NUREG-0313
Rev. 2

Technical Report on Material Selection and Processing Guidelines for BWR Coolant Pressure Boundary Piping

Final Report

U.S. Nuclear Regulatory Commission

Office of Nuclear Reactor Regulation

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Technical Report on Material Selection and Processing Guidelines for BWR Coolant Pressure Boundary Piping

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ABSTRACT

This report updates and supersedes the technical recommendations of NUREG-0313, "Technical Report on Material Selection and Processing Guidelines for BWR Coolant Pressure Boundary Piping," published in July 1977, and its subsequent revision published in July 1980.

This report provides the technical bases for the NRC staff's revised recommended methods to control the intergranular stress corrosion cracking susceptibility of BWR piping. For piping that does not fully comply with the material selection, testing, and processing guideline combinations of this document, varying degrees of augmented inservice inspection are recommended. This revision also includes guidance and NRC staff recommendations (not requirements) regarding crack evaluation and weld overlay repair methods for long-term operation or for continuing interim operation of plants until a more permanent solution is implemented.

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ABBREVIATIONS

ANL	Argonne National Laboratory
ASME	American Society of Mechanical Engineers
ASTM	American Society of Testing Materials
BWR	Boiling Water Reactors
BWROG	Boiling Water Reactor Owners Group
CFR	Code of Federal Regulations
CRC	Corrosion Resistant Cladding
EPRI	Electric Power Research Institute
GE	General Electric
GMAW	Gas Metal Arc Welding
GTAW	Gas Tungsten Arc Welding
HAZ	Heat Affected Zone
HSW	Heat Sink Welding
HWC	Hydrogen Water Chemistry
IE	Office of Inspection and Enforcement
IGSCC	Intergranular Stress Corrosion Cracking
IHSI	Induction Heating Stress Improvement
ISI	Inservice Inspection
LPHSW	Last Past Heat Sink Welding Process
MSIP	Mechanical Stress Improvement Process
NDE	Nondestructive Examinations
NRC	Nuclear Regulatory Commission
PNL	Pacific Northwest Laboratory
PPB	Part per Billion
PT	Penetrant Inspection
RHR	Residual Heat Removal
SECY	Office of the Secretary of the Commission
SHT	Solution Heat Treatment
SI	Stress Improvement
UT	Ultrasonic Testing

EXECUTIVE SUMMARY

This revision to NUREG-0313, Rev. 1, "Technical Report on Material Selection and Processing Guidelines for BWR Coolant Pressure Boundary Piping" provides the technical bases for the staff's recommendations regarding actions that can be taken to ensure that the integrity and reliability of BWR piping will be maintained.

The staff long-range plan regarding BWR pipe cracks was presented to the Commission in SECY 84-301. A major task in this plan was to revise NUREG-0313 to include the recommendations of the Piping Review Committee Task Group on Pipe Cracking, issued as NUREG-1061, Vol. 1.

The subjects covered by this revision include recommendations regarding piping and weld material, special processing to minimize crack susceptibility, improvements in BWR primary coolant chemistry and control, inspection requirements, repair methods, and leak detection. These recommendations and conclusions are consistent with those made in NUREG-1061, Vol. 1, and are summarized as follows:

BWR piping weldments made of austenitic stainless steel are susceptible to intergranular stress corrosion cracking (IGSCC). The three elements that, in combination, cause IGSCC are, a susceptible (sensitized) material, a significant tensile stress, and an aggressive environment.

The staff technical recommendation is that improvements in all three of these elements should be pursued. Nevertheless, significant reduction in the probability of IGSCC can be accomplished even by improving one or two of these three elements. From a practical standpoint, this is more readily accomplished in the near term, and can provide acceptable assurance of continued integrity and reliability.

There is no practical way to reduce the sensitization of weldments already installed, so the only way to reduce the susceptibility of the material is to replace the piping with material that is resistant to sensitization by welding. Solution heat treatment of individual spool pieces in the pipe fabrication shop before field erection is practicable, and is recommended. Austenitic materials considered by the staff to be adequately resistant to sensitization by welding are the following:

(1) Low carbon wrought austenitic stainless steel. These include 304L, 304NG, 316L, 316NG, 347NG, and similar types.

(2) Low carbon weld metal of type 308L and similar grades with a minimum of 7.5% ferrite as deposited. This may also be used as a cladding on the inside of the pipe.

(3) Cast austenitic stainless steel with less than 0.035% carbon and a minimum of 7.5% ferrite.

(4) Other materials such as nickel base alloys, etc., may be sufficiently resistant, and may be evaluated in special cases. Inconel 82 is the only nickel base weld metal considered to be resistant.

Service-induced stresses on most BWR piping are relatively low. The source of the high stress primarily responsible for IGSCC is the high tensile stress on the inside of the pipe caused by normal welding practice. Stress Improvement (SI) can be accomplished on weldments already installed by the Induction Heating Stress Improvement (IHSI) process, or by the Mechanical Stress Improvement Process (MSIP).

SI can be applied to new or replaced piping, or can be applied at any time during plant life. The staff strongly recommends that SI be applied on all new or replacement piping, and preferably within two years for piping already installed. For piping with more than 2 years of operation, SI is considered to be less effective, because cracking may already be present.

BWR primary coolant normally contains oxygen from radiolytic dissociation of water, and also contains other impurities such as chlorides, carbonates, and sulfur species. If the oxygen levels are reduced by using hydrogen injection, and other impurities are kept to very low levels, IGSCC of even sensitized material will be drastically reduced. This combination of water chemistry improvement is referred to as Hydrogen Water Chemistry (HWC). The staff recommends that HWC be implemented as soon as the practical and safety aspects have been worked out.

Some utilities have decided not to replace piping at this time. The staff has developed guidelines for interim actions that should be taken in these instances. Augmented inspection schedules for susceptible and repaired weldments are based on judgment regarding the probability that significant cracks or leaks will develop, considering the effectiveness of any repair or mitigative actions applied.

The staff believes that replacing degraded, susceptible piping with IGSCC resistant materials will provide the highest degree of assurance against future cracking problems. Nevertheless, the staff concludes that if the recommendations provided herein are implemented, adequate levels of piping integrity and reliability can be achieved.

The approved Staff Positions derived from the recommendations in this Report are implemented by Generic Letter 88-01.

TECHNICAL REPORT ON MATERIAL SELECTION AND PROCESSING GUIDELINES FOR BWR COOLANT PRESSURE BOUNDARY PIPING

1.0 INTRODUCTION

1.1 History

The subject of intergranular stress corrosion cracking (IGSCC) at welds in boiling water reactor (BWR) piping has been of continuous concern for almost 20 years. An ever-increasing amount of research and developmental activity related to understanding the causes of the cracking and ways to prevent it has been going on during this time period. Under the auspices of NRC, two Pipe Crack Study Groups have reviewed the problem in BWRs--one in 1975 and the other in 1979. Reports of the findings of these groups were published (NUREG-75/067 and NUREG-0531), and staff guidelines prepared to implement their recommendations were published as NUREG-0313 entitled "Technical Report on Material Selection and Processing Guidelines for BWR Coolant Pressure Boundary Piping," and NUREG-0313, Revision 1.

Until recently, significant cracking of large-diameter piping (12-in. diameter and larger) was considered to be relatively unlikely, and even if it occurred it was expected that cracks would remain shallow. In Japan some cracks had been detected in the 12-in-diameter recirculation riser pipes. Because of this, NUREG-0313, Rev. 1 recommended that augmented inservice inspection (ISI) on a sampling basis be performed for these pipes. Shallow cracking was discovered in pipes larger than 12-in-diameter in Germany but it was not clear that either the Japanese or German experience was relevant to plants built in the United States.

During a hydrostatic test in March 1982, slight leakage was detected at two of the furnace-sensitized recirculation safe ends at Nine Mile Point. When these safe ends had been examined ultrasonically 9 months earlier, no cracking was reported. Additional ultrasonic testing (UT) using more sensitive procedures disclosed cracks at many of the 28-in-diameter recirculation piping welds.

This finding was important for two reasons:

(1) It could no longer be believed that large pipes were relatively immune to significant cracking.

(2) It cast doubt on the adequacy of the UT procedures used at that time to detect cracks in large pipes.

IE Bulletin 82-03 was issued to specify augmented inspections of large piping in the recirculation systems of plants (9 units) with outages scheduled in late 1982 and spring 1983. It also specified that inspection teams demonstrate that they could detect and properly identify cracks in large-diameter pipe welds. IE Bulletin 83-02 was later issued to require inspections at all other operating BWRs (14 units) with more than 2 years of operating service, and to upgrade the UT performance capability demonstrations required of the inspection teams. Reinspections at the next refueling outage were required by Generic Letter 84-11, which also provided specific guidance regarding flaw evaluation and repair for interim operation.

The results of these inspections varied greatly from plant to plant. Some found very little, if any, cracking. Others found very significant cracking in a large percentage of the recirculation, residual heat removal (RHR) system, and reactor water cleanup system piping welds.

The discovery of significant cracking in the large-diameter piping, the development of ASME Code procedures for evaluating flaws in such piping, and results of further development of materials and processes to mitigate or prevent IGSCC led to the decision to revise NUREG-0313.

1.2 Revision 1 of NUREG-0313

NUREG-0313 was revised in 1980 to provide guidance and recommendations regarding materials and processes that could be used to minimize IGSCC and to provide recommendations about augmentation of the extent and frequency of ISI on welds considered to be susceptible to IGSCC.

Revision 1 also provided recommendations about upgrading leak detection systems and leakage limits for plants with susceptible welds.

1.3 Revision 2 of NUREG-0313

This present (second) revision updates these recommendations and adds several subjects:

(1) It provides guidance for performing ASME Code, Section XI, IWB 3600, calculations for flaw evaluation.

(2) It provides recommendations regarding repair of cracked piping.

(3) It recommends formal performance demonstration tests for UT examiners, such as those prescribed by IE Bulletins 82-03 and 83-02 and currently being conducted under the NDE Coordination Plan, agreed upon by NRC, EPRI, and the BWROG. This will provide additional assurance that inspections for IGSCC in BWR piping will be performed in an effective manner.

The approach used in previous editions of NUREG-0313 to identify welds that require augmented inspection is simplified, but is expanded to include consideration of reinspections of welds found to be cracked, with or without repair or mitigation actions. The current approach is based on the following:

(1) All stainless steel welds in high-temperature BWR systems are considered to be subject to IGSCC unless measures have been taken to make them resistant.

(2) The frequency and sample size used to inspect all safety related piping welds in BWR plants will depend on the material and processing used. Simple bases are provided for such classification.

(3) Some utilities may choose not to replace, or to operate for some interim period of time before making major modifications or replacing piping. This would mean that operation with cracked or repaired welds will be desired. Guidance is provided to cover these situations.

1.4 Bases for Recommendations

Extensive work sponsored by industry through the Electric Power Research Institute (EPRI), General Electric (GE), and the U.S. Nuclear Regulatory Commission (NRC) has been carried out since the second Pipe Crack Study Group reported in 1978-1979 (NUREG-0531). It is not the objective of this report to cover this work in detail. NUREG-1061, Vol. 1 was prepared by the Pipe Crack Task Group of the Piping Review Committee. It represents an in-depth discussion of the technical aspects of IGSCC in BWR piping, and provides recommendations regarding materials and processes available to mitigate or eliminate the problem. It also includes a discussion of the technical basis for the guidelines for interim operation used by the staff.

This revision is based primarily on the information presented in NUREG-1061, as modified by more recent advances in ultrasonic testing and fracture mechanics evaluation methods. It also takes cognizance of work in progress related to serviceability of cracked pipes reinforced by weld overlay or mitigated by IHSI being performed at General Electric and PNL under EPRI and the BWROG sponsorship, and related work at ANL funded by the NRC, as well as public comments received on NUREG-1061, Vol. 1.

1.5 Piping Replacement

As stated in the staff paper to the Commission (SECY-84-301), it is the staff's long range goal to bring all affected plants in line with regulations without undue reliance on augmented inspections. Although not required, utilities with degraded and repaired piping systems should consider replacing such piping in their future plans, taking into account relevant aspects of their situations.

Procedural guidance regarding pipe replacement licensing activities is provided in Generic Letter 84-07, dated March 14, 1984.

2.0 METHODS TO REDUCE OR ELIMINATE IGSCC

There are three primary ways to minimize the occurrence of IGSCC in BWR piping:

(1) Use material that is not subject to sensitization by welding, or solution heat treat after welding.

(2) Use processes that reduce the tensile stress level at the inner surface of the pipe near the weld.

(3) Modify the BWR water chemistry to control the levels of oxygen and other aggressive contaminants to very low levels.

Each of these three basic approaches are discussed below, and recommendations regarding each are presented.

2.1 Materials for New or Replacement Piping

Sensitization involves carbon diffusion out of solution forming carbides at grain boundaries upon moderate heating; therefore, reducing the carbon content of the material will result in reducing the degree of sensitization resulting from a given thermal exposure, assuming that other factors remain equal. However, because the susceptibility of an austenitic stainless steel is also affected by other variables, such as grain size, previous heat treatment, amount of cold work, trace impurities, and overall compositional balance, complete dependence on reduced carbon content may not be effective unless the carbon level is very low. Nevertheless, a high degree of protection against IGSCC will result if the carbon content is kept below 0.035%, as specified for type 304L grade material. Freedom from sensitization will be much more certain if the carbon levels are controlled to even lower levels.

If carbon is limited to very low levels (such as below 0.02%), the strengthening effect of the carbon is lost, and the material has lower strength, which results in lower Code-allowable stresses. Some heats of type 304L material will also have strength levels too low to meet the minimum specified strength level for standard type 304. Therefore, the replacement of piping with low carbon grades may require redesigning or using thicker wall pipes.

Industry has overcome these problems by developing special grades of austenitic stainless steel. Carbon content is kept very low, and the reduction in strength is compensated for by adding controlled amounts of nitrogen. Molybdenum is often added; it enhances strength and resistance to sensitization.

The grades of austenitic stainless steels developed for increased resistance to sensitization are listed below.

Series 300 stainless steels developed for increased resistance to sensitization

Steel	C %, max.	Cr %	Ni %	Mo %	N %
304L	0.035	18.0-20.0	8-10.5	--	--
304NG*	0.02	18.0-20.0	8-12.0	--	0.06-0.10
316L	0.035	16.0-18.0	10.0-14.0	2.0-3.0	--
316NG*	0.02	16.0-18.0	10.0-14.0	2.0-3.0	0.06-0.10
347NG	0.03	17.0-19.0	9.0-13.0	**	

*304NG and 316NG were formerly called 304K and 316K, respectively.
**Minimum Nb + Ta = 10 x %C.

Weld metal with low carbon and controlled ferrite (such as 308L with 7.5% minimum ferrite) is resistant to sensitization and IGSCC. This resistance is also somewhat dependent on the microstructure produced by the specific welding process used. Weld passes diluted with high carbon base material will not have suitable resistance

Cast austenitic stainless steel with low carbon and high ferrite content is also resistant to sensitization and IGSCC.

Other common materials such as carbon steels are suitable for many BWR piping systems and are immune to the problem of sensitization and resultant IGSCC. Higher strength alloy steels are less desirable; they may be subject to other types of cracking.

2.1.1 Staff Recommendations on Materials

The materials considered resistant to sensitization and IGSCC in BWR piping systems are:

(1) Low carbon wrought austenitic stainless steel, which includes types 304L, 304NG, 316NG and similar low carbon grades with a maximum carbon content of 0.035%. Type 347, as modified for nuclear use, will be resistant with somewhat higher carbon content, the usual maximum of 0.04% is adequate. These materials are generally tested for resistance to sensitization in accordance with ASME A262-A, -E1, or equivalent standard.

(2) Low carbon weld metal, including types 308L, 316L, 309L and similar grades, with a maximum carbon content of 0.035% and a minimum of 7.5 percent (or FN) ferrite as deposited. Low carbon weld filler material especially developed for joining modified type 347 is also resistant as deposited.

Welds joining resistant material that meet the ASME Boiler and Pressure Vessel Code requirement of 5 percent (or FN) ferrite, but are below 7.5% may be sufficiently resistant, depending on carbon content and other factors. These will be evaluated on an individual case basis.

(3) Piping weldments are considered resistant to IGSCC if the weld heat affected zone on the inside of the pipe is protected by a cladding of resistant weld metal. This is often referred to as corrosion resistant cladding (CRC).

(4) Cast austenitic stainless steel with a maximum of 0.035% carbon and a minimum of 7.5 percent (or FN) ferrite. Weld joints between resistant piping and cast valve or pump bodies that do not meet these requirements are considered to be special cases, and are covered in the Staff Position on Inspection Schedules below.

(5) Austenitic stainless steel piping that does not meet the requirements of (1) above is considered to be resistant if it is given a solution heat treatment after welding.

(6) Other austentic materials, including nickel base alloys such as Inconel 600, will be evaluated on an individual case basis. Inconel 82 is the only commonly used nickel base weld considered to be resistant.

The staff recommends that no austenitic material be considered to be resistant to cracking in the presence of a crevice, such as formed by a partial penetration weld, where the crevice is exposed to reactor coolant.

2.2 Processes for New, Replacement, or Older Piping

Special or controlled processing during or after fabrication can provide protection from IGSCC in three ways:

(1) removing sensitization,
(2) preventing sensitization, and
(3) providing favorable state of residual stress.

There are several special processes that have proved effective in one or more of these ways; they are discussed below:

Solution Heat Treatment

The normal metallurgical treatment used to ensure freedom from sensitization is to perform a complete solution heat treatment (SHT) to the piece after welding or other processing. It consists of heating the material to a high enough temperature to dissolve all carbides, then cooling fast enough to retain the carbon in solution. Standard specifications are used to control the process; the chief concern is providing fast cooling.

Note that the solution heat treatment must be performed after welding, and complex piping sections may be difficult to cool fast enough from the solution temperature. Interiors of long or complex piping runs may pose a particular problem.

To be effective, solution heat treatments must be performed in accordance with written procedures that have been proven to be effective for the size and geometry of the piece, and must be in accordance with applicable specifications.

Heat Sink Welding

Heat sink welding (HSW) is a term applied to a method of butt welding pipes or fittings in which the major portion of the weld is produced with cooling water inside the pipe. The cooling effect of the water minimizes the sensitization caused by the welding process, and in addition, produces a steep temperature gradient through the pipe wall during welding. This steep temperature gradient causes tensile thermal stresses on the inside of the pipe to exceed the yield strength of the material. After the welding is completed and the weldment is cooled, the inner portion of the weld is under high compressive residual stress. This is the opposite of what is caused by normal welding. The high compressive stresses are maintained through about half the wall thickness. The combination of reduced sensitization and high beneficial residual stresses provides significant resistance to IGSCC.

Stress Improvement Processes

One of the major sources of stress causing IGSCC is the residual tensile stress that remains on the inside of the weld joint after the normal butt welding process. Processes have been developed that effectively reverse this residual stress distribution, and actual pipe tests have shown that this is very effective in inhibiting IGSCC in sensitized welds that have been treated by a Stress Improvement Process (SIP). There are two such processes that are considered fully qualified to provide this mitigation.

Induction Heating Stress Improvement (IHSI)

Induction heating stress improvement (IHSI) is a process originally developed in Japan for treating piping weldments already fabricated or installed in a plant. It consists of heating the outside of the pipe by induction coils to controlled temperatures (≈800°F) while cooling water is circulated inside the pipe. The high gradients produce the same effect as HSW. The inside of the pipe is plastically strained in tension during the process, causing residual compressive stresses after the process is completed.

Mechanical Stress Improvement Process

The Mechanical Stress Improvement Process (MSIP) is a later development that uses a hydraulic system to uniformly compress the entire pipe at a location near the weld joint. It also causes slight plastic strain, and the residual stresses remaining after the treatment are compressive in the location susceptible to IGSCC because of weld sensitization.

Last Pass Heat Sink Welding

The last pass heat sink welding (LPHSW) process is similar to HSW, except that only the last welding passes are performed when there is cooling water inside the pipe. Although some preliminary tests appear promising, it cannot be considered to be fully effective at this time.

2.2.1 Staff Recommendations on Processes

The processes considered to be qualified for providing resistance to IGSCC in BWR piping welds are:

(1) Solution Heat Treatment (SHT)
(2) Heat Sink Welding (HSW)
(3) Induction Heating Stress Improvement (IHSI)
(4) Mechanical Stress Improvement Process (MSIP)

Although last pass heat sink welding (LPHSW) is not considered to be fully qualified, specific cases may be evaluated individually.

2.3 Water Chemistry Modifications

Intergranular stress corrosion cracking of sensitized and stressed stainless steel requires a corrosive environment. Although BWR reactor coolant is comparatively pure water, the small amounts of impurities usually present are enough to cause IGSCC. These impurities fall into two general classes; those that increase the oxidizing potential, and those that increase the electrical conductivity of the water. Both must be reduced to very low levels to achieve an electrochemical potential below which IGSCC cannot be initiated or propagated.

Oxygen is formed in the core of light water reactors by the disassociation of water by radiolysis. This reaction can be inhibited by the addition of hydrogen to the water, as is done in pressurized water reactors. Until recently, this was not considered to be feasible in boiling water reactors, therefore, the normal oxygen content of BWR reactor water is about 200 parts per billion (PPB), providing an oxidizing environment conducive to IGSCC in the entire BWR primary system.

Efforts to find ways to reduce the oxygen levels in BWRs led to the development of a hydrogen addition methodology that appears to be effective and practicable. Tests conducted in the Dresden 2 plant over the past several years indicate that oxygen levels can be reduced to levels of 10 to 20 PPB, although occasional excursions to higher levels may occur. Tests indicate that IGSCC will not occur at an oxygen level of 20 PPB or less, if other contaminants are controlled to keep conductivity low.

Contaminants that increase the conductivity of the reactor water can come from several sources, such as condenser leakage, resin beds, etc. They include chlorides, carbonates, and sulfur species. Because the electrochemical potential causing IGSCC depends on both the oxidizing state and the conductivity of the water, the conductivity must be held to very low levels. Laboratory tests have indicated that conductivity levels should be kept to a maximum of 0.3 micro-Siemens (μS) per centimeter with oxygen at 20 PPB or less to prevent IGSCC. Although the tests in Dresden 2 indicated that such conductivity levels could be attained, occasional excursions must be anticipated, and plant to plant variations are likely to be significant in this regard.

This combination of oxygen and conductivity control is commonly referred to as Hydrogen Water Chemistry, or HWC. Although tests have shown that HWC can inhibit IGSCC, some questions regarding radiation effects, fuel performance, etc. are still being resolved. Field implementation and engineering are being actively pursued by the industry, and it is expected that within the next few years, HWC will be considered a practical method of control.

2.3.1 Staff Recommendation on Water Chemistry

The use of hydrogen water chemistry, together with stringent controls on conductivity, will inhibit the initiation and growth of IGSCC. However, the responses of BWRs to hydrogen injection differs from plant to plant, and the development and verification of a generic HWC specification is not yet complete. For these reasons, reduction in piping inspection frequency based on the use of HWC will be considered on an individual case basis at the present time. Staff criteria for evaluating the effectiveness of HWC are under development. If fully effective HWC is maintained, a factor of two in reduction of inspection frequency may be justified for susceptible weldments.

3.0 EVALUATION AND REPAIR OF CRACKED WELDMENTS

When cracks are found in BWR piping, several alternatives (and combinations) are available to provide assurance of further safe operation of affected welds.

If the cracking is not too severe, the rules of ASME Code Section XI, IWB 3600 (as modified and expanded in Section 8) may be used for short-term interim operation. Further, SI may be applied to reduce the probability of further crack growth.

If the cracking is too severe to meet these rules, the affected piping must be repaired or replaced before the plant can be returned to service.

3.1 Repair Procedures

IGSCC in BWR piping initiates at the inner surface of the pipe and grows progressively through the wall toward the outside. It commonly initiates near the weld root and progresses up the heat-affected zone (HAZ) close to the weld, and sometimes in the weld. Therefore, cracking can affect a region of the pipe longer in axial extent than the maximum width of the weld if cracks occur on both sides of the weld. The usual repair process during construction is to grind out the defective area and fill the area with weld metal. This is not practical for repair of IGSCC, because IGSCC starts from the inside surface, requiring removal of essentially the entire weld and HAZ area.

There are several repair methods available for at least short-term operation:

(1) Weld overlay reinforcement
(2) Partial replacement
(3) SI (for minor cracks)
(4) Approved clamping devices

These are discussed below.

3.1.1 Weld Overlay Reinforcement

Weld overlay reinforcement consists of applying weld metal over the weld and for a specified minimum distance beyond the weld on both sides. This is done completely around the outside surface of the pipe overlapping each pass. IGSCC-resistant low-carbon, high-ferrite type 308L weld metal is used, and the process is usually performed with an automatic welding machine using the Gas Tungsten arc (GTAW) or Gas Metal arc (GMAW) processes. Weld overlay is performed with cooling water in the pipe during welding, and there is no need to drain the pipe during repair. More specific design details and quality control recommendations are covered in Section 4.0.

3.1.2 Partial Replacement

A very effective repair method is to cut out a section of the pipe containing the defective weldments and to weld in another piece of pipe. The major drawback to this approach is that the affected run of pipe must be drained and dried. Either all fuel must be removed from the reactor vessel or special plugs must be installed when this type of repair is used in portions of piping that cannot be isolated.

If this method can be used, a fully effective repair can be made with resistant material, using welding processes such as heat sink welding for the new installation welds and high-ferrite type 308L weld material. SI can also be applied.

Another disadvantage of this process (assuming that draining is feasible) is that high radiation exposures to workers may be encountered at older plants from the inner surfaces of the pipes. Prior decontamination can alleviate this problem.

Both weld overlay and partial replacement cause the pipe to shrink in the axial direction. If several such repairs are made in one length of pipe, additional stresses will be introduced by this shrinkage which must be taken into account in the stress analysis required for the repair, and in the fracture mechanics analyses of crack growth in other welds of the pipe system. Measurements of shrinkage on weld procedure qualification test pieces can provide guidance regarding how much shrinkage can be expected. Actual measurements made during the repair should be used in the final stress analysis.

3.1.3 Stress Improvement

As discussed above, SI alters the residual stress pattern, putting the inner part of the pipe wall in compression, thus inhibiting crack initiation. If cracks are present, the situation is more complex. If cracks are shallow the process will probably prevent further growth, as long as the residual stress pattern remains favorable. The process may stretch cracks open but tests have shown that they are not extended in depth by the process. Such stretching may even be beneficial for shallow cracks because it enhances the resulting compressive stress around the crack tip.

The tips of deeper cracks, particularly those penetrating deeper than half way through the pipe wall, are likely to be in a general tensile stress field after SI processes. This could cause such cracks to propagate through the wall, faster than they would without the SI treatment. Cracks will not be expected to grow longer because of the beneficial residual stress on the inside portion of the pipe. Therefore, neither short cracks of medium depth or longer shallow cracks are expected to grow to a significant size after an SI treatment.

3.1.4 Mechanical Clamping Devices

Another approach to reinforcing a cracked weldment is to use a mechanical clamp. One advantage of this approach is that the clamp may be periodically removed for weld examination. Such clamping devices will be reviewed for adequacy of mechanical design, materials of construction, and installation methods on a case basis.

3.2 Staff Recommendations on Repairs

3.2.1 Staff Recommendations on Weld Overlay Reinforcement

Weld overlay reinforcement made in accordance with recommendations described in this report are considered to be acceptable at least for short-term operation. Weld overlay may be considered for longer term operation provided:

(1) The overlays are in conformance with the criteria of Section 4.0 of this report; and

(2) they are inspected in accordance with the criteria of Section 5.0 by UT examiners and procedures qualified to inspect overlayed welds.

Weld overlays not meeting (1) above may be reinforced to the extent necessary to meet the staff position, if desired.

3.2.2 Staff Recommendations on Partial Replacement

Repair of cracked weldments by partial replacement can be considered to be fully effective if appropriate materials and weld processes are used, and therefore are considered to be resistant to IGSCC.

3.2.3 Staff Recommendations on SI of Cracked Weldments

SI may be considered as a partial mitigation process when applied to weldments with short or shallow cracks. Details of allowable crack sizes in this regard are covered in the next section. Note that SI is only considered effective if it is followed by a qualified UT examination, and if cracks are found they must be sized, both in depth and length, by procedures and personnel qualified to perform sizing examinations according to recommendations given in Section 5.1 of this report.

3.2.4 Staff Recommendations on Clamping Devices

Clamping devices may be used for temporary reinforcement of cracked weldments. Each case must be reviewed and approved on an individual basis.

4.0 CRACK CHARACTERIZATION AND REPAIR CRITERIA

4.1 Flaw and Repair Evaluation Criteria

This section provides guidance and staff positions regarding methods to evaluate IGSCC cracks for limited further operation. It also covers evaluation methods and acceptance criteria for repairs if immediate pipe replacement is not practicable.

The methods and criteria described in this section are generally in accordance with IWB 3640 of Section XI of the ASME Boiler and Pressure Vessel Code. In particular, IWB 3642 provides for flaw evaluation using fracture mechanics or other applicable methods. The Code requires that crack growth be calculated, and the flawed joint is acceptable for further operation only for the time period that the flaw remains small enough that the Code-intended safety or design margins are maintained.

In IWB 3641, the Code (Winter 83 Addenda) provided simple tables of allowable crack depth as a function of the primary stress level and crack length. These tables are based on limit load calculations, and assume that the material is tough. An overall margin of about 2.77 against net section collapse (limit load) failure mode is factored into the tables.

It was recognized that these tables did not provide an acceptable level of margin against failure for low toughness materials such as fluxed welds (SAW, SMAW). This is because low toughness material may fail at load levels below limit load, and secondary stresses (not considered in the original IWB 3641 tables) may also contribute to failure of low toughness materials.

This problem has now been addressed by the Code, and the 1986 Edition provides appropriate criteria for all types of welds.

4.2 Crack Growth Calculations

The rate of growth of cracks by IGSCC has been the subject of discussion and controversy for many years. Part of the problem is that the rate of growth as a function of stress is affected by the degree of sensitization of the material and the severity of the environment. A further complication has been that ways to measure the degree of sensitization have proved to be inaccurate or not relevant to the particular problem of BWR piping. For these reasons, many crack growth tests have been performed that were either too severe or not severe enough. The staff recommends a crack growth rate curve that is believed to be near the upper bound for weld-sensitized material in actual BWR environments. (See Appendix A)

Crack growth by IGSCC appears to follow a classical trend. If the logarithm of the growth rate is plotted against the logarithm of severity of loading, measured by the stress intensity factor (a fracture mechanics parameter) K_I, a linear relationship is found. As the K_I changes with crack growth, iterative calculations will track the growth of the crack with time. The calculational procedures recommended by the staff to predict crack growth are detailed in Appendix A.

Actual circumferential cracks in welds are usually very long in relation to their depth; therefore, crack growth in a congruent manner (maintaining the same shape) cannot be assumed, particularly for large-diameter pipes. The growth in the length direction, therefore, may be more than in the depth direction. Specifically, the growth along the length should be assumed to increase the aspect ratio (length to depth) by the same factor that the depth is increased. For example, if a crack with an aspect ratio of 3 to 1 grows to twice the original depth, the new length will be assumed to give an aspect ratio of 6 to 1. Cracks with aspect ratios over 20 to 1 are assumed not to change shape with crack growth.

Although axially oriented cracks are not likely to grow significantly beyond the sensitized zones on each side of the weld, they will grow through the weld if the weld metal is marginal in resistance to sensitization, and therefore was sensitized during welding. Axial cracks will therefore be assumed to grow through the wall but the length is limited to 1.5 times the thickness of the pipe.

4.3 Multiple and Complex Crack Characterization

Case 1

If Multiple cracks are present that will remain less than 20% of the circumference in total length after crack growth, they may be treated as one crack with the length equal to the sum of the lengths.

Case 2

If multiple cracks are present that will remain less than 30% of the circumference in total length after crack growth, they may be treated as one crack with the length equal to the sum of the lengths, provided that after crack growth each crack is separated by at least 20% of the circumference from all other cracks.

Case 3

All other situations regarding multiple cracks will be considered as a single 360° crack.

Case 4

Cracks on both sides of the weld will be treated as if they were all on the side of the weld with the thinnest wall; overlapping cracks or overlapping areas are considered as one crack.

4.4 Weld Overlay Design Criteria

4.4.1 Standard Overlay Design

The standard overlay should be designed to provide a nominal margin of 2.77 against limit load failure, assuming that the original crack was completely through the wall for 360°. The calculation method described in Section 4.1 is recommended. Because none of the original weld or heat affected zone is considered in the analysis, the stresses to be used in the analysis depend only on the kind of weld metal used for the overlay. Specifically, if the overlay is made using GTAW or GMAW processes, secondary stress need not be considered. Calculations are made using the as-overlayed joint dimensions and stress levels.

4.4.2 Design Overlays

In cases where cracks are perpendicular to the weld (axial) or short in the circumferential direction, even a small amount of overlay will prevent further growth in the length direction, because high compressive stresses are induced at the inner surface of the pipe. In such cases the overlay will also act to prevent leakage.

Weldments with a total length of circumferential cracking less than approximately 10% of the circumference, with no more than four axial cracks, are considered apropriate for repair by a designed overlay. A standard overlay should be used for more severe cracking.

The thickness of the designed overlay should be at least two layers of weld metal after the surface has passed surface examination by penetrant inspection (PT). If credit is taken for the thickness of the first layer, it should be shown by actual test to contain a minimum of 7.5% ferrite, and the original surface must have passed PT.

Because designed overlays take credit for part of the original pipe in their design, there are several ways that the lower toughness of the original fluxed weld may be taken into account. An acceptable design approach is to assume that the crack or cracks requiring the overlay are completely through the original pipe wall for the total length of crack involved. The overlay thickness is calculated so that the as-overlayed cracked weldment meets the IWB 3641 tables in Section XI of the ASME Boiler and Pressure Vessel Code.

Other approaches to overlay design may be evaluated on a case basis. In general, it is recommended that highly stressed welds should be reinforced with standard overlays.

4.4.3 Limited Service Overlays

Overlay designs not meeting the above criteria for either Standard or Designed overlays are only recommended for limited service, such as one fuel cycle of operation. (See 5.3.2.6)

4.5 SI Crack Mitigation Criteria

In general, SI is only recommended for use on weldments with minor cracking. This is because the tips of deep cracks can be in an area of high tensile stress caused by the process, and further crack growth may even be accelerated by the SI treatment. Because the effectiveness of the SI treatment is also related to the applied stress on the weldment, mitigation by SI is not recommended for weldments with service stresses over 1.0 S_m, cracks deeper than 30% of the wall, circumferential cracking longer than 10% of the circumference, or axial cracks of any extent. (See 5.3.2.6)

5.0 INSPECTION OF PIPING FOR IGSCC

5.1 Weldments Subject to Inspection

The discussion and recommendations in this section apply to BWR piping made of austenitic stainless steel that is four inches or larger in nominal diameter and contains reactor coolant at a temperature above 200°F during power operation regardless of code classification. It also applies to reactor vessel attachments and appurtenances such as jet pump instrumentation penetration assemblies and head spray and vent components.

This section does not apply to piping made of carbon steel classified as P-1 by the ASME Boiler and Pressure Vessel Code.

5.2 Inspection Methods

One positive result of the extensive investigations performed on BWR piping is that no significant mode of degradation other than IGSCC has been noted. This means that inspections can focus on those approaches that are best suited for detecting and evaluating IGSCC. A less favorable finding is that special methods and specific operator training are required to reliably detect and characterize IGSCC in the presence of the variable geometric configurations of the weldments.

It is not the intent of this report to provide specific guidance to operators regarding details of equipment and procedures. This function is best handled by Code activities in which industry and regulatory participants reach a consensus. It is not a simple problem; finding and recognizing IGSCC by UT is still as much an art as it is a science. The intent of the recommendations in this report is to ensure that the UT operators inspecting BWR piping for IGSCC can detect and characterize IGSCC in the welds they inspect, and that they will accomplish these two functions reliably in the field.

5.2.1 Staff Recommendations on Inspection Methods and Personnel

Although examinations should be performed in general accordance with the ultrasonic examination requirements of the applicable edition of the ASME Code, details of the examination method, acceptance criteria, and personnel qualification should be upgraded to ensure that the examinations will be effective.

All examination procedures and the specific equipment used in the field inspections, and all level 2 and 3 NDE examiners or operators for flaw detection and sizing should demonstrate their field performance capability on cracked, preferably service-induced, samples in a manner acceptable to the NRC. No NDE examiner or operator should perform examinations of BWR piping without proving his competence even if he must take special training to gain specific skills and knowledge required to perform these inspections. The program being conducted at EPRI NDE center in Charlotte, North Carolina, in accordance with the NDE Coordination Plan agreed upon by NRC, EPRI, and BWROG, as upgraded in September 1985 is considered to be acceptable. Any future changes in this program should be in conformance with the Coordination Plan and approved by the Executive Director for Operations, NRC

Specialized radiographic techniques developed for detection of IGSCC may be used in cases where ultrasonic examination is not practical, or to augment the UT method.

5.2.2 Flaw Size Uncertainty

Inspections performed under IE Bulletins 82-03 and 83-02 were often performed by examiners with limited knowledge and experience in sizing IGSCC. Although the length of the cracks could usually be defined satisfactorily, must UT operators could not determine their throughwall depth accurately and reliably. After this was shown to be true in industry-wide evaluation projects, the industry developed more effective and diverse techniques, and the NDE Center initiated a training and qualification program specifically for crack depth sizing. The NRC staff participated in this effort by defining acceptable levels of performance, based on the level of accuracy required to ensure safe operation. The staff now believes that flaw sizes determined by examiners and procedures qualified by test will not be grossly underestimated or overestimated provided that an inspectable weld joint configuration and weld surface exist.

The depth of cracks not sized by fully qualified personnel or with limitations to examination (such as wide weld crowns, obstructions, or other adverse geometrical configurations) should be assumed to be at least 75% of the wall in depth, and the flaw so evaluated.

5.3 Inspection Frequency

5.3.1 Weldment IGSCC Condition Category Definitions

The purpose of inservice inspection of piping is to provide continued assurance that the structural integrity and reliability (e.g., see 10 CFR 50.55a(g)(6)(ii)) of the piping is maintained and that there continues to be an extremely low probability of abnormal leakage (10 CFR 50 Appendix A, Criterion 14). Piping with weldments that are susceptible to degradation mechanisms such as IGSCC require more frequent inspections to provide such continued assurance. Weldments in BWRs will have different degrees of susceptibility to IGSCC depending on the materials and processing involved. Therefore, the inspection frequencies recommended by the staff are based on the condition of each weldment

The extent of augmented inspection recommended depends on the number of cracked welds in the plant as well as the condition of each individual weldment. In addition, welds that have already been found to be cracked will have varying degrees of susceptibility to further cracking, depending on the remedial actions taken.

Some may be considered repaired, at least on a conditional basis; whereas others with marginal or no repair are considered fit for only very limited service without additional action. These seven categories of weldment conditions are listed in Table 1 and defined in detail below.

5.3.1.1 Definition of IGSCC Category A Weldments

IGSCC Category A Weldments are those with no known cracks, that have a low probability of incurring IGSCC problems, because they are made entirely of IGSCC resistant materials or have been solution heat treated after welding. CRC is considered to be IGSCC resistant, and welds joining cast pump and valve bodies to resistant piping are considered to be resistant weldments.

5.3.1.2 Definition of IGSCC Category B Weldments

IGSCC Category B Weldments are those not made of resistant materials but have had an SI performed either before service or within two years of operation. If the SI is performed after plant operation, a UT examination after SI to ensure that they are not cracked is required.

5.3.1.3 Definition of IGSCC Category C Weldments

IGSCC Category C Weldments are those not made of resistant materials (see 2.1.1), and have been given an SI process after more than two years of operation. An ultrasonic examination to ensure that they are not cracked should be performed after the SI treatment as part of the process.

5.3.1.4 Definition of IGSCC Category D Weldments

IGSCC Category D Weldments are those not made with resistant materials, and have not been given an SI treatment, but have been inspected by examiners and procedures in conformance with section 5.2.1, and found to be free of cracks.

5.3.1.5 Definition of IGSCC Category E Weldments

IGSCC Category E Weldments are those with known cracks but have been reinforced by an acceptable weld overlay or have been mitigated by an SI treatment with subsequent examination by qualified examiners and procedures to verify the extent of cracking. Guidelines for acceptable weld overlay reinforcement and extent of cracking considered amenable to SI treatment are covered in Sections 3.2 and 4.5 of this document.

5.3.1.6 Definition of IGSCC Category F Weldments

IGSCC Category F Weldments are those with known cracks that have been approved by analysis for limited additional service without repair. Weldments found to have significant cracking or a questionable extent of cracking that have been minimally overlay reinforced (not in conformance with Section 4.1) are considered acceptable only for interim operation. Weldments with significant cracking that have been SI treated may also be considered to be in this category. Detailed guidelines used to evaluate specific cases are provided in Sections 3.0 and 4.0 of this document.

5.3.1.7 Definition of IGSCC Category G Weldments

IGSCC Category G Weldments are those not made of resistant materials, have not been given an SI treatment and have not been inspected in accordance with Section 5.2.1. Stress improved welds that were not inspected after the SI treatment are considered to be Category G weldments until the post-SI inspection has been performed.

5.3.2 Staff Recommendations on Inspection Schedules

The staff recommendations in the extent and frequency of inspection for various weldments categorized in accordance with 5.3.1 are discussed in detail below and summarized in Table 1.

5.3.2.1 Inspection Schedule for IGSCC Category A Weldments

IGSCC Category A welds should be inspected according to a schedule similar to that called for in Section XI of the Code. A representative sample of 25% of the welds should be examined every 10 year interval. The sample selection should reflect the best technical judgment of the plant owner.

5 3.2.2 Inspection Schedule for IGSCC Category B Weldments

IGSCC Category B welds are more likely to develop cracking than Category A welds, so a larger sample size is needed. Specifically, a representative sample of 50% of IGSCC Category B welds should be examined every 10 year interval.

5 3.2.3 Inspection Schedule for IGSCC Category C Weldments

IGSCC Category C welds have longer service life prior to SI than IGSCC Category B welds, so are more likely to contain undetected cracking. All IGSCC Category C welds should be inspected within two refueling cycles after the post-SI inspection, and every 10 years thereafter.

5.3.2.4 Inspection Schedule for IGSCC Category D Weldments

Category D Weldments should be inspected at least once every two refueling cycles. Approximately half of the IGSCC Category D weldments in the plant should be inspected each refueling outage.

5.3.2.5 Inspection Schedule for IGSCC Category E Weldments

Repaired and stress improved cracked weldments, IGSCC Category E should be inspected at least once every two refueling cycles after repair. Approximately half of them should be inspected during the first refueling outage after repair.

If it is desired to operate for more than two fuel cycles with overlay reinforcement repairs, the overlayed weldments should be inspected to ensure that the overlays will continue to provide the necessary safety margin. For standard and designed overlays meeting the requirements of Section 4.0, the inspection method should provide positive assurance that cracks have not progressed into the overlay. It is also desirable that the inspection procedure be capable of detecting cracks that originally were deeper than 75% of the original wall thickness, or that have grown to be deeper than 75% of the original wall thickness. Ultrasonic inspections should be performed using a procedure that has been demonstrated to be reliable and effective, and should be performed by personnel that have been trained and qualified in the specific methods for inspections of overlays.

5.3.2.6 Inspection Schedule for IGSCC Category F Weldments

IGSCC Category F Weldments are approved for limited service only, and should be inspected every refueling outage, unless a shorter service period has been specified. Weldments that are classified as IGSCC Category F because overlay repairs or SI treatment mitigation is not according to recommendations in Sections 3.2 and 4.5 may be upgraded to IGSSC Category E after 4 successive examinations indicate no adverse change in cracking condition.

5.3.2.7 Inspection Schedule for IGSCC Category G Weldments

IGSCC Category G Weldments should be inspected at the next refueling outage.

5.3.3 Inspection Schedules with HWC

If improved water chemistry control, including hydrogen additions is implemented, the time schedule for inspections may be extended. Although specific details of such extensions will be evaluated on a case basis, it is anticipated that periods between inspections could be lengthened by about a factor of two for category B, C, D and E weldments.

5.3.4 Staff Recommendations on Sample Expansion

If one or more cracked welds in IGSCC Categories A, B, or C, are found by a sample inspection during the 10 year interval, an additional sample of the welds in that category should be inspected, approximately equal in number to the original sample. This additional sample should be similar in distribution (according to pipe size, system, and location) to the original sample, unless it is determined that there is a technical reason to select a different distribution. If any cracked welds are found in this second sample, all of the welds in that IGSCC Category should be inspected.

If significant crack growth, or additional cracks are found during the inspection of one or more IGSCC Category E welds, all other Category E welds should be examined.

a) Significant crack growth for overlayed welds is defined as crack extension to deeper than 75% of the original wall thickness, or for cracks originally deepter than 75% of the pipe wall, evidence of crack growth into the effective weld overlay.

b) Significant crack growth for SI mitigated Category E welds is defined as growth to a length or depth exceeding the criteria for SI mitigation. (10% of circumference or 30% in depth).

TABLE 1

SUMMARY OF RECOMMENDED INSPECTION SCHEDULES FOR BWR PIPING WELDMENTS

DESCRIPTION OF WELDMENTS	NOTES	IGSCC CATEGORY	INSPECTION EXTENT & SCHEDULE
Resistant Materials		A	25% every 10 years (at least 12% in 6 years)
Nonresistant Matls SI within 2 yrs of operation (1)	(1)	B	50% every 10 years (at least 25% in 6 years)
Nonresistant Matls SI after 2 yrs of operation	(1)	C	All within the next 2 refueling cycles, then all every 10 years (at least 50% in 6 years)
Non Resistant Matl No SI	(1)	D	All every 2 refueling cycles
Cracked Reinforced by weld overlay or mitigated by SI	(1)(2)	E	50% next refueling outage, then all every 2 refueling cycles
Cracked Inadequate or no repair	(2)	F	All every refueling outage
Non Resistant Not Inspected	(3)	G	All next refueling outage

Notes:

(1) All welds in non-resistant material should be inspected after a stress improvement process as part of the process. Schedules shown should be followed after this initial inspection.

(2) See recommendations for acceptance weld overlay reinforcements and stress improvement mitigation.

(3) Welds that are not UT inspectable should be replaced, "sleeved", or local leak detection applied. RT examination or visual inspection for leakage may also be considered.

6.0 LEAK DETECTION

The staff reviewed the leak detection and leakage limits that have been applied to BWRs by past revisions of NUREG-0313, Bulletins, and Generic Letter 84-11. In NUREG 1061 Vol. 1, "Report of the U.S. Nuclear Regulatory Commission Piping Review Committee," the report of the Pipe Crack Task Group, it was recommended that leakage detection equipment should be improved, and that the upper limit on unidentified leakage should be decreased from 5 gpm to 3 gpm.

As a result of this review, the staff concluded that if the other recommendations of this report are followed, present leak detection systems will be adequate. Further, the staff concluded that the decrease in the limit on unidentified leakage recommended in NUREG-1061 Vol. 1, would constitute a backfit that could not be justified by a supporting Regulatory Analysis, in accordance with the new backfit rule, 10 CFR50.109.c.

Accordingly, the staff recommendations on leak detection and leakage limits are in accordance with past staff positions on the subject. Relaxation of the operability requirements for those plants with resistant or mitigated noncracked piping is also in accordance with past staff positions.

6.1 Staff Recommendations on Leak Detection

Leakage detection systems should be in conformance with Position C of Regulatory Guide 1.45 "Reactor Coolant Pressure Boundary Leakage Detection Systems, or as otherwise approved by the NRC.

1. Plant shutdown should be initiated for inspection and corrective action when, within any period of 24 hours or less, any leakage detection system indicates an increase in rate of unidentified leakage in excess of 2 gpm or its equivalent, or when the total unidentified leakage attains a rate of 5 gpm or equivalent, whichever occurs first. For sump level monitoring systems with fixed-measurement-interval methods, the level should be monitored at approximately 4-hour intervals or less.

2. Unidentified leakage should include all leakage other than

   (a) leakage into closed systems, such as pump seal or valve packing leaks that are captured, flow metered, and conducted to a sump or collecting tank, or

   (b) leakage into the containment atmosphere from sources that are both specifically located and known either not to interfere with the operations of unidentified leakage monitoring systems or not to be from a throughwall crack in the piping within the reactor coolant pressure boundary.

3. For plants operating with any IGSCC Category D, E, F, or G welds, at least one of the leakage measurement instruments associated with each sump shall be operable, and the outage time for inoperable instruments shall be limited to 24 hours, or immediately initiate an orderly shutdown.

APPENDIX A - CRACK GROWTH CALCULATIONS

Introduction

Crack growth calculations are required to evaluate the continued structural integrity of a weld with known cracks, if it is desired to continue operation without repair or reinforcement. The rate of growth of IGSCC is not easy to predict, because the several important factors are usually imperfectly known. Research work in this area has been helpful in defining the general effect of these factors but a large uncertainty in crack growth predictions still remain.

Nevertheless crack growth calculations can be performed within certain limits with enough confidence to ensure plant safety without excessive conservatism.

Crack growth calculations are based on the fundamental concept that the crack growth rate of a specific material in a specific environment will be a function of the applied stress intensity factor, K_I. Laboratory crack growth data are usually presented in this manner, details of the calculational methods used to calculate K_I are provided later in this Appendix but an important point to note here is that K_I depends on the crack depth therefore it changes continuously during crack growth.

Crack growth analysis methods are, therefore, iterative in nature. Given an initial crack depth, the K_I is calculated for the particular stress distribution of interest. Knowing the K_I, the amount of growth for a specific time is calculated, the growth is added to the initial crack depth, a new K_I is calculated, and the process is repeated Time intervals selected can vary from 1 hour to 1000 hours, depending on the rate of growth and rate of change in K_I with crack depth.

Selection of Crack Growth Rate Parameters

Although only two parameters, crack growth rate and K_I, are used, they are both highly dependent on several factors.

Crack growth rate is affected by the degree of sensitization of the material and by the severity of the environment. Our interest as it relates to BWR piping is primarily in a degree of sensitization normally caused by welding, and in an environment similar to normal BWR water conditions.

Most formal crack growth studies are carried out with standard fracture mechanics specimens, which makes K_I determination easy. These specimens are not readily machined from pipe walls, so the material is given an artificial sensitization treatment, intended either to simulate the effect of welding or, in some cases, the more severe effect of furnace sensitization. Tests to ascertain whether the intended degree of sensitization has been obtained are still inexact, causing significant scatter in laboratory test results intended to apply to a similar metallurgical state.

Tests to simulate the BWR environment are usually run at operating temperature in high purity water containing 0.2 gpm oxygen. This is generally accepted to be a representative condition, although higher oxygen levels could occur locally for short periods of time. Tests are also often run in water containing up to 8 gpm oxygen, usually to achieve accelerated comparisons of materials or conditions.

In addition to these standardized tests for crack growth rate, results of actual pipe tests are available. Many hundreds of welds have been tested in General Electric's pipe test facility. These tests, although generally more relevant in terms of material condition and environment, are more difficult to evaluate. K_I is more difficult to calculate, and accurate crack growth rates are also more difficult to measure. Nevertheless this body of data has been used to augment those data from the more standard laboratory tests to select appropriate crack growth rates.

Figure 1 (from NUREG/CR-3292) * shows much of the relevant laboratory data in the conventional form, where measured rates are plotted against K_I. This plot clearly shows the large scatter resulting from a wide variation in material condition and environment. This information, together with additional information from actual pipe tests, was used to select a crack growth curve that is appropriate for use in safety evaluations. Note that if the fastest crack growth rate shown in Figure I is used, cracks would be predicted to grow completely through pipe walls in a matter of days. Clearly this would not reasonably represent reality.

The curve selected for use by the NRC staff is shown on Figure 2. Note that it is a curved line on the semilogarithmic chart used in Figure 1. On log-log coordinates, as used in Figure 2, it plots as a straight line. In calculations, it is expressed as:

$$da/dt = 3.590 \times 10^{-8} \times K_I^{2.161} \quad \text{inches per hour}$$

As can be seen, the crack growth rate is a very strong function of K_I. In laboratory tests, K_I is easily determined with good accuracy. This is not the case for real pipes and real pipe cracks. There are two major sources of uncertainty: knowledge of the actual crack size and shape, and the actual stress distribution in the area of the crack to be evaluated. The service distribution at a pipe weld is made up of the stress caused by the service loading and the residual stresses caused by the welding process. Of these, knowledge of the residual stress is the more uncertain. Nevertheless, a residual stress distribution through the pipe wall must be defined, if realistic crack growths are to be calculated. Although this is covered later in more detail, several comments are in order here.

The residual stress distribution caused by welding is the major stress component causing IGSCC. Welding causes a high tensile residual stress on the inside surface of the pipe near the root of the weld where the material is sensitized.

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*Shack, W.J., et al., "Environmentally Assisted Cracking in Light Water Reactors: Annual Report, October 1981 - September 1982" NUREG/CR-3292, Washington DC. U.S. Nuclear Regulatory Commission, June 1983.

This residual stress level has been calculated and measured to be up to or above the yield strength of the material. It typically is four or five times as high as the service-induced stress. In fact, without this very high residual stress at the sensitized area, IGSCC would not be a problem in BWR piping. This fundamental observation is helpful; wherever this combination of stress and sensitization occurs, cracking occurs. In actual cases, if there are significant cracks, there must be significant tensile residual stresses, and this should be accounted for in the crack growth analysis. The method used by the staff is described below.

Stress Intensity Factor Calculations

There are several relatively standard analytical solutions available for calculating the stress intensity factor (K_I) caused by stress distributions of the type found at BWR pipe welds. The method using influence functions is the one used by the staff and will be summarized here. Other methods, such as those described in the ASME Boiler and Pressure Vessel Code, Section XI, Appendix A, may also be used where appropriate.

Stress Analysis

The total stress state, including residual stress, pressure stress, and other stresses caused by normal operation must be known or assumed. Note that factors such as stress indices used for other purposes should not be used when calculating stress levels that apply to K_I calculations.

Residual Stress

The laboratory-measured throughwall axial residual stresses on pipe wall thickness $\geq$ 1 inch are presented in Figure 3 (from NUREG/CR-3292). The solid line in Figure 3 is the axial residual stress distribution used for the calculation of stress intensity factors for pipe sizes of 12" diameter and larger. The residual stress distribution is the most complex analytical problem involved. This is handled by fitting the curve of residual stress distribution through the wall by an analytical expression. For this particular residual stress distribution, the nondimensional expression given below is used.

$$\sigma/\sigma_i = \sum_{j=o}^{4} \sigma_j \ \xi^j$$

where

σ_0 = 1.0
σ_1 = -6.910
σ_2 = 8.687
σ_3 = -0.480
σ_4 = -2.027
ξ = x/t
σ_i = stress magnitude at ξ = 0 (inner surface)

The above formula permits calculation of the residual stress value at any point (x) through the vessel wall thickness (t) as a function of the peak residual stress value at the inside diameter (ID), σ_i.

The stress intensity factor caused by the residual stress from welding (K_{IR}), is calculated using influence functions taken from NUREG CR-3384,* page A.19, Table (7). The influence functions i_j, given in this Appendix are for a 360° circumferential crack in a cylinder with a R/t ratio of 10. In view of other analytical conservatisms and uncertainties (i.e., assumed crack geometry and initial depths), it is believed that they may be used for cylinders with R/t ratios of from 9 to 11 to obtain reasonable and conservative estimates of crack growth versus time. For R/t ratios significantly different from 10, other influence functions or other analytical methods should be used.

The specific formula used by the staff is:

$$K_{IR}/(\sigma_i\sqrt{t}) = \sqrt{\pi\alpha}\ \sum_{j=0}^{4} \sigma_j\ a^j\ i_j$$

where:

$\sigma_o, \ldots \sigma_4$ and σ_i are as above
i_o = $1.1220 + 0.3989\ \alpha + 1.5778\ \alpha^2 + 0.6049\ \alpha^3$
i_1 = $0.6830 + 0.1150\ \alpha + 0.7556\ \alpha^2 + 0.1667\ \alpha^3$
i_2 = $0.5260 + 0.1911\ \alpha - 0.1000\ \alpha^2 + 0.5802\ \alpha^3$
i_3 = $0.4450 + 0.0783\ \alpha + 0.0556\ \alpha^2 + 0.3148\ \alpha^3$
i_4 = $0.3880 + 0.1150\ \alpha - 0.1333\ \alpha^2 + 0.3519\ \alpha^3$
α = a/t
a = crack depth
t = wall thickness

<u>Membrane Stress</u>

The membrane stresses are assumed constant through the wall thickness, so

$$\sigma_m = \sigma_p$$

where

σ_p = membrane stress (σ_m) from pressure

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*Stevens, D.L., et al., "VISA-A Computer Code for Predicting the Probability of Reactor Pressure Vessel Failure" NUREG/CR-3384, PNL-4774, Washington, D.C. U.S. Nuclear Regulatory Commission, September 1983.

The stress intensity factor for a 360° circumferential crack from pressure K_{IP}, is calculated from

$$K_{IP} = (PR/2t) \sqrt{t} \sqrt{\pi\alpha} \ (1.122 + 0.3989\,\alpha + 1.5778\,\alpha^2 + 0.6049\,\alpha^3)$$

where

α, t are as above
P = pressure
R = radius to center of pipe wall

The total stress intensity factor, K_{IT}, is given by

$$K_{IT} = K_{IP} + K_{IR}$$

where

K_{IP} and K_{IR} are defined as above.

Correlation with Service Experience

Although the residual stress is assumed to be the same for all welds, the applied stresses, primary and secondary, vary from weld to weld; therefore, calculations must be performed for each weld evaluated. Figure 4 shows the results of K_I calculations for several pipe sizes using a nominal applied stress of 7500 psi. Note that at relatively shallow depths the K_I is high; therefore, the crack growth rate will be relatively fast. However, the K_I actually diminishes as the crack grows to about half way through the wall. This prediction is consistent with service experience; very few, if any, actual cracks of significant circumferential extent have been found deeper than about 50% of the wall thickness.

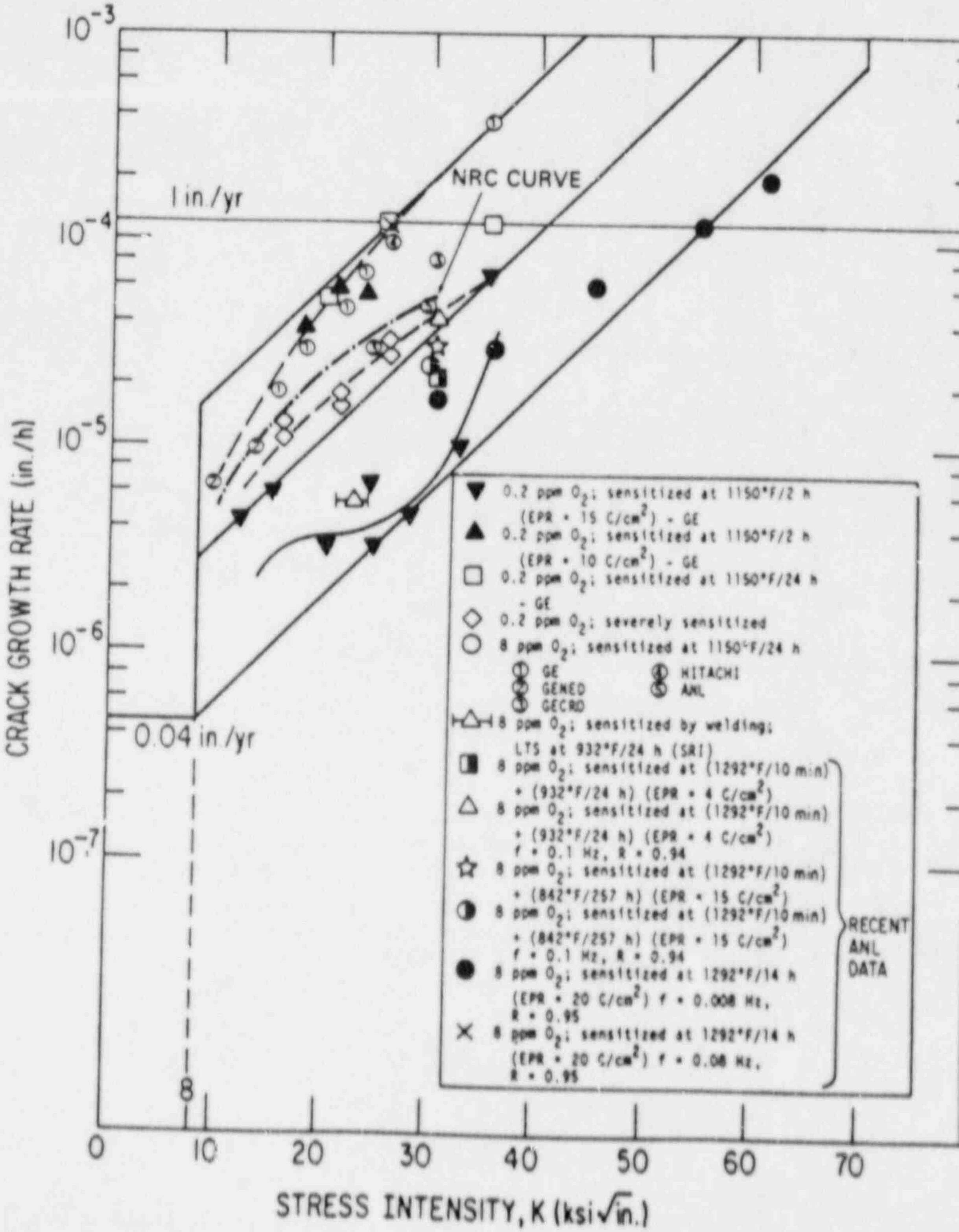

Figure 1
CRACK GROWTH RATE DATA

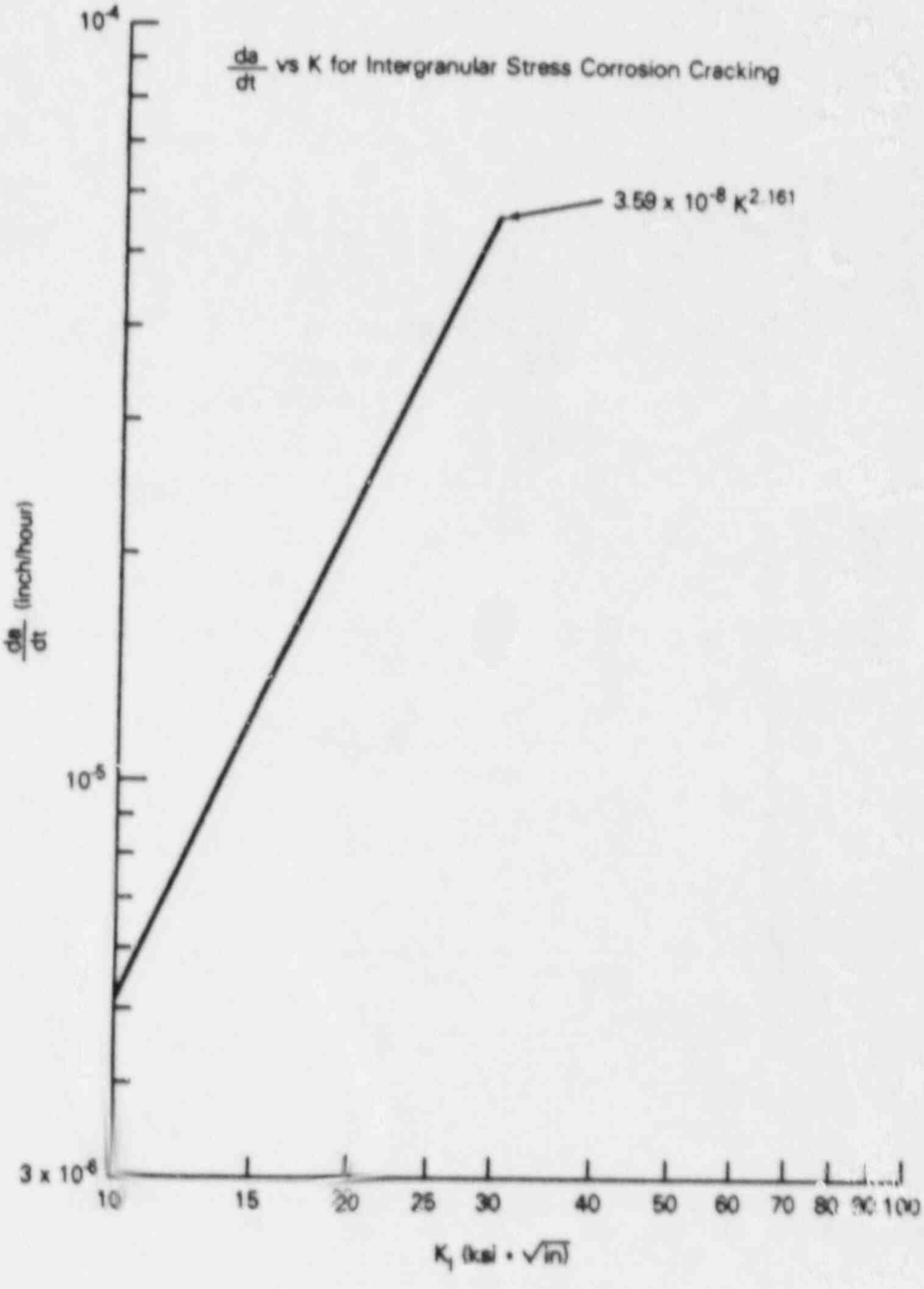

Figure 2
$\frac{da}{dt}$ vs K for Intergranular Stress Corrosion Cracking

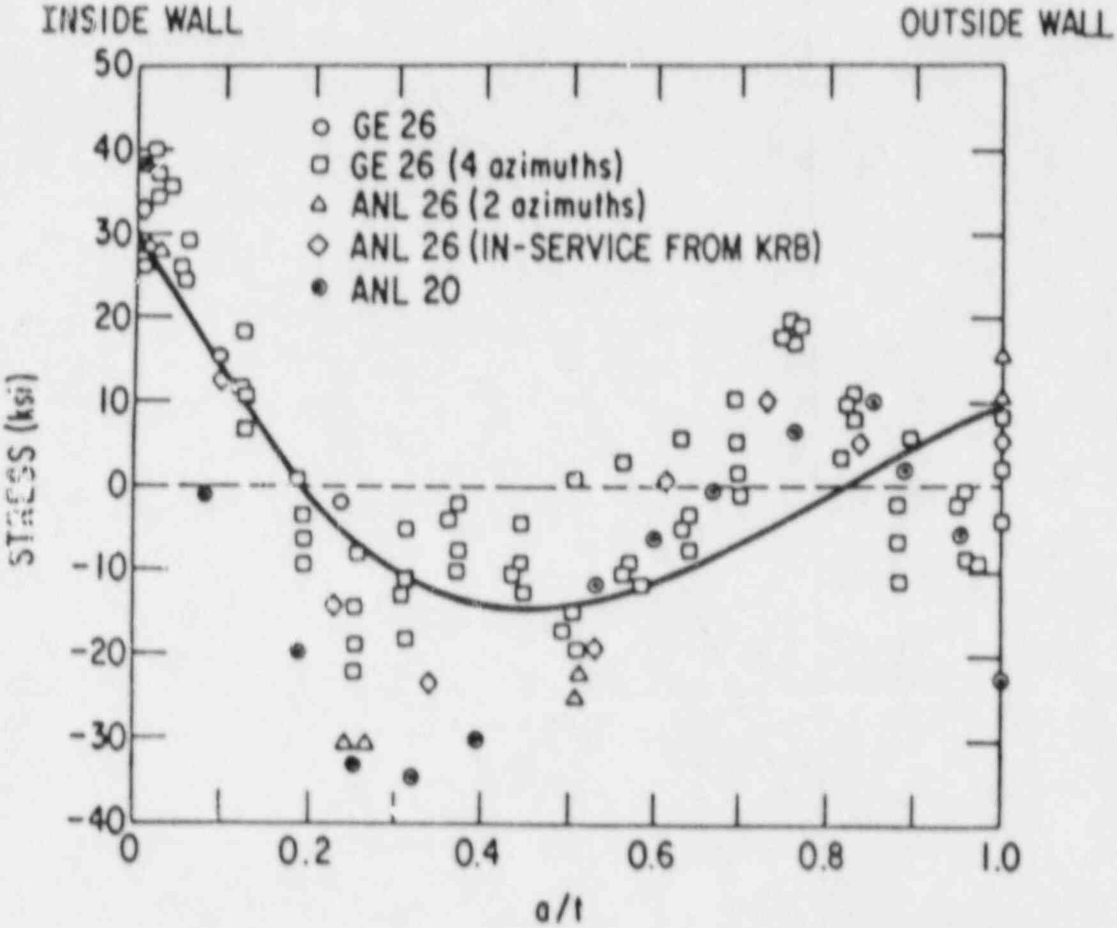

Figure 3
Through-wall Distribution of Axial Residual Stress in Large-Diameter Pipes (t $\geq$ 1 in.)

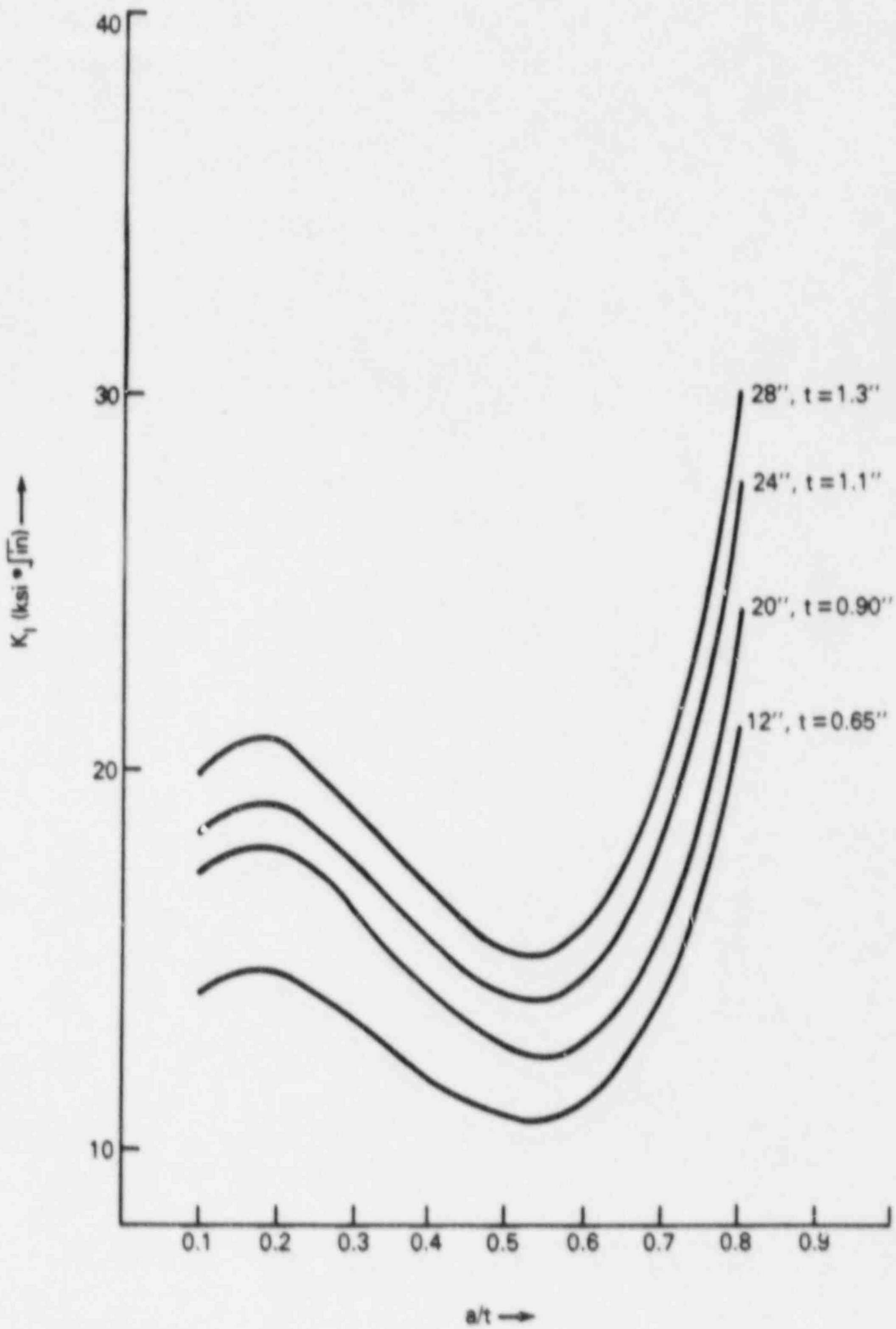

Figure 4
THROUGH-WALL DISTRIBUTION K_I WITH APPLIED STRESS OF 7500 PSI

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This report updates and supersedes the technical recommendations of NUREG-0313, "Technical Report on Material Selection and Processing Guidelines for BWR Coolant Pressure Boundary Piping," published in July 1977, and its subsequent revision published in July 1980.

This report provides the technical bases for the NRC staff's revised recommended methods to control the intergranular stress corrosion cracking susceptibility of BWR piping. For piping that does not fully comply with the material selection, testing, and processing guideline combinations of this document, varying degrees of augmented inservice inspection are recommended. This revision also includes guidance and NRC staff recommendations (not requirements) regarding crack evaluation and weld overlay repair methods for long-term operation or for continuing interim operation of plants until a more permanent solution is implemented.

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