI	- CONSTANT -		5.0000D+00			1	ISI
8	FREQ-ISI	- CONSTANT -		1.0000D+01			2	ISI
9	EPST-PND	- CONSTANT -		1.0000D-03			3	ISI
10	ASTAR-PND	- CONSTANT -		-2.4000D-01			4	ISI
11	ANUU-PND	- CONSTANT -		1.6000D+00			5	ISI
12	HOURS/YR	NORMAL	YES	7.4473D+03	1.0500D+00	.00	1	SSC
13	PRESSURE	NORMAL	YES	1.3000D+00	1.0323D+00	.00	2	SSC
14	SIG-DW&TH	NORMAL	YES	6.7961D+00	1.2599D+00	.00	3	SSC
15	SCC-COEFF	NORMAL	YES	3.5900D-11	2.3714D+00	.00	4	SSC
16	SCC-EXPNT	- CONSTANT -		2.1610D+00			5	SSC
17	WASTAGE	NORMAL	YES	1.2740D-12	2.3714D+00	.00	6	SSC
18	DSIG-VIBR	NORMAL	YES	4.5098D-04	1.3465D+00	.00	1	TRC
19	CYCLES/YR	- CONSTANT -		2.0000D+01			2	TRC
20	DSIG-FATG	NORMAL	YES	3.0891D+01	1.4142D+00	.00	3	TRC
21	FCG-COEFF	NORMAL	YES	9.1401D-12	2.8508D+00	.00	4	TRC
22	FCG-EXPNT	- CONSTANT -		4.0000D+00			5	TRC
23	FCG-THOLD	- CONSTANT -		1.5000D+00			6	TRC
24	LDEPTH-SL	- CONSTANT -		0.0000D+00			1	FMD
25	SIG-FLOW	NORMAL	NO	6.1783D+01	3.2000D+00	.00	2	FMD
26	STRESS-DL	NORMAL	YES	1.6064D+01	1.4142D+00	.00	3	FMD
27	B-SDLEAK	- CONSTANT -		1.7477D+01			4	FMD
28	B-MDLEAK	- CONSTANT -		3.9312D+00			5	FMD

PROBABILITIES OF FAILURE MODE: EXCEED FLOW STRESS BEFORE LEAK DETECTION

NUMBER FAILED = 400 NUMBER OF TRIALS = 406

END OF CYCLE	FAILURE PROBABILITY WITHOUT FOR PERIOD	CUM. TOTAL	AND WITH INSERVICE FOR PERIOD	INSPECTIONS CUM. TOTAL
1.0	2.99412D-12	2.99412D-12	2.99412D-12	2.99412D-12
2.0	6.47833D-13	3.64195D-12	6.47833D-13	3.64195D-12
3.0	4.76090D-16	3.64243D-12	4.76090D-16	3.64243D-12
4.0	3.98280D-15	3.64641D-12	3.98280D-15	3.64641D-12
5.0	2.34338D-14	3.66984D-12	2.34338D-14	3.66984D-12
6.0	1.98722D-15	3.67183D-12	2.51823D-17	3.66987D-12
9.0	8.99870D-18	3.67184D-12	4.49253D-20	3.66987D-12
10.0	4.77340D-14	3.71957D-12	2.71951D-16	3.67014D-12
15.0	3.19828D-12	6.91786D-12	1.33489D-14	3.68349D-12
17.0	1.00966D-17	6.91787D-12	6.06496D-22	3.68349D-12
25.0	6.73570D-18	6.91787D-12	9.50804D-23	3.68349D-12
26.0	4.62736D-15	6.92250D-12	3.20769D-22	3.68349D-12
40.0	0.00000D+00	6.92250D-12	0.00000D+00	3.68349D-12

DEVIATION ON CUMULATIVE TOTALS = 4.21290D-14 1.74366D-13

Output Print File for Input From S6PROFSL.REF

STRUCTURAL RELIABILITY AND RISK ASSESSMENT (SRRA)

WESTINGHOUSE PROBABILITY OF FAILURE PROGRAM LEAKPROF ESBU-NSD

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INPUT VARIABLES FOR CASE 1: 316 STAINLESS STEEL PIPE WELD SMALL LEAK

NCYCLE =	40	NFAILS =	400	NTRIAL =	40000
NOVARS =	28	NUMSET =	6	NUMISI =	5
NUMSSC =	6	NUMTRC =	6	NUMFMD =	5

VARIABLE NO.	NAME	DISTRIBUTION TYPE	LOG	MEDIAN VALUE	DEVIATION OR FACTOR	SHIFT MV/SD	USAGE NO.	SUB
1	PIPE-ODIA	NORMAL	NO	5.5630D+00	2.4000D-02	.00	1	SET
2	WALL/ODIA	NORMAL	NO	5.0000D-02	1.5500D-03	.00	2	SET
3	SRESIDUAL	NORMAL	YES	1.0000D-03	1.4142D+00	.00	3	SET
4	INT%DEPTH	NORMAL	YES	3.5792D+01	1.1947D+00	2.00	4	SET
5	L/D-RATIO	NORMAL	YES	6.0000D+00	1.7126D+00	1.00	5	SET
6	FLAWS/IN	- CONSTANT -		4.5820D-03			6	SET
7	FIRST-ISI	- CONSTANT -		5.0000D+00			1	ISI
8	FREQ-ISI	- CONSTANT -		1.0000D+01			2	ISI
9	EPST-PND	- CONSTANT -		1.0000D-03			3	ISI
10	ASTAR-PND	- CONSTANT -		-2.4000D-01			4	ISI
11	ANUU-PND	- CONSTANT -		1.6000D+00			5	ISI
12	HOURS/YR	NORMAL	YES	7.4473D+03	1.0500D+00	.00	1	SSC
13	PRESSURE	NORMAL	YES	1.3000D+00	1.0323D+00	.00	2	SSC
14	SIG-DW&TH	NORMAL	YES	6.7961D+00	1.2599D+00	.00	3	SSC
15	SCC-COEFF	NORMAL	YES	3.2310D-12	2.3714D+00	.00	4	SSC
16	SCC-EXPNT	- CONSTANT -		2.1610D+00			5	SSC
17	WASTAGE	NORMAL	YES	1.2740D-12	2.3714D+00	.00	6	SSC
18	DSIG-VIBR	NORMAL	YES	4.5098D-04	1.3465D+00	.00	1	TRC
19	CYCLES/YR	- CONSTANT -		2.0000D+01			2	TRC
20	DSIG-FATG	NORMAL	YES	3.0891D+01	1.4142D+00	.00	3	TRC
21	FCG-COEFF	NORMAL	YES	9.1401D-12	2.8508D+00	1.00	4	TRC
22	FCG-EXPNT	- CONSTANT -		4.0000D+00			5	TRC
23	FCG-THOLD	- CONSTANT -		1.5000D+00			6	TRC
24	LDEPTH-SL	- CONSTANT -		-9.9900D-01			1	FMD
25	SIG-FLOW	NORMAL	NO	6.1783D+01	3.2000D+00	.00	2	FMD
26	STRESS-DL	- CONSTANT -		0.0000D+00			3	FMD
27	B-SDLEAK	- CONSTANT -		0.0000D+00			4	FMD
28	B-MDLEAK	- CONSTANT -		0.0000D+00			5	FMD

PROBABILITIES OF FAILURE MODE: THROUGH-WALL CRACK DEPTH FOR SMALL LEAK

NUMBER FAILED = 400 NUMBER OF TRIALS = 1681

END OF CYCLE	FAILURE PROBABILITY WITHOUT FOR PERIOD	CUM. TOTAL	AND WITH INSERVICE INSPECTIONS FOR PERIOD	CUM. TOTAL
1.0	5.79065D-07	5.79065D-07	5.79065D-07	5.79065D-07
2.0	8.15879D-07	1.39494D-06	8.15879D-07	1.39494D-06
3.0	4.78590D-06	6.18084D-06	4.78590D-06	6.18084D-06
4.0	8.89638D-06	1.50772D-05	8.89638D-06	1.50772D-05
5.0	7.58855D-06	2.26658D-05	7.58855D-06	2.26658D-05
6.0	9.95638D-06	3.26221D-05	5.25836D-08	2.27183D-05
7.0	3.09373D-06	3.57159D-05	1.72538D-08	2.27356D-05
8.0	1.06643D-05	4.63802D-05	1.15208D-07	2.28508D-05
9.0	1.92208D-05	6.56010D-05	2.10549D-07	2.30614D-05
10.0	6.26047D-06	7.18615D-05	1.20133D-07	2.31815D-05
11.0	9.65346D-06	8.15150D-05	2.96352D-07	2.34778D-05
12.0	5.06257D-06	8.65775D-05	1.20340D-07	2.35982D-05
13.0	3.90717D-05	1.25649D-04	3.82179D-06	2.74200D-05
14.0	2.04285D-05	1.46078D-04	1.89849D-06	2.93185D-05
15.0	1.08188D-05	1.56897D-04	3.66923D-07	2.96854D-05
16.0	1.06821D-05	1.67579D-04	7.70623D-10	2.96861D-05
17.0	3.45874D-06	1.71037D-04	3.87344D-10	2.96865D-05
18.0	1.14793D-05	1.82517D-04	1.18858D-09	2.96877D-05
19.0	4.21303D-05	2.24647D-04	9.00021D-08	2.97777D-05
20.0	7.90481D-06	2.32552D-04	3.29999D-09	2.97810D-05
21.0	1.85852D-06	2.34410D-04	4.78313D-10	2.97815D-05
22.0	4.63558D-06	2.39046D-04	2.31719D-09	2.97838D-05
23.0	7.82093D-06	2.46867D-04	3.68948D-09	2.97875D-05
24.0	8.28438D-06	2.55151D-04	4.91200D-09	2.97924D-05
25.0	1.76427D-05	2.72794D-04	7.63412D-09	2.98001D-05
26.0	5.93129D-06	2.78725D-04	5.06287D-12	2.98001D-05
27.0	1.04343D-05	2.89159D-04	2.52469D-11	2.98001D-05
28.0	1.92098D-05	3.08369D-04	1.45872D-10	2.98002D-05
29.0	2.26075D-05	3.30977D-04	1.14417D-10	2.98003D-05
30.0	8.34029D-05	4.14380D-04	8.01040D-09	2.98084D-05
31.0	7.49154D-05	4.89295D-04	6.20277D-09	2.98146D-05
32.0	3.06487D-08	4.89326D-04	1.22641D-14	2.98146D-05
33.0	1.33649D-05	5.02691D-04	1.89711D-10	2.98148D-05
34.0	3.64926D-06	5.06340D-04	8.70967D-12	2.98148D-05
35.0	1.53713D-05	5.21711D-04	1.84234D-10	2.98149D-05
36.0	3.54990D-06	5.25261D-04	3.36583D-14	2.98149D-05
37.0	9.36934D-05	6.18954D-04	1.23389D-10	2.98151D-05
38.0	2.05523D-05	6.39507D-04	1.05518D-11	2.98151D-05
39.0	1.95749D-04	8.35255D-04	1.56259D-09	2.98166D-05
40.0	1.57995D-05	8.51055D-04	5.46366D-12	2.98166D-05

DEVIATION ON CUMULATIVE TOTALS = 3.71576D-05 7.93395D-06

Output Print File for Input From S6PROFSS.REF

STRUCTURAL RELIABILITY AND RISK ASSESSMENT (SRRA)

WESTINGHOUSE PROBABILITY OF FAILURE PROGRAM LEAKPROF ESBU-NSD

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INPUT VARIABLES FOR CASE 1: 304 ST STEEL PIPE WELD SMALL LEAK BY SCC

NCYCLE =	40	NFAILS =	400	NTRIAL =	10000
NOVARS =	28	NUMSET =	6	NUMISI =	5
NUMSSC =	6	NUMTRC =	6	NUMFMD =	5

VARIABLE NO.	NAME	DISTRIBUTION TYPE	LOG	MEDIAN VALUE	DEVIATION OR FACTOR	SHIFT MV/SD	USAGE NO.	SUB
1	PIPE-ODIA	NORMAL	NO	5.5630D+00	2.4000D-02	.00	1	SET
2	WALL/ODIA	NORMAL	NO	5.0000D-02	1.5500D-03	.00	2	SET
3	SRESIDUAL	NORMAL	YES	1.0000D+01	1.4142D+00	.00	3	SET
4	INT%DEPTH	NORMAL	YES	3.5792D+01	1.1947D+00	1.00	4	SET
5	L/D-RATIO	NORMAL	YES	6.0000D+00	1.7126D+00	.00	5	SET
6	FLAWS/IN	- CONSTANT -		4.5820D-03			6	SET
7	FIRST-ISI	- CONSTANT -		5.0000D+00			1	ISI
8	FREQ-ISI	- CONSTANT -		1.0000D+01			2	ISI
9	EPST-PND	- CONSTANT -		1.0000D-03			3	ISI
10	ASTAR-PND	- CONSTANT -		-2.4000D-01			4	ISI
11	ANUU-PND	- CONSTANT -		1.6000D+00			5	ISI
12	HOURS/YR	NORMAL	YES	7.4473D+03	1.0500D+00	.00	1	SSC
13	PRESSURE	NORMAL	YES	1.3000D+00	1.0323D+00	.00	2	SSC
14	SIG-DW&TH	NORMAL	YES	6.7961D+00	1.2599D+00	.00	3	SSC
15	SCC-COEFF	NORMAL	YES	8.9750D-09	2.3714D+00	.00	4	SSC
16	SCC-EXPNT	- CONSTANT -		2.1610D+00			5	SSC
17	WASTAGE	NORMAL	YES	1.2740D-12	2.3714D+00	.00	6	SSC
18	DSIG-VIBR	NORMAL	YES	4.5098D-04	1.3465D+00	.00	1	TRC
19	CYCLES/YR	- CONSTANT -		2.0000D+01			2	TRC
20	DSIG-FATG	NORMAL	YES	1.8535D+01	1.4142D+00	.00	3	TRC
21	FCG-COEFF	NORMAL	YES	9.1401D-12	2.8508D+00	.00	4	TRC
22	FCG-EXPNT	- CONSTANT -		4.0000D+00			5	TRC
23	FCG-THOLD	- CONSTANT -		1.5000D+00			6	TRC
24	LDEPTH-SL	- CONSTANT -		-9.9900D-01			1	FMD
25	SIG-FLOW	NORMAL	NO	6.1783D+01	3.2000D+00	.00	2	FMD
26	STRESS-DL	- CONSTANT -		0.0000D+00			3	FMD
27	B-SDLEAK	- CONSTANT -		0.0000D+00			4	FMD
28	B-MDLEAK	- CONSTANT -		0.0000D+00			5	FMD

PROBABILITIES OF FAILURE MODE: THROUGH-WALL CRACK DEPTH FOR SMALL LEAK

NUMBER FAILED = 400 NUMBER OF TRIALS = 406

END OF CYCLE	FAILURE PROBABILITY WITHOUT FOR PERIOD	CUM. TOTAL	AND WITH INSERVICE FOR PERIOD	INSPECTIONS CUM. TOTAL
1.0	1.30962D-03	1.30962D-03	1.30962D-03	1.30962D-03
2.0	6.93862D-03	8.24824D-03	6.93862D-03	8.24824D-03
3.0	8.97485D-03	1.72231D-02	8.97485D-03	1.72231D-02
4.0	1.06968D-02	2.79199D-02	1.06968D-02	2.79199D-02
5.0	7.50611D-03	3.54260D-02	7.50611D-03	3.54260D-02
6.0	7.41637D-03	4.28424D-02	4.38019D-05	3.54698D-02
7.0	4.92203D-03	4.77644D-02	1.11930D-04	3.55817D-02
8.0	1.43101D-03	4.91954D-02	1.09815D-04	3.56915D-02
9.0	3.12501D-03	5.23204D-02	4.56495D-04	3.61480D-02
10.0	2.10899D-03	5.44294D-02	4.20146D-04	3.65682D-02
11.0	3.49847D-03	5.79279D-02	4.38178D-04	3.70064D-02
12.0	1.72674D-03	5.96546D-02	2.17480D-04	3.72238D-02
13.0	1.63926D-03	6.12939D-02	4.22802D-04	3.76466D-02
14.0	1.96024D-03	6.32541D-02	7.59214D-04	3.84059D-02
15.0	1.25844D-03	6.45126D-02	5.73773D-04	3.89796D-02
16.0	8.97876D-04	6.54104D-02	6.69933D-07	3.89803D-02
17.0	4.73111D-04	6.58835D-02	8.26439D-08	3.89804D-02
18.0	4.79233D-05	6.59315D-02	1.63059D-07	3.89806D-02
19.0	1.09378D-03	6.70253D-02	7.92088D-05	3.90598D-02
20.0	1.07812D-03	6.81034D-02	4.73886D-05	3.91071D-02
21.0	2.38746D-04	6.83421D-02	2.40356D-06	3.91096D-02
23.0	3.28961D-05	6.83750D-02	1.07766D-06	3.91106D-02
24.0	4.04871D-04	6.87799D-02	1.75394D-04	3.92860D-02
25.0	2.87305D-04	6.90672D-02	1.90370D-05	3.93051D-02
26.0	7.31015D-04	6.97982D-02	2.18067D-07	3.93053D-02
28.0	6.28939D-04	7.04271D-02	1.03847D-07	3.93054D-02
29.0	2.96148D-04	7.07233D-02	1.76235D-07	3.93056D-02
30.0	2.04955D-04	7.09282D-02	4.52455D-06	3.93101D-02
32.0	1.19547D-04	7.10478D-02	4.48126D-06	3.93146D-02
33.0	8.42387D-05	7.11320D-02	5.08544D-08	3.93146D-02
36.0	1.32564D-04	7.12646D-02	1.92155D-09	3.93146D-02
39.0	8.65807D-04	7.21304D-02	1.51907D-06	3.93161D-02
40.0	3.11911D-04	7.24423D-02	4.94236D-07	3.93166D-02

DEVIATION ON CUMULATIVE TOTALS = 4.40870D-04 1.82243D-03

Output Print File for Input From S6PROFLL.REF

STRUCTURAL RELIABILITY AND RISK ASSESSMENT (SRRA)

WESTINGHOUSE PROBABILITY OF FAILURE PROGRAM LEAKPROF ESBU-NSD

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INPUT VARIABLES FOR CASE 1: 316 ST STEEL PIPE WELD LARGE LEAK

NCYCLE = 40 NFAILS = 400 NTRIAL = 50000
NOVARS = 28 NUMSET = 6 NUMISI = 5
NUMSSC = 6 NUMTRC = 6 NUMFMD = 5

VARIABLE NO.	NAME	DISTRIBUTION TYPE	LOG	MEDIAN VALUE	DEVIATION OR FACTOR	SHIFT MV/SD	USAGE NO.	SUB
1	PIPE-ODIA	NORMAL	NO	5.5630D+00	2.4000D-02	.00	1	SET
2	WALL/ODIA	NORMAL	NO	5.0000D-02	1.5500D-03	.00	2	SET
3	SRESIDUAL	NORMAL	YES	1.0000D-03	1.4142D+00	.00	3	SET
4	INT%DEPTH	NORMAL	YES	3.5792D+01	1.1947D+00	2.00	4	SET
5	L/D-RATIO	NORMAL	YES	6.0000D+00	1.7126D+00	2.00	5	SET
6	FLAWS/IN	- CONSTANT -		4.5820D-03			6	SET
7	FIRST-ISI	- CONSTANT -		5.0000D+00			1	ISI
8	FREQ-ISI	- CONSTANT -		1.0000D+01			2	ISI
9	EPST-PND	- CONSTANT -		1.0000D-03			3	ISI
10	ASTAR-PND	- CONSTANT -		-2.4000D-01			4	ISI
11	ANUU-PND	- CONSTANT -		1.6000D+00			5	ISI
12	HOURS/YR	NORMAL	YES	7.4473D+03	1.0500D+00	.00	1	SSC
13	PRESSURE	NORMAL	YES	1.3000D+00	1.0323D+00	.00	2	SSC
14	SIG-DW&TH	NORMAL	YES	6.7961D+00	1.2599D+00	.00	3	SSC
15	SCC-COEFF	NORMAL	YES	3.2310D-12	2.3714D+00	.00	4	SSC
16	SCC-EXPNT	- CONSTANT -		2.1610D+00			5	SSC
17	WASTAGE	NORMAL	YES	1.2740D-12	2.3714D+00	.00	6	SSC
18	DSIG-VIBR	NORMAL	YES	4.5098D-04	1.3465D+00	.00	1	TRC
19	CYCLES/YR	- CONSTANT -		2.0000D+01			2	TRC
20	DSIG-FATG	NORMAL	YES	3.0891D+01	1.4142D+00	.00	3	TRC
21	FCG-COEFF	NORMAL	YES	9.1401D-12	2.8508D+00	1.00	4	TRC
22	FCG-EXPNT	- CONSTANT -		4.0000D+00			5	TRC
23	FCG-THOLD	- CONSTANT -		1.5000D+00			6	TRC
24	LDEPTH-SL	- CONSTANT -		0.0000D+00			1	FMD
25	SIG-FLOW	NORMAL	NO	6.1783D+01	3.2000D+00	.00	2	FMD
26	STRESS-DL	NORMAL	YES	1.6064D+01	1.4142D+00	.00	3	FMD
27	B-SDLEAK	- CONSTANT -		6.4297D+00			4	FMD
28	B-MDLEAK	- CONSTANT -		1.7477D+01			5	FMD

PROBABILITIES OF FAILURE MODE: EXCEED DISABLING LEAK RATE OR BREAK

NUMBER FAILED = 400 NUMBER OF TRIALS = 2004

END OF CYCLE	FAILURE PROBABILITY WITHOUT FOR PERIOD	CUM. TOTAL	AND WITH INSERVICE INSPECTIONS FOR PERIOD	CUM. TOTAL
1.0	2.13555D-10	2.13555D-10	2.13555D-10	2.13555D-10
2.0	6.29105D-08	6.31240D-08	6.29105D-08	6.31240D-08
3.0	4.81518D-07	5.44642D-07	4.81518D-07	5.44642D-07
4.0	2.15773D-07	7.60415D-07	2.15773D-07	7.60415D-07
5.0	4.99913D-07	1.26033D-06	4.99913D-07	1.26033D-06
6.0	6.69937D-07	1.93027D-06	1.08739D-09	1.26142D-06
7.0	2.78620D-07	2.20888D-06	8.72076D-10	1.26229D-06
8.0	7.05273D-07	2.91416D-06	1.15593D-09	1.26344D-06
9.0	1.76713D-06	4.68129D-06	7.68184D-09	1.27113D-06
10.0	2.20623D-06	6.88752D-06	6.91186D-09	1.27804D-06
11.0	5.88422D-07	7.47594D-06	3.90210D-09	1.28194D-06
12.0	4.39631D-06	1.18722D-05	4.54083D-08	1.32735D-06
13.0	1.14801D-06	1.30203D-05	1.72559D-08	1.34460D-06
14.0	2.01246D-06	1.50327D-05	3.74797D-08	1.38208D-06
15.0	2.78906D-06	1.78218D-05	1.02835D-07	1.48492D-06
16.0	7.67990D-06	2.55017D-05	2.43320D-10	1.48516D-06
17.0	7.33334D-06	3.28350D-05	2.14952D-10	1.48538D-06
18.0	2.30623D-07	3.30656D-05	2.59316D-12	1.48538D-06
19.0	1.76658D-06	3.48322D-05	8.99282D-11	1.48547D-06
20.0	2.08964D-05	5.57286D-05	1.65624D-09	1.48713D-06
21.0	3.32880D-06	5.90574D-05	1.23062D-10	1.48725D-06
22.0	1.44358D-05	7.34932D-05	9.51119D-10	1.48820D-06
23.0	5.55894D-06	7.90522D-05	2.94622D-10	1.48849D-06
24.0	2.39597D-06	8.14481D-05	1.55983D-10	1.48865D-06
25.0	1.33212D-06	8.27803D-05	2.21135D-10	1.48887D-06
26.0	6.67135D-06	8.94516D-05	1.76921D-12	1.48887D-06
27.0	2.14025D-06	9.15919D-05	1.24811D-13	1.48887D-06
28.0	2.75525D-06	9.43471D-05	1.08685D-11	1.48888D-06
29.0	8.57899D-07	9.52050D-05	2.88904D-13	1.48888D-06
30.0	4.77513D-07	9.56825D-05	1.90115D-13	1.48888D-06
31.0	9.63694D-07	9.66462D-05	2.60764D-13	1.48889D-06
32.0	3.25137D-07	9.69714D-05	5.72292D-12	1.48889D-06
33.0	2.90300D-06	9.98744D-05	7.49268D-12	1.48890D-06
34.0	3.28270D-06	1.03157D-04	4.50439D-12	1.48890D-06
35.0	8.24039D-07	1.03981D-04	1.08868D-12	1.48890D-06
36.0	1.52340D-04	2.56321D-04	4.02562D-09	1.49293D-06
37.0	2.05356D-06	2.58375D-04	1.64018D-14	1.49293D-06
38.0	4.87675D-05	3.07142D-04	3.03950D-13	1.49293D-06
39.0	4.45024D-07	3.07587D-04	8.21722D-15	1.49293D-06
40.0	7.22146D-06	3.14809D-04	7.02520D-15	1.49293D-06

DEVIATION ON CUMULATIVE TOTALS = 1.40857D-05 1.08372D-06

Output Print File for Input From S6PROFDL.REF

STRUCTURAL RELIABILITY AND RISK ASSESSMENT (SRRA)

WESTINGHOUSE PROBABILITY OF FAILURE PROGRAM LEAKPROF ESBU-NSD

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INPUT VARIABLES FOR CASE 1: 316 ST STEEL PIPE WELD LARGE LEAK

NCYCLE =	40	NFAILS =	400	NTRIAL =	60000
NOVARS =	28	NUMSET =	6	NUMISI =	5
NUMSSC =	6	NUMTRC =	6	NUMFMD =	5

VARIABLE NO.	NAME	DISTRIBUTION TYPE	LOG	MEDIAN VALUE	DEVIATION OR FACTOR	SHIFT MV/SD	USAGE NO.	SUB
1	PIPE-ODIA	NORMAL	NO	5.5630D+00	2.4000D-02	.00	1	SET
2	WALL/ODIA	NORMAL	NO	5.0000D-02	1.5500D-03	.00	2	SET
3	SRESIDUAL	NORMAL	YES	1.0000D-03	1.4142D+00	.00	3	SET
4	INT%DEPTH	NORMAL	YES	3.5792D+01	1.1947D+00	2.00	4	SET
5	L/D-RATIO	NORMAL	YES	6.0000D+00	1.7126D+00	2.00	5	SET
6	FLAWS/IN	- CONSTANT -		4.5820D-03			6	SET
7	FIRST-ISI	- CONSTANT -		5.0000D+00			1	ISI
8	FREQ-ISI	- CONSTANT -		1.0000D+01			2	ISI
9	EPST-PND	- CONSTANT -		1.0000D-03			3	ISI
10	ASTAR-PND	- CONSTANT -		-2.4000D-01			4	ISI
11	ANUU-PND	- CONSTANT -		1.6000D+00			5	ISI
12	HOURS/YR	NORMAL	YES	7.4473D+03	1.0500D+00	.00	1	SSC
13	PRESSURE	NORMAL	YES	1.3000D+00	1.0323D+00	.00	2	SSC
14	SIG-DW&TH	NORMAL	YES	6.7961D+00	1.2599D+00	.00	3	SSC
15	SCC-COEFF	NORMAL	YES	3.2310D-12	2.3714D+00	.00	4	SSC
16	SCC-EXPNT	- CONSTANT -		2.1610D+00			5	SSC
17	WASTAGE	NORMAL	YES	1.2740D-12	2.3714D+00	.00	6	SSC
18	DSIG-VIBR	NORMAL	YES	4.5098D-04	1.3465D+00	.00	1	TRC
19	CYCLES/YR	- CONSTANT -		2.0000D+01			2	TRC
20	DSIG-FATG	NORMAL	YES	3.0891D+01	1.4142D+00	.00	3	TRC
21	FCG-COEFF	NORMAL	YES	9.1401D-12	2.8508D+00	2.00	4	TRC
22	FCG-EXPNT	- CONSTANT -		4.0000D+00			5	TRC
23	FCG-THOLD	- CONSTANT -		1.5000D+00			6	TRC
24	LDEPTH-SL	- CONSTANT -		0.0000D+00			1	FMD
25	SIG-FLOW	NORMAL	NO	6.1783D+01	3.2000D+00	.00	2	FMD
26	STRESS-DL	NORMAL	YES	1.6064D+01	1.4142D+00	.00	3	FMD
27	B-SDLEAK	- CONSTANT -		6.4297D+00			4	FMD
28	B-MDLEAK	- CONSTANT -		3.9312D+00			5	FMD

PROBABILITIES OF FAILURE MODE: EXCEED LARGE LEAK RATE (BREAK) BEFORE DL

NUMBER FAILED = 400 NUMBER OF TRIALS = 7030

END OF CYCLE	FAILURE PROBABILITY WITHOUT FOR PERIOD	CUM. TOTAL	AND WITH INSERVICE INSPECTIONS FOR PERIOD	CUM. TOTAL
1.0	4.40425D-07	4.40425D-07	4.40425D-07	4.40425D-07
2.0	5.83996D-08	4.98825D-07	5.83996D-08	4.98825D-07
3.0	1.59646D-07	6.58470D-07	1.59646D-07	6.58470D-07
4.0	9.55502D-08	7.54021D-07	9.55502D-08	7.54021D-07
5.0	1.05162D-06	1.80564D-06	1.05162D-06	1.80564D-06
6.0	4.96566D-08	1.85530D-06	8.48306D-11	1.80572D-06
7.0	3.23918D-07	2.17921D-06	5.62422D-10	1.80629D-06
8.0	3.07773D-06	5.25694D-06	9.62078D-09	1.81591D-06
9.0	1.78733D-08	5.27482D-06	2.84717D-10	1.81619D-06
10.0	5.49687D-08	5.32979D-06	5.39066D-10	1.81673D-06
11.0	4.70118D-05	5.23416D-05	1.55828D-06	3.37502D-06
12.0	2.50988D-07	5.25926D-05	9.99666D-09	3.38501D-06
13.0	3.02450D-08	5.26228D-05	8.92055D-10	3.38590D-06
14.0	1.05788D-08	5.26334D-05	2.21465D-10	3.38613D-06
15.0	3.18595D-09	5.26366D-05	6.97218D-11	3.38620D-06
16.0	1.09710D-08	5.26476D-05	9.76071D-13	3.38620D-06
17.0	1.79641D-08	5.26655D-05	1.62346D-12	3.38620D-06
18.0	7.06917D-10	5.26662D-05	3.79877D-14	3.38620D-06
20.0	1.81050D-07	5.28473D-05	1.14249D-09	3.38734D-06
21.0	3.50676D-08	5.28823D-05	4.29546D-12	3.38734D-06
22.0	3.39498D-09	5.28857D-05	5.38786D-13	3.38735D-06
23.0	2.37042D-10	5.28860D-05	3.44825D-14	3.38735D-06
24.0	1.62913D-10	5.28861D-05	3.86554D-13	3.38735D-06
25.0	4.91425D-07	5.33776D-05	4.59103D-09	3.39194D-06
26.0	1.42431D-09	5.33790D-05	2.91911D-15	3.39194D-06
27.0	1.26305D-04	1.79684D-04	1.28779D-08	3.40481D-06
28.0	2.22918D-07	1.79906D-04	3.92093D-14	3.40481D-06
29.0	4.58021D-10	1.79907D-04	5.53195D-16	3.40481D-06
30.0	4.97712D-08	1.79957D-04	2.01219D-14	3.40481D-06
31.0	5.86564D-07	1.80543D-04	2.10912D-12	3.40482D-06
32.0	4.77191D-10	1.80544D-04	1.26496D-14	3.40482D-06
33.0	1.60488D-10	1.80544D-04	3.70925D-16	3.40482D-06
34.0	2.35098D-07	1.80779D-04	4.24143D-13	3.40482D-06
35.0	3.77293D-11	1.80779D-04	4.43802D-18	3.40482D-06
36.0	6.45874D-07	1.81425D-04	4.29557D-14	3.40482D-06
37.0	3.20838D-10	1.81425D-04	1.04703D-18	3.40482D-06
38.0	5.52649D-10	1.81426D-04	1.16340D-18	3.40482D-06
39.0	2.99324D-10	1.81426D-04	1.65524D-18	3.40482D-06
40.0	2.65622D-09	1.81429D-04	1.20742D-15	3.40482D-06
DEVIATION ON CUMULATIVE TOTALS =			8.81021D-06	1.24214D-06

Output Print File for Input From S6PROFLS.REF

STRUCTURAL RELIABILITY AND RISK ASSESSMENT (SRRA)
WESTINGHOUSE PROBABILITY OF FAILURE PROGRAM LEAKPROF ESBU-NSD

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INPUT VARIABLES FOR CASE 1: 316 ST STEEL PIPE WELD LARGE LEAK BY SCC

NCYCLE = 40	NFAILS = 400	NTRIAL = 20000
NOVARS = 28	NUMSET = 6	NUMISI = 5
NUMSSC = 6	NUMTRC = 6	NUMFMD = 5

VARIABLE NO.	NAME	DISTRIBUTION TYPE	LOG	MEDIAN VALUE	DEVIATION OR FACTOR	SHIFT MV/SD	USAGE NO.	SUB
1	PIPE-ODIA	NORMAL	NO	5.5630D+00	2.4000D-02	.00	1	SET
2	WALL/ODIA	NORMAL	NO	5.0000D-02	1.5500D-03	.00	2	SET
3	SRESIDUAL	NORMAL	YES	1.0000D+01	1.4142D+00	.00	3	SET
4	INT%DEPTH	NORMAL	YES	3.5792D+01	1.1947D+00	1.00	4	SET
5	L/D-RATIO	NORMAL	YES	6.0000D+00	1.7126D+00	2.00	5	SET
6	FLAWS/IN	- CONSTANT -		4.5820D-03			6	SET
7	FIRST-ISI	- CONSTANT -		5.0000D+00			1	ISI
8	FREQ-ISI	- CONSTANT -		1.0000D+01			2	ISI
9	EPST-PND	- CONSTANT -		1.0000D-03			3	ISI
10	ASTAR-PND	- CONSTANT -		-2.4000D-01			4	ISI
11	ANUU-PND	- CONSTANT -		1.6000D+00			5	ISI
12	HOURS/YR	NORMAL	YES	7.4473D+03	1.0500D+00	.00	1	SSC
13	PRESSURE	NORMAL	YES	1.3000D+00	1.0323D+00	.00	2	SSC
14	SIG-DW&TH	NORMAL	YES	6.7961D+00	1.2599D+00	.00	3	SSC
15	SCC-COEFF	NORMAL	YES	1.6155D-09	2.3714D+00	.00	4	SSC
16	SCC-EXPNT	- CONSTANT -		2.1610D+00			5	SSC
17	WASTAGE	NORMAL	YES	1.2740D-12	2.3714D+00	.00	6	SSC
18	DSIG-VIBR	NORMAL	YES	4.5098D-04	1.3465D+00	.00	1	TRC
19	CYCLES/YR	- CONSTANT -		2.0000D+01			2	TRC
20	DSIG-FATG	NORMAL	YES	1.8535D+01	1.4142D+00	.00	3	TRC
21	FCG-COEFF	NORMAL	YES	9.1401D-12	2.8508D+00	1.00	4	TRC
22	FCG-EXPNT	- CONSTANT -		4.0000D+00			5	TRC
23	FCG-THOLD	- CONSTANT -		1.5000D+00			6	TRC
24	LDEPTH-SL	- CONSTANT -		0.0000D+00			1	FMD
25	SIG-FLOW	NORMAL	NO	6.1783D+01	3.2000D+00	.00	2	FMD
26	STRESS-DL	NORMAL	YES	1.6064D+01	1.4142D+00	.00	3	FMD
27	B-SDLEAK	- CONSTANT -		6.4297D+00			4	FMD
28	B-MDLEAK	- CONSTANT -		1.7477D+01			5	FMD

PROBABILITIES OF FAILURE MODE: EXCEED DISABLING LEAK RATE OR BREAK

NUMBER FAILED = 400 NUMBER OF TRIALS = 582

END OF CYCLE	FAILURE PROBABILITY WITHOUT FOR PERIOD	CUM. TOTAL	AND WITH INSERVICE INSPECTIONS FOR PERIOD	CUM. TOTAL
2.0	1.85618D-07	1.85618D-07	1.85618D-07	1.85618D-07
3.0	9.65477D-08	2.82165D-07	9.65477D-08	2.82165D-07
4.0	9.13305D-06	9.41522D-06	9.13305D-06	9.41522D-06
5.0	9.90947D-05	1.08510D-04	9.90947D-05	1.08510D-04
6.0	8.74184D-05	1.95928D-04	1.41655L-07	1.08652D-04
7.0	1.17887D-05	2.07717D-04	2.53885D-08	1.08677D-04
8.0	8.90366D-05	2.96754D-04	1.44586D-07	1.08822D-04
9.0	1.26068D-04	4.22822D-04	2.06237D-07	1.09028D-04
10.0	8.99086D-05	5.12730D-04	1.51921D-07	1.09180D-04
11.0	1.41392D-03	1.92665D-03	2.29918D-06	1.11479D-04
12.0	1.22623D-05	1.93891D-03	3.92039D-08	1.11518D-04
13.0	2.04639D-04	2.14355D-03	3.58077D-07	1.11876D-04
14.0	5.87437D-05	2.20229D-03	2.69445D-07	1.12146D-04
15.0	9.29534D-05	2.29525D-03	6.64362D-07	1.12810D-04
16.0	7.21228D-04	3.01648D-03	3.10576D-08	1.12841D-04
17.0	9.85710D-04	4.00218D-03	1.73810D-08	1.12858D-04
18.0	5.44712D-04	4.54690D-03	8.26015D-09	1.12867D-04
19.0	1.97822D-04	4.74472D-03	6.57688D-09	1.12873D-04
20.0	1.51436D-04	4.89616D-03	3.81033D-09	1.12877D-04
21.0	2.66017D-04	5.16217D-03	7.06199D-09	1.12884D-04
22.0	7.74433D-04	5.93660D-03	3.19341D-08	1.12916D-04
23.0	1.59738D-04	6.09634D-03	2.44160D-08	1.12940D-04
24.0	6.52025D-04	6.74837D-03	1.82663D-07	1.13123D-04
25.0	3.86624D-04	7.13499D-03	1.20313D-08	1.13135D-04
26.0	2.88482D-04	7.42347D-03	1.73375D-11	1.13135D-04
27.0	2.44258D-03	9.86605D-03	6.70422D-10	1.13136D-04
28.0	1.05926D-03	1.09253D-02	2.09599D-10	1.13136D-04
29.0	2.51681D-04	1.11770D-02	3.87624D-11	1.13136D-04
30.0	8.60845D-05	1.12631D-02	2.13557D-11	1.13136D-04
31.0	8.94073D-05	1.13525D-02	1.63240D-11	1.13136D-04
32.0	5.77848D-04	1.19303D-02	8.71384D-11	1.13136D-04
33.0	5.74626D-04	1.25050D-02	3.49607D-10	1.13137D-04
34.0	1.74120D-04	1.26791D-02	2.52762D-11	1.13137D-04
35.0	4.72666D-04	1.31517D-02	3.30311D-10	1.13137D-04
36.0	2.44622D-04	1.33964D-02	3.41490D-13	1.13137D-04
37.0	5.51568D-05	1.34515D-02	2.42180D-14	1.13137D-04
38.0	1.46769D-04	1.35983D-02	1.98288D-14	1.13137D-04
39.0	2.29562D-04	1.38279D-02	9.31177D-14	1.13137D-04
40.0	1.36417D-05	1.38415D-02	9.82947D-15	1.13137D-04

DEVIATION ON CUMULATIVE TOTALS = 3.87347D-04 6.24473D-05

Output Print File for Input From S6PROFDS.REF

STRUCTURAL RELIABILITY AND RISK ASSESSMENT (SRRA)

WESTINGHOUSE PROBABILITY OF FAILURE PROGRAM LEAKPROF ESBU-NSD

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INPUT VARIABLES FOR CASE 1: 316 ST STEEL PIPE WELD LARGE LEAK BY SCC

NCYCLE =	40	NFAILS =	400	NTRIAL =	30000
NOVARS =	28	NUMSET =	6	NUMISI =	5
NUMSSC =	6	NUMTRC =	6	NUMFMD =	5

VARIABLE NO.	NAME	DISTRIBUTION TYPE	LOG	MEDIAN VALUE	DEVIATION OR FACTOR	SHIFT MV/SD	USAGE NO.	SUB
1	PIPE-ODIA	NORMAL	NO	5.5630D+00	2.4000D-02	.00	1	SET
2	WALL/ODIA	NORMAL	NO	5.0000D-02	1.5500D-03	.00	2	SET
3	SRESIDUAL	NORMAL	YES	1.0000D+01	1.4142D+00	.00	3	SET
4	INT%DEPTH	NORMAL	YES	3.5792D+01	1.1947D+00	1.00	4	SET
5	L/D-RATIO	NORMAL	YES	6.0000D+00	1.7126D+00	2.00	5	SET
6	FLAWS/IN	- CONSTANT -		4.5820D-03			6	SET
7	FIRST-ISI	- CONSTANT -		5.0000D+00			1	ISI
8	FREQ-ISI	- CONSTANT -		1.0000D+01			2	ISI
9	EPST-PND	- CONSTANT -		1.0000D-03			3	ISI
10	ASTAR-PND	- CONSTANT -		-2.4000D-01			4	ISI
11	ANUU-PND	- CONSTANT -		1.6000D+00			5	ISI
12	HOURS/YR	NORMAL	YES	7.4473D+03	1.0500D+00	.00	1	SSC
13	PRESSURE	NORMAL	YES	1.3000D+00	1.0323D+00	.00	2	SSC
14	SIG-DW&TH	NORMAL	YES	6.7961D+00	1.2599D+00	.00	3	SSC
15	SCC-COEFF	NORMAL	YES	3.2310D-12	2.3714D+00	1.00	4	SSC
16	SCC-EXPNT	- CONSTANT -		2.1610D+00			5	SSC
17	WASTAGE	NORMAL	YES	1.2740D-12	2.3714D+00	.00	6	SSC
18	DSIG-VIBR	NORMAL	YES	4.5098D-04	1.3465D+00	.00	1	TRC
19	CYCLES/YR	- CONSTANT -		2.0000D+01			2	TRC
20	DSIG-FATG	NORMAL	YES	3.0891D+01	1.4142D+00	.00	3	TRC
21	FCG-COEFF	NORMAL	YES	9.1401D-12	2.8508D+00	1.00	4	TRC
22	FCG-EXPNT	- CONSTANT -		4.0000D+00			5	TRC
23	FCG-THOLD	- CONSTANT -		1.5000D+00			6	TRC
24	LDEPTH-SL	- CONSTANT -		0.0000D+00			1	FMD
25	SIG-FLOW	NORMAL	NO	6.1783D+01	3.2000D+00	.00	2	FMD
26	STRESS-DL	NORMAL	YES	1.6064D+01	1.4142D+00	.00	3	FMD
27	B-SDLEAK	- CONSTANT -		6.4297D+00			4	FMD
28	B-MDLEAK	- CONSTANT -		3.9312D+00			5	FMD

PROBABILITIES OF FAILURE MODE: EXCEED LARGE LEAK RATE (BREAK) BEFORE DL

NUMBER FAILED = 400 NUMBER OF TRIALS = 23477

END OF CYCLE	FAILURE PROBABILITY WITHOUT FOR PERIOD	CUM. TOTAL	AND WITH INSERVICE FOR PERIOD	INSPECTIONS CUM. TOTAL
1.0	6.44508D-06	6.44508D-06	6.44508D-06	6.44508D-06
2.0	7.48885D-08	6.51997D-06	7.48885D-08	6.51997D-06
3.0	6.36006D-07	7.15598D-06	6.36006D-07	7.15598D-06
4.0	2.61711D-06	9.77308D-06	2.61711D-06	9.77308D-06
5.0	8.27001D-06	1.80431D-05	8.27001D-06	1.80431D-05
6.0	1.72056D-06	1.97637D-05	2.80165D-09	1.80459D-05
7.0	6.82725D-07	2.04464D-05	1.40768D-09	1.80473D-05
8.0	4.99757D-07	2.09461D-05	1.04949D-09	1.80484D-05
9.0	1.65017D-07	2.11112D-05	2.85211D-09	1.80512D-05
10.0	2.47673D-09	2.11136D-05	6.21036D-11	1.80513D-05
11.0	3.34146D-07	2.14478D-05	1.08265D-08	1.80621D-05
12.0	4.53263D-09	2.14523D-05	1.82060D-10	1.80623D-05
13.0	1.23494D-07	2.15758D-05	4.12631D-09	1.80664D-05
14.0	5.87481D-07	2.21633D-05	9.30418D-08	1.81594D-05
15.0	1.49830D-07	2.23131D-05	4.07142D-09	1.81635D-05
16.0	6.67815D-09	2.23198D-05	5.41575D-13	1.81635D-05
17.0	1.99401D-07	2.25192D-05	2.28674D-11	1.81635D-05
18.0	1.28093D-09	2.25205D-05	4.18079D-13	1.81635D-05
19.0	1.14156D-06	2.36620D-05	8.33559D-10	1.81644D-05
20.0	9.09101D-07	2.45711D-05	2.81103D-10	1.81647D-05
21.0	3.87570D-07	2.49587D-05	3.14813D-10	1.81650D-05
22.0	3.56545D-09	2.49623D-05	4.00976D-12	1.81650D-05
23.0	1.07014D-08	2.49730D-05	1.31663D-11	1.81650D-05
24.0	3.04100D-07	2.52771D-05	1.03960D-09	1.81660D-05
25.0	1.24419D-06	2.65213D-05	1.51608D-09	1.81675D-05
26.0	6.36642D-09	2.65276D-05	6.05536D-14	1.81675D-05
27.0	1.07985D-08	2.65384D-05	4.63154D-13	1.81675D-05
28.0	3.03454D-06	2.95730D-05	1.05010D-09	1.81686D-05
29.0	7.54568D-06	3.71187D-05	5.43370D-08	1.82229D-05
30.0	1.30651D-08	3.71317D-05	2.99650D-13	1.82229D-05
31.0	5.00828D-07	3.76325D-05	2.22949D-12	1.82229D-05
32.0	6.45970D-08	3.76971D-05	3.10745D-13	1.82229D-05
33.0	7.79356D-08	3.77751D-05	1.23251D-12	1.82229D-05
34.0	1.28603D-08	3.77879D-05	5.49423D-13	1.82229D-05
35.0	1.33449D-07	3.79214D-05	3.18313D-13	1.82229D-05
36.0	2.07244D-06	3.99938D-05	4.06874D-13	1.82229D-05
37.0	3.54385D-08	4.00293D-05	1.29408D-13	1.82229D-05
38.0	6.62560D-07	4.06918D-05	2.91932D-13	1.82229D-05
39.0	6.95589D-08	4.07614D-05	1.46591D-13	1.82229D-05
40.0	6.74184D-08	4.08288D-05	8.17334D-13	1.82229D-05

DEVIATION ON CUMULATIVE TOTALS = 2.02402D-06 1.35867D-06

Output Print File for Input From S6PROFDB.REF

STRUCTURAL RELIABILITY AND RISK ASSESSMENT (SRRA)

WESTINGHOUSE PROBABILITY OF FAILURE PROGRAM LEAKPROF ESBU-NSD

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INPUT VARIABLES FOR CASE 1: 316 ST STEEL PIPE WELD FULL BREAK

NCYCLE =	40	NFAILS =	400	NTRIAL =	60000
NOVARS =	28	NUMSET =	6	NUMISI =	5
NUMSSC =	6	NUMTRC =	6	NUMFMD =	5

VARIABLE NO.	NAME	DISTRIBUTION TYPE	LOG	MEDIAN VALUE	DEVIATION OR FACTOR	SHIFT MV/SD	USAGE NO.	SUB
1	PIPE-ODIA	NORMAL	NO	5.5630D+00	2.4000D-02	.00	1	SET
2	WALL/ODIA	NORMAL	NO	5.0000D-02	1.5500D-03	.00	2	SET
3	SRESIDUAL	NORMAL	YES	1.0000D-03	1.4142D+00	.00	3	SET
4	INT%DEPTH	NORMAL	YES	3.5792D+01	1.1947D+00	6.00	4	SET
5	L/D-RATIO	NORMAL	YES	6.0000D+00	1.7126D+00	6.00	5	SET
6	FLAWS/IN	- CONSTANT -		4.5820D-03			6	SET
7	FIRST-ISI	- CONSTANT -		5.0000D+00			1	ISI
8	FREQ-ISI	- CONSTANT -		1.0000D+01			2	ISI
9	EPST-PND	- CONSTANT -		1.0000D-03			3	ISI
10	ASTAR-PND	- CONSTANT -		-2.4000D-01			4	ISI
11	ANUU-PND	- CONSTANT -		1.6000D+00			5	ISI
12	HOURS/YR	NORMAL	YES	7.4473D+03	1.0500D+00	.00	1	SSC
13	PRESSURE	NORMAL	YES	1.3000D+00	1.0323D+00	.00	2	SSC
14	SIG-DW&TH	NORMAL	YES	6.7961D+00	1.2599D+00	.00	3	SSC
15	SCC-COEFF	NORMAL	YES	3.2310D-12	2.3714D+00	.00	4	SSC
16	SCC-EXPNT	- CONSTANT -		2.1610D+00			5	SSC
17	WASTAGE	NORMAL	YES	1.2740D-12	2.3714D+00	.00	6	SSC
18	DSIG-VIBR	NORMAL	YES	4.5098D-04	1.3465D+00	.00	1	TRC
19	CYCLES/YR	- CONSTANT -		2.0000D+01			2	TRC
20	DSIG-FATG	NORMAL	YES	3.0891D+01	1.4142D+00	.00	3	TRC
21	FCG-COEFF	NORMAL	YES	9.1401D-12	2.8508D+00	.00	4	TRC
22	FCG-EXPNT	- CONSTANT -		4.0000D+00			5	TRC
23	FCG-THOLD	- CONSTANT -		1.5000D+00			6	TRC
24	LDEPTH-SL	- CONSTANT -		0.0000D+00			1	FMD
25	SIG-FLOW	NORMAL	NO	6.1783D+01	3.2000D+00	.00	2	FMD
26	STRESS-DL	NORMAL	YES	1.6064D+01	1.4142D+00	.00	3	FMD
27	B-SDLEAK	- CONSTANT -		1.7447D+01			4	FMD
28	B-MDLEAK	- CONSTANT -		3.9312D+00			5	FMD

PROBABILITIES OF FAILURE MODE: EXCEED FLOW STRESS BEFORE LEAK DETECTION

NUMBER FAILED = 400 NUMBER OF TRIALS = 406

END OF CYCLE	FAILURE PROBABILITY WITHOUT FOR PERIOD	CUM. TOTAL	AND WITH INSERVICE INSPECTIONS FOR PERIOD	CUM. TOTAL
1.0	2.99412D-12	2.99412D-12	2.99412D-12	2.99412D-12
2.0	6.47833D-13	3.64195D-12	6.47833D-13	3.64195D-12
4.0	4.76090D-16	3.64243D-12	4.76090D-16	3.64243D-12
5.0	2.74162D-14	3.66984D-12	2.74162D-14	3.66984D-12
6.0	4.06916D-19	3.66984D-12	1.38599L-21	3.66984D-12
10.0	8.99870D-18	3.66985D-12	4.64352D-20	3.66984D-12
11.0	4.77340D-14	3.71759D-12	2.78601D-16	3.67012D-12
12.0	1.98722D-15	3.71957D-12	2.65707D-17	3.67015D-12
24.0	3.19828D-12	6.91786D-12	5.09088D-17	3.67020D-12
27.0	1.00966D-17	6.91787D-12	4.76162D-24	3.67020D-12
31.0	4.63409D-15	6.92250D-12	4.72334D-22	3.67020D-12
40.0	0.00000D+00	6.92250D-12	0.00000D+00	3.67020D-12
	DEVIATION ON CUMULATIVE TOTALS =		4.21290D-14	1.74396D-13