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Acceptance Criteria for Ultrasonic Flaw
Indications in the Inner Liner of
Double-Shell Waste Storage Tanks

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Abstract

Radioactive defense waste, resulting from the chemical processing of spent nuclear fuel, has been stored in double-shell tanks (DSTs) at the Hanford Site since 1970. As part of the program to assure that the DSTs maintain their structural integrity, an inspection plan is being developed and implemented.

This report provides recommendations and technical bases for acceptance criteria for flaw indications detected during ultrasonic inspection of inner liners of the DSTs. The types of indications addressed are crack-like flaws, wall thinning, and pitting. In establishing acceptable flaw sizes, the evaluations have taken into consideration the potential for crack growth by the mechanism of stress corrosion cracking. Consideration was given to technical approaches used in ASME Codes, for reactor tanks at the Department of Energy Savannah River facilities, and in recommendations by the Tank Structural Integrity Panel. The goal was to ensure that indications discovered during inspections are not large enough to ever cause a leak or rupture of the tank inner liner. The acceptance criteria are intended to be simple to apply using a set of tables giving acceptable flaw sizes. These tables are sufficiently conservative to be applicable to all double-shell tanks. In those cases that a flaw exceeds the size permitted by the tables, it is proposed that additional criteria permit more detailed and less conservative evaluations to address specific conditions of stress levels, operating temperature, flaw location, and material properties.

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Executive Summary

Radioactive defense waste, resulting from the chemical processing of spent nuclear fuel, has been stored in double-shell tanks (DSTs) at the Hanford Site since 1970. As part of the program to assure that the DSTs maintain their structural integrity, an inspection plan is being developed and implemented. This report provides recommendations and technical bases for acceptance criteria for flaw indications detected during ultrasonic inspection of inner liners of the DSTs.

This report describes prior evaluations of tank stresses and reviews the materials and welding procedures used in the construction of the DSTs. A review of fracture mechanics properties relevant to the tank materials is presented with particular attention to the selection of toughness properties needed for elastic-plastic fracture mechanics calculations. Results of finite element calculations for elastic crack-tip stress intensity factors are presented for use in evaluating the integrity of the more highly stressed lower knuckle region of the tank. Critical flaw sizes for through-wall cracks are estimated for the stress levels and expected toughness levels of the tank materials. With appropriate safety factors, these critical flaw size calculations form the basis for recommended flaw acceptance standards. In establishing acceptable flaw sizes, the evaluations have also taken into consideration the potential for crack growth by the mechanisms of stress corrosion cracking, fatigue, and ductile tearing. A final topic of this report addresses limits on acceptable tank wall degradation due to wall thinning and pitting.

Consideration was given to technical approaches used in ASME Codes, for reactor tanks at the Department of Energy Savannah River facilities, and in recommendations by the Tank Structural Integrity Panel (TSIP). The goal was to ensure that indications discovered during inspections are not large enough to ever cause a leak or rupture of the tank inner liner. Detailed fracture mechanics evaluations form the technical basis for the recommended acceptance criteria and these calculations are documented in this report. The acceptance criteria are intended to be simple to apply by making use of a set of tables giving acceptable flaw sizes. The tables are sufficiently conservative to bound the results of the fracture mechanics calculations and to be applicable to all double-shell tanks. In those cases that a particular flaw exceeds the size permitted by the tables, it is proposed that additional criteria permit more detailed and less conservative evaluations to address flaw-specific conditions of stress levels, operating temperature, flaw location, and material properties.

The recommended acceptance criteria for cracks in the inner liner of double-shell tanks are given by Tables E.1, E.2, and E.3. The acceptable crack sizes are case-specific with the key variables being the flaw location, flaw orientation, and whether the flaw is at the critical inner surface of the tank liner. Table E.1 addresses all flaw locations and flaw orientations except for two high-stress locations corresponding to circumferential flaws in the lower knuckle and axial flaws in the vertical tank wall, which are addressed by Tables E.2 and E.3. Flaw lengths up to 61 cm (24 in.) and inner-surface flaw depths up to 40% of the wall thickness are acceptable at the lower stress locations addressed by Table E.1. With the high levels of bending stress in the lower knuckle, the acceptable depths of inner-surface flaws at this location are limited by Table E.2 to $a/t < 15\%$ to preclude flaw growth by stress corrosion cracking. Table E.3 addresses the specific case of axial flaws in the vertical tank wall. Because relatively short through-wall flaws of this type can grow by unstable ductile tearing, this table has been expanded to address the effects of the tank operating

Table E.1. Acceptable Sizes for Axial and Circumferential Cracks - Excluding 1) Axial Cracks in Vertical Tank Wall, and 2) Circumferential Cracks in the Lower Knuckle

Flaw Length	Acceptable Flaw Depth	
	Inner Surface Flaws	Buried and Outer Surface Flaws
Length > 61 cm (24 in.)	< 10% t	< 20% t
Length < 61 cm (24 in.)	< 40% t	< 50% t

Table E.2. Acceptable Sizes for Circumferential Cracks in the Lower Knuckle

Flaw Length	Acceptable Flaw Depth	
	Inner Surface Flaws	Buried and Outer Surface Flaws
Length > 40.6 cm (16 in.)	< 10% t	< 20% t
Length < 40.6 cm (16 in.)	< 15% t	< 40% t

temperature on critical flaw sizes. For the 21°C (70°F) lower bound on tank wall temperature, the acceptable flaw length is limited to 8.9 cm (3.5 in.).

Recommended acceptance criteria for wall thinning are given in Table E.4. For the lower stressed bottom plates, unlimited wall thinning of depth $a/t = 20\%$ is permitted, whereas this depth of thinning is permitted in the more highly stressed vertical wall of the tank only if the vertical extent of the thinned region is less than 45.7 cm (18 in.). For a larger region of thinning, a depth of $a/t = 12.5\%$ applies. For the highly stressed lower knuckle, the acceptable depth of $a/t = 12.5\%$ also applies.

Table E.5 addresses pitting of the tank wall, with deeper pits permitted if the pits are more widely spaced. Pit depths up to the $a/t = 50\%$ are permitted only if the pits are clearly isolated and widely spaced within the stated limits. Pit depths of $a/t = 12.5\%$ are permitted without regard to spacing criteria. If arrays of pits cannot be characterized as being isolated pits, Table E.5 states that the array should be enveloped by a boundary and then treated as an equivalent situation of wall thinning using the criteria of Table E.4.

It is believed that essentially all degradation of the sizes expected to be encountered during inservice inspections can be accepted on the basis of the simplified and general-purpose tables as

given by Tables E.1 through E.5. A review of published data on the numbers and sizes of welding defects is presented in this report, and it is concluded that cracks of rejectable size are unlikely to exist in the tank welds. If flaws do exceed the sizes given in the tables, detailed fracture mechanics calculations based on flaw-specific inputs for stresses and material properties can be performed to determine if these flaws can be accepted.

Table E.3. Acceptable Sizes for Axial Cracks in Vertical Tank Wall

Temperature	Flaw Length	Acceptable Flaw Depth	
		Inner Surface Flaws	Buried and Outer Surface Flaws
> 21°C (70°F)	Length > 9 cm (3.5 in.)	< 20% t	< 40% t
> 21°C (70°F)	Length < 9 cm (3.5 in.)	< 20% t	< 50% t
> 38°C (100°F)	Length > 14 cm (5.5 in.)	< 20% t	< 40% t
> 38°C (100°F)	Length < 14 cm (5.5 in.)	< 20% t	< 50% t
> 54°C (130°F)	Length > 23 cm (9.0 in.)	< 20% t	< 40% t
> 54°C (130°F)	Length < 23 cm (9.0 in.)	< 20% t	< 50% t

Table E.4. Acceptable Depths for Wall Thinning Extending Around Entire Circumference

Location	Vertical Extent of Wall Thinning	Acceptable Depth of Thinning
Bottom Plates	N/A	< 20% t
Lower Knuckle	N/A	< 12.5% t
Vertical Tank Wall	> 45.7 cm (18 in.)	< 12.5% t
	< 45.7 cm (18 in.)	< 20% t

Table E.5. Acceptable Depths for Wall Pitting

Location	Spacing of Pits Ratio of Center-to-Center Spacing to Pit Diameter	Acceptable Depth of Pitting
Isolated Pits	> 4.0	< 50% t
	> 2.0	< 25% t
	> 1.0	< 12.5% t
Arrays of Pits (cases where center-to-center spacing cannot be demonstrated to be greater than 1.0)	N/A	Use criteria for wall thinning by enveloping of extent and depth of pitted region

Contents

Abstract	iii
Executive Summary	v
Acronyms	xv
1.0 Introduction	1.1
2.0 Approach to Flaw Acceptance Criteria	2.1
2.1 Objectives and Attributes	2.1
2.2 Acceptance Criteria from Other Studies	2.2
3.0 Tank Materials	3.1
4.0 Fracture Mechanics Data	4.1
4.1 Sources of Fracture Data	4.3
4.2 Ductile-to-Brittle Transition Temperature	4.3
4.3 Recommend Toughness Values	4.4
5.0 Stress Intensity Factor Solutions	5.1
6.0 Elastic-Plastic Fracture Mechanics Methodology	6.1
6.1 Failure Assessment Diagram Approach	6.1
6.2 Results of Calculations	6.2
7.0 Acceptable Lengths for Through-Wall Cracks	7.1
7.1 Safety Factor Considerations	7.1
7.2 Axial Through-Wall Cracks in Tank Wall	7.2
7.3 Circumferential Through-Wall Cracks in Lower Knuckle	7.4
7.4 Through-Wall Cracks at Other Locations	7.6
8.0 Acceptable Depths for Part-Through Surface Cracks	8.1
8.1 Stress Intensity Factors for Surface Cracks	8.1
8.2 Assessment of Stress Corrosion Cracking	8.4
8.3 Assessment of Fatigue Crack Growth	8.5
8.4 Assessment of Ductile Tearing	8.7
9.0 Acceptance Criteria for Crack-Like Flaws	9.1
9.1 Review of Acceptance Criteria for Savannah River Reactor Tanks	9.1
9.2 Review of Recommendations of Tank Structural Integrity Panel	9.2
9.3 Option for Detailed Fracture Mechanics Evaluation	9.2
9.4 Strategy for Flaw Acceptance Tables	9.3
9.5 Recommended Flaw Acceptance Tables for Cracks	9.4

10.0	Acceptance Standards for Wall Thinning	10.1
10.1	Three Criteria for Acceptable Wall Thinning	10.1
10.2	Methods for Evaluating Local Wall Thinning	10.1
10.3	Example Calculations for Wall Thinning at Location "J"	10.3
10.4	Example Calculations for Wall Thinning at Location "H"	10.6
10.5	Review of Recommendations of Tank Structural Integrity Panel	10.6
10.6	Option for Detailed Evaluations	10.9
10.7	Recommended Acceptance Criteria for Wall Thinning (Including Pitting)	10.9
11.0	Expected Flaws in Tank Welds	11.1
12.0	Conclusions	12.1
13.0	References	13.1
Appendix A: Tank Configuration and Stresses		A.1
Appendix B: Recommendations of Tank Structural Integrity Panel		B.1
Appendix C: Elastic-Plastic Fracture Mechanics Calculations		C.1

Figures

1.1. Schematic of a Double-Shell Tank	1.2
2.1. Proposed Strategy for Flaw Acceptance	2.3
4.1. Tearing Resistance Curves of Ferritic Materials	4.5
4.2. Comparison of Transition Temperature for COD Bend Specimens to 610-mm (24-in.) Diameter 9.5-mm (0.375-in.) Thick 5LX Stress Relieved Pipe with Axial Surface Cracks (Flaws in Base Metal)	4.6
5.1. Finite Element Model of Primary Tank Liner with Embedded Crack Within Lower Knuckle Region	5.2
5.2. Finite Element Model of Primary Tank Liner Showing Loading and Boundary Condi- tions	5.3
5.3. Finite Element Model of Primary Tank Liner Showing Mesh Detail at Tip of Embedded Crack	5.4
5.4. Calculated Meridional Stress in Lower Knuckle of Primary Liner of Tank	5.5
5.5. Calculated Crack Opening for Through Wall Crack in Lower Knuckle of Primary Tank Liner	5.6
5.6. Calculated Crack Tip Stress Intensity Factor as Function of Crack Length for Through- Wall Cracks in Lower Knuckle of Primary Tank Liner	5.9
5.7. Calculated Crack Tip Stress Intensity Factor as Function of Angular Location for Through-Wall Cracks in Lower Knuckle of Primary Tank Liner	5.10
6.1. Failure Assessment Diagram Indicating Critical Crack Lengths. Safety Factors of 1.0 on K_I and 1.0 on S_r . Highest Level of J-Resistance Curve. Hoop Stress of 125 MPa (18.1 ksi).	6.5
7.1. Acceptable Crack Lengths for Axial Crack in Vertical Wall of Tank as a Function of Hoop Stress and Temperature for Safety Factors of 2.77 on K_I and 1.5 on S_r	7.5
10.1. Wall Thinning within Vertical Wall of Tank Inner Liner Showing Dimensions Defining Region of Thinning	10.2
10.2. Allowable Wall Thickness for Case 1 (Thinning Extending Partially Around Tank Circumference) at Location "J" within Vertical Wall of Tank Inner Liner	10.4
10.3. Allowable Wall Thickness for Case 2 (Thinning Extending Around Full Tank Circum- ference) at Location "J" within Vertical Wall of Tank Inner Liner	10.5
10.4. Allowable Wall Thickness for Case 1 (Thinning Extending Partially Around Tank Circumference) at Location "H" within Vertical Wall of Tank Inner Liner	10.7
10.5. Allowable Wall Thickness for Case 2 (Thinning Extending Around Full Tank Circum- ference) at Location "H" within Vertical Wall of Tank Inner Liner	10.8
A.1. Dimensions of the Primary Tank	A.2
A.2. Wall Thickness in the Primary Tank (in.)	A.3
A.3. Hoop Stresses (psi) in the Primary Tank	A.4
A.4. Axial (Meridional) Stresses (psi) in the Primary Tank	A.5
C.1. Failure Assessment Diagram Indicating Critical Crack Lengths	C.4
C.2. Failure Assessment Diagram Indicating Acceptable Crack Lengths	C.4
C.3. Failure Assessment Diagram Indicating Acceptable Crack Lengths	C.5
C.4. Failure Assessment Diagram Indicating Acceptable Crack Lengths	C.5
C.5. Failure Assessment Diagram Indicating Acceptable Crack Lengths	C.6
C.6. Failure Assessment Diagram Indicating Critical Crack Lengths	C.6

C.7.	Failure Assessment Diagram Indicating Acceptable Crack Lengths	.....	C.7
C.8.	Failure Assessment Diagram Indicating Acceptable Crack Lengths	.....	C.7
C.9.	Failure Assessment Diagram Indicating Acceptable Crack Lengths	.....	C.8
C.10.	Failure Assessment Diagram Indicating Acceptable Crack Lengths	.....	C.8
C.11.	Failure Assessment Diagram Indicating Acceptable Crack Lengths	.....	C.9
C.12.	Failure Assessment Diagram Indicating Acceptable Crack Lengths	.....	C.9
C.13.	Failure Assessment Diagram Indicating Acceptable Crack Lengths	.....	C.10
C.14.	Failure Assessment Diagram Indicating Acceptable Crack Lengths	.....	C.10
C.15.	Failure Assessment Diagram Indicating Acceptable Crack Lengths	.....	C.11
C.16.	Failure Assessment Diagram Indicating Acceptable Crack Lengths	.....	C.11
C.17.	Failure Assessment Diagram Indicating Acceptable Crack Lengths	.....	C.12
C.18.	Failure Assessment Diagram Indicating Acceptable Crack Lengths	.....	C.12

Tables

E.1. Acceptable Sizes for Axial and Circumferential Cracks - Excluding 1) Axial Cracks in Vertical Tank Wall, and 2) Circumferential Cracks in the Lower Knuckle	vi
E.2. Acceptable Sizes for Circumferential Cracks in the Lower Knuckle	vi
E.3. Acceptable Sizes for Axial Cracks in Vertical Tank Wall	vii
E.4. Acceptable Depths for Wall Thinning Extending Around Entire Circumference	vii
E.5. Acceptable Depths for Wall Pitting	viii
4.1. Summary of Fracture Toughness Data for Ferritic Steels	4.1
5.1. Summary of Calculation for Crack Tip Stress Intensity Factor for Through-Wall Cracks in Lower Knuckle of Primary Tank Liner	5.7
7.1. Effect of Safety Factor on Acceptable Lengths of Through-Wall Cracks	7.3
7.2. Summary of Acceptable Sizes for Through-Wall Vertical (Axial) Cracks in Tank Wall as Established by Fracture Mechanics Calculations	7.4
7.3. Acceptable Lengths of Through-Wall Cracks in the Primary Tank for a Temperature of 21°C (70°F)	7.7
7.4. Acceptable Lengths of Through-Wall Cracks in the Primary Tank for a Temperature of 130°F	7.8
8.1. Stress Intensity Factors for Inner-Surface Axial Cracks at Location "H" within the Tank Wall	8.1
8.2. Stress Intensity Factors for Inner-Surface Axial Cracks at Location "G" within the Tank Wall	8.2
8.3. Stress Intensity Factors for Inner-Surface Circumferential Cracks at Location "D" within the Lower Knuckle	8.2
8.4. Stress Intensity Factors for Inner-Surface Circumferential Cracks at Location "C" within the Tank Bottom Plate	8.3
8.5. Acceptable Flaw Depths to Preclude Flaw Growth by the Mechanism of Stress Corrosion Cracking	8.5
8.6. Summary of Acceptable Sizes for Part-Through Vertical (Axial) Cracks in Tank Wall as Established by Fracture Mechanics Calculations	8.6
9.1. Acceptable Sizes for Axial and Circumferential Cracks - Excluding 1) Axial Cracks in Vertical Tank Wall, and 2) Circumferential Cracks in the Lower Knuckle	9.4
9.2. Acceptable Sizes for Circumferential Cracks in the Lower Knuckle	9.5
9.3. Acceptable Sizes for Axial Cracks in Vertical Tank Wall	9.5
10.1. Acceptable Depths for Wall Thinning Extending Around Entire Circumference	10.10
10.2. Acceptable Depths for Wall Pitting	10.10
11.1. Expected Number of Flaws in Welds of Each Inspected Tank	11.2
B.1. Examinations of Carbon or Low-Alloy and Austenitic Stainless Steel or High-Alloy Tank Containing High-Level Waste	B.2

Acronyms

ASME	American Society of Mechanical Engineers
BCL	Battelle Columbus Laboratory
COD	Crack Opening Displacement
CVN	Charpy V-Notch
DOE	Department of Energy
DST	Double Shell Tank
RT	Room Temperature
TSIP	Tank Structural Integrity Panel
UT	Ultrasonic Testing

CONVERSIONS		
To convert	To	Multiply by
inches	meters (m)	0.0254
ft	meters (m)	0.3048
lb/in ² (psi)	MPa	0.00690
Kip/in ² (ksi)	MPa	6.90
°F	°C	(t°F-32)/1.8
ksi√in	MPa√m	1.099
in-lb/in. ²	KJ/m ²	0.175

1.0 Introduction

Radioactive defense waste, resulting from the chemical processing of spent nuclear fuel, has been stored in double-shell tanks (DSTs) at the Hanford Site since 1970. There are 28 DSTs and they must remain in service until waste disposal operations are completed. As part of the program to assure the DSTs maintain their structural integrity, an inspection plan is being developed and implemented (Pfluger 1994). To support this plan, this report provides recommendations and technical bases for acceptance criteria for flaw indications detected during ultrasonic inspection of the inner liner of the DSTs. The types of indications addressed are crack-like flaws, wall thinning, and pitting.

The 28 DSTs are located in six separate tank farms. The design and construction of tanks within a given tank farm are the same. Among tank farms, the design and construction of tanks are similar. All DSTs have a nominal capacity of one million gallons. The DSTs are 24.4-m-dia. (80-ft-dia.) reinforced-concrete, cylindrical, dome-roofed, buried tanks with two steel liners. The primary steel liner consists of a floor, an independent 22.9-m-dia. (75-ft-dia.) cylindrical shell, and a dome that is integral with the reinforced-concrete dome. Figure 1.1 is a schematic of a DST. The primary liner provides containment of the liquid waste and resists the hydrostatic and hydrodynamic loads. The secondary steel liner provides a redundant leakage barrier for containment of the liquid waste. The reinforced-concrete tank and dome carry the surface loads and the static and dynamic soil loads. There is a nominal 76.2-cm (30-in.) air gap between the primary steel tank and the lined reinforced-concrete tank wall.

The calculated results presented in this report are an extension of prior work (Shurrab et al. 1991), which was based on the design and construction of the 241-SY Tank Farm tanks. Stresses and calculated crack-tip stress intensity factors are for tanks subjected to normal loads. The results identify locations of highest stresses and locations where cracks or other forms of tank-wall degradation, if present, will be most detrimental to tank integrity. These results are intended to guide inspection requirements and criteria for the acceptance of flaw indications detected during inspections.

The flaw acceptance criteria are intended to be both simple to apply and sufficiently conservative to be applicable to all double-shell tanks. It is proposed that the criteria permit more detailed and less conservative evaluations to address specific conditions of stress levels, operating temperature, flaw location, and material properties. Efforts were made to follow technical approaches used in ASME codes, and as developed for reactor tanks at the Department of Energy's Savannah River facilities.

The report contains a summary of prior evaluations of tank stresses and a review of the materials and welding procedures used in the construction of the DSTs. A review of fracture mechanics properties relevant to the tank materials is then presented with particular attention to the selection of toughness properties needed for elastic-plastic fracture mechanics calculations. Results of finite element calculations for elastic crack-tip stress intensity factors are presented for later use in evaluating the integrity of the more highly stressed, lower knuckle region of the tank. Critical flaw sizes are estimated for the stress levels and expected material toughness levels. With appropriate safety factors, these critical flaw size calculations form the basis for recommended tables of flaw acceptance standards. In establishing acceptable flaw sizes, the evaluations have taken into consider-

potential for crack growth by the mechanism of stress corrosion cracking. A final part of this report addresses limits on acceptable tank-wall degradation due to wall thinning and pitting.

Figure 1.1. Schematic of a Double-Shell Tank

2.0 Approach to Flaw Acceptance Criteria

This section reviews the overall objectives and desired attributes of flaw acceptance criteria along with approaches that have been developed for other relevant applications including the ASME Section XI Code (ASME 1993) for reactor piping, criteria for reactor tanks at the DOE Savannah River facilities (Daugherty 1990), and recommendations of the Tank Structural Integrity Panel (TSIP 1994).

2.1 Objectives and Attributes

Flaw acceptance standards are an essential element of any inspection program, because an effective inspection procedure may detect the small, benign flaws that do not degrade the integrity of the structure. Acceptance standards provide a basis for making decisions whether repairs or other corrective actions are needed. In the case of the DST, it is proposed that the acceptance standards have the following desired attributes:

- Ensure tank structural integrity and containment of the stored waste within the tank
- Ensure appropriate action for service-related initiation and growth of flaws
- Easy/quick to apply using generalized tables for the benign fabrication flaws that are expected to be detected during inservice inspections
- Permit detailed evaluations for those cases where flaws exceed the limits of the generalized tables
- Preclude unneeded corrective actions and repairs
- Have a sound and defensible technical basis.

It is desirable that acceptance criteria be designed for application in a step-wise screening process as is used in the approach of the ASME Section XI Code. The first step should define conservative criteria in terms of simple and easy-to-apply tables of acceptable flaw sizes. This step permits quick decisions to be made in the field when flaws are detected during inspections. In some cases, the detected flaw could be larger than those permitted by the conservative assumptions used in establishing the tables of acceptable sizes. The acceptance criteria then need to permit more detailed (but less conservative) evaluations of the acceptability of these larger flaws.

The present development of flaw acceptance criteria was in support of a larger overall effort to perform ultrasonic inspections of the inner liners of DSTs. In this regard, there were no results from prior inservice examinations or evidence of any service-related degradation to focus the development of acceptance standards on particular degradation mechanisms. Therefore, the acceptance standards were designed to address postulated failure mechanisms, which have not actually occurred in the Hanford DSTs nor are considered particularly likely in the future. The following potential mechanisms were postulated for purposes of developing flaw acceptance standards:

- stress corrosion cracking
- low energy fracture assuming operating temperatures in the ductile brittle transition temperature range for the ferritic steel
- wall thinning or wastage most likely localized near the vapor-liquid interface
- local pitting most likely localized at the upper levels near the vapor-liquid interface.

The mechanisms specifically excluded were:

- the initiation and growth of fatigue cracks because there is a lack of significant cyclic components to the stress state
- embrittlement of the ferritic steel by radiation effects because the radiation fields of the service environment lack the high-energy neutrons that are the common source of embrittlement effects to ferritic steel components.

2.2 Acceptance Criteria from Other Studies

Acceptance criteria for ultrasonic indications have been developed by Daugherty (1990) for the Savannah River reactor tanks. The technical basis for these criteria and the resulting acceptable flaw sizes were reviewed as part of the present work as a potential source of guidance for acceptance standards for the DSTs. Section 9.1 of this report summarizes the Savannah River work in the context of the situation for double-shell tanks.

The Savannah River evaluations provide useful guidance for the present work on DST acceptance criteria. However, the high toughness stainless steel materials and low levels of hoop stress permitted a high level of conservatism in the Savannah River flaw evaluations, with little penalty in terms of unreasonably small flaw sizes for the flaw acceptance criteria. Such levels of conservatism have not been used in the present evaluations, because the resulting sizes of rejectable flaws would be unreasonably small. Furthermore, the consequences of a leak or rupture of the waste tanks are less, so additional conservatism for this case is not warranted.

The Tank Structural Integrity Panel (1994) has provided guidance for tank inspection, including some specific recommendations for flaw acceptance standards. The tables in Appendix B summarize the recommendations of the panel. Section 9.2 of the present report reviews the panel recommendations and addresses differences between the present calculations and the panel recommendations.

Figure 2.1 shows the overall strategy for flaw acceptance proposed by the panel. The strategy includes an ongoing role of a panel to assess the implications of inspection findings. In cases where no flaw indications are detected, the panel assessment would be limited to a periodic review of the tank inspection program. The review would address the adequacy of the inspection methods, inspection frequencies, and inspection locations relative to current knowledge of known and potential degradation mechanisms.

Figure 2.1. Proposed Strategy for Flaw Acceptance

3.0 Tank Materials

The 28 double-shell tanks are nominally of the same design. All tanks use low carbon steels for the inner tank. There are individual differences between tanks as to the specific grade of steel, and differences in details of the welding processes used in the fabrication. Variations in the tank materials and effects on fracture toughness levels were reviewed by Battelle Columbus Laboratory as a funded task of the present study, and their conclusion was that for purposes of the present fracture mechanics evaluations the various grades of tank materials can be treated as falling within a single scatter band of fracture properties for low carbon steels. Variations within a given grade of steel were believed to be as large as variations from one grade to another.

Some specific materials and welding processes for the tanks were identified as follows:

- Plate Materials
  - A-515 Grade 60
  - A-516 Grade 65
  - A-537 Grade 80
- Welding Processes
  - Shielded metal arc (majority of welds)
  - Submerged arc
- Post Weld Heat Treatment
  - Section VIII procedure
  - 677°C (1100°F)
  - 1 hour per inch of thickness
- Weld Inspection Used During Construction
  - Radiograph
  - Visual
  - Some magnetic particle
  - Plates given UT scan by manufacturer

A search for details on the construction of particular tanks was beyond the scope of the present study, as the present objective was to develop flaw acceptance criteria that are applicable to all double-shell tanks. It was learned that tank-specific information such as on welding procedures can be obtained by requesting records from archive storage off-site. Westinghouse Hanford staff did locate an example of a typical welding procedure. For this example, the vertical welds in the 241-AW series of tanks constructed by American Bridge were made by the shielded metal arc process using E7018 filler metal. The horizontal welds, including the girth welds in the side wall of the tank, were made by the submerged arc process using F72-EM12K filler metal.

It may in the future be useful to seek additional archival information on materials and on welding procedures for purposes of detailed fracture mechanics evaluations of flaws that may be detected during future inspections. Such information could justify less conservative fracture mechanics calculations than used in the present evaluations for the generic flaw acceptance criteria.

4.0 Fracture Mechanics Data

The elastic-plastic fracture mechanics calculations of critical flaw sizes for the DST inner liner required a review of fracture data for ferritic steels. A summary of the fracture toughness data for the tank materials is given in Table 4-1.

Table 4.1. Summary of Fracture Toughness Data for Ferritic Steels

Source of Data	Fracture Toughness, MPa√m (ksi√in.)			
	21°C (70°F)		54°C (130°F)	
	Initiation	With Crack Growth	Initiation	With Crack Growth
Pellini Document (1983) $K_{I(t)}$ - Intermediate loading rates	—	98 (89)	—	204 (186)
J-resistance curve F49W-1 (static) from Battelle Colum- bus; exhibiting transition to cleavage	145 (132)	201 (183) $\Delta a = 0.35$ mm		
J-resistance curve F49W-2 (static) from Battelle Colum- bus; exhibiting transition to cleavage	169 (154)	254 (231) $\Delta a = 0.5$ mm		
Sindelar and Wiersma (1994), A285 Grades A and B, 5/8-in. plate thickness, K_{Ic} (dynamic) at 4°C (40°F)	157 - 271 (143 - 247) (4°C)	—		
Sindelar and Wiersma (1994), A285 Grades A and B, 5/8-in. plate thickness, K_{Ic} (dynam- ic) at 4°C (40°F)	66 - 104 (60 - 95) (4°C)	—		
Sindelar and Wiersma (1994), A285-B, K_{Ic} , CVN (toughness vs. temperature curve)	—	123 (112)	—	165 (150)
Tandon, Bamford, Cowfer, and Ostrowski (1993), Savan- nah River Carbon Steel Piping	No data cited in this paper. Acceptance standards based on mean of data minus twice the standard deviation. All data points were enveloped by this lower bound.			

Source of Data	Fracture Toughness, MPa√m (ksi√in.)			
	21°C (70°F)		54°C (130°F)	
	Initiation	With Crack Growth	Initiation	With Crack Growth
Glover, McGrath, and Eatson ¹ , J-R curves at RT for submerged metal arc weld metal; A515 and A36 plate	136 - 197 (124 - 179)	145 - 260 (132 - 237) $\Delta a = 3.8$ mm	--	--
Wilson and McDonald (1989), A516 Grade 70 plate, minimum and maximum for all orientations assumed to be room temperature	174 - 387 (158 - 352)	--	--	--
Wilson (1979), A516 Grade 70 plate, 93°C, minimum and maximum for all orientations			160 - 335 (146 - 305)	
Wood and Stevens ² , E7016-1 weld metal, room temperature	141 (128)	374 (340) $\Delta a = 1$ mm		
Choy, Yang, Kim, and Seok ³ , A516 Grade 70 plate, TL orientation	162 (147)	270 (246) $\Delta a = 2$ mm	151 (137) (at 49°C)	223 (203) $\Delta a = 2$ mm (at 100°C)
A106 Class C pipe, various orientations, NUREG/CR-3142, Vol. 2 (Kanninen et al. 1983)	189 - 354 (172 - 322)			
Reed, McHenry, and Kasen (1979), weld metal E7010G and E8010G	134 - 151 (122 - 137)	242 (220) $\Delta a = 1$ mm		

¹Glover, A. G., J. T. McGrath, and N. F. Nelson, "Fracture Toughness of Submerged Arc Weld Metal," pp. 143-160, (Reference 3 of P. M. Scott letter to F. A. Simonen of August 4, 1994).

²Wood, G. R. and R. I Stevens, "Slow Stable Crack Growth and Instability in Elastic-Plastic Weld Metals and Structural Integrity," pp. 841-848, (Reference 7 of P. M. Scott letter to F. A. Simonen of August 4, 1994).

³Choy, Y. S., W. H. Wang, Y. J. Kim, and C. S. Seok, "Effect of Temperature on the Elastic Plastic Fracture Toughness in A516 Gr70 Steel," pp. 301-306 (Reference 9 of P. M. Scott letter to F. A. Simonen of August 4, 1994).

4.1 Sources of Fracture Data

The main inputs to the review were as follows:

- Pellini (1983) - The prior calculations of critical flaw sizes (Shurrah et al. 1991) were based on the conservative approach of Pellini (1983). The conservative toughness levels used in these calculations served as a point of reference for the present considerations. The 1991 calculations assumed that the tank operating temperature was 54°C (130°F) for which the Pellini approach gave an estimated fracture toughness of 204 MPa√m (186 ksi√in.). At 21°C (70°F), the estimated fracture toughness was 98 MPa√m (89 ksi√in.). These 1991 estimates were believed to be conservative due to 1) the inherent bounding nature of Pellini's work, 2) the relatively thick sections addressed by Pellini compared to DST wall thicknesses of 2.54 cm (1 in.) or less, and 3) the toughness levels of Pellini were based on rapid loading rates on the order of about one second.
- Sindelar and Wiersma (1994) - This recent document reviewed ferritic steel toughness data relevant to the integrity of the high-level nuclear waste storage tanks at the Savannah River site. Because the recommendations of Sindelar and Wiersma (1994) are believed to be directly applicable to the Hanford tanks, consistent levels of fracture toughness levels have been used in the calculations of the present report. The Savannah River work resulted in static fracture toughness levels of 157 to 271 MPa√m (143 to 247 ksi√in.) for temperatures as low as 4°C (40°F).
- Battelle Columbus Review - G. M. Wilkowski and P. M. Scott served as consultants on a funded task of the present study, and provided data on fracture properties of ferritic materials relevant to Hanford waste storage tanks. Much of the data cited in Table 4.1 came from existing files and a literature search performed by Battelle Columbus Laboratories. Wilkowski and Scott also provided recommendations for the fracture evaluations based on their extensive experience from work on reactor piping for the U.S. Nuclear Regulatory Commission and from pipe testing for the gas pipeline industry.

Information was provided to Battelle Columbus that listed the various grades of ferritic steels and welding methods used in tank construction. Given the expected variations of toughness properties within grades of these steels, the Battelle Columbus consultants considered data for a broad class of structural steels to be relevant to the present evaluations, and the data cited in Table 4.1 reflect this assumption.

4.2 Ductile-to-Brittle Transition Temperature

The importance of the ductile-to-brittle-transition temperature for ferritic steels is emphasized in the report by Sindelar and Wiersma (1994). Tank operating temperatures are not sufficiently high to completely ensure upper shelf fracture by ductile tearing rather than by brittle cleavage. The Sindelar report and Battelle Columbus staff indicate that some fracture tests at the lower temperature range of tank operation [21°C (70°F)] may exhibit initiation of crack growth by the ductile tearing mode, and then after a relatively small amount of ductile tearing have the fracture mode convert to

that of low energy brittle cleavage fracture. This behavior is expected only in exceptional cases for some materials, and for adverse crack orientations relative to the plate-rolling direction.

Figure 4.1 shows several representative J-resistance curves for ferritic steels. Two of these curves (i.e., BCL data sheets) were selected for purposes of the present calculations as the representative curves to describe a material that exhibits a transition to cleavage fracture. The curve labeled "A106 Class C Pipe at 550°F" was used for the calculations as representative of the more expected fracture toughness behavior. The fracture mode in this case exhibits a fully ductile tearing mode that is characteristic of material behavior at upper shelf temperatures.

Figure 4.2 was provided by Battelle Columbus. This plot compares the differing fracture response for part through-wall cracks as opposed to through-wall cracks. Figure 4.2 indicates that the fracture mode remains ductile at lower temperatures for part through-wall cracks. These results are for relatively thin sections [i.e., 2.54-cm (1-in.) thick or less], which are typical of the Hanford tank construction. Hence, it is conservative in the calculations of this report to use fracture data generated from tests of through-wall cracks for application to the more ductile situation of part through-wall cracks.

4.3 Recommend Toughness Values

An estimated fracture toughness of 204 MPa√m (186 ksi√in.) was assumed in the 1991 calculations of allowable flaw sizes (Shurrab et al. 1991) with the minimum assumed tank-wall temperature being 54°C (130°F). These calculations were based on linear elastic fracture mechanics. Given the trend of the data of Table 4.1, and following the recommendations of Sindelar and Wiersma (1994), it was concluded that the use of the 204 MPa√m (186 ksi√in.) value in linear elastic calculations was appropriate for temperatures down to 54°C (70°F).

Static values of fracture toughness are recommended as appropriate to address normal operating conditions for Hanford tanks, because there are no expected sources of significant dynamic loads for normal operation. Seismic conditions will involve a dynamic contribution to the stress state in the tank. However, these dynamic stresses will be less than the static hydrostatic stress from normal operation. Because a reduced safety factor would be used in calculations of acceptable flaws for seismic conditions, the stress levels and the higher safety factor for the normal operating condition will govern by giving more conservative flaw sizes for the acceptance standards.

For the present calculations, there was a need to select appropriate J-resistance curves for use in elastic-plastic fracture mechanics calculations of critical flaw sizes. Given that a safety factor on load is used in establishing the flaw acceptance standards, J-resistance curves should be conservative relative to mean curves but not necessarily be true lower-bound curves. Accordingly, the curve labeled F49W-1 was selected for conservative elastic plastic fracture mechanics calculations. This curve exhibits a transition to cleavage fracture, and has toughness levels within the 204 MPa√m (186 ksi√in.) range as recommended for conservative linear elastic-plastic fracture toughness calculations. For best estimate calculations, to determine more representative or expected sizes of critical flaws, the curve of Figure 4.1 labeled "A106B Class C Pipe at 550°F" from NUREG/CR-3142 Vol. 2 was selected.

Figure 4.1. Tearing Resistance Curves of Ferritic Materials

Figure 4.2. Comparison of Transition Temperature for COD Bend Specimens to 610-mm (24-in.) Diameter 9.5-mm (0.375-in.) Thick 5LX Stress Relieved Pipe with Axial Surface Cracks (Flaws in Base Metal)

5.0 Stress Intensity Factor Solutions

The primary steel tank consists of a flat bottom, a cylindrical shell for the side wall, a curve knuckle transition joining the flat bottom to the cylindrical side wall, and a domed roof. The wall thicknesses are relatively thin [9.5 to 22.2 mm (3/8 to 7/8 in.)] compared to the radius of the tank [11.43 m (37.5 ft.)]. There are no exact solutions for crack-tip stress intensity factors, K_I , except for flat plate solutions that are applicable to the bottom, and for cylindrical shells that are applicable to the side wall of the tanks. The previous fracture evaluations (Shurrah et al. 1991) were based on various estimates of stress intensity factors using published solutions for more simple geometries that approximated geometric aspects of the tank. These approximations were based mostly on flat plate solutions that neglect curvature effects. These have been shown by Kobayashi et al. (1977) to give relatively good results for shallow surface flaws for $a/t < 50\%$.

The main shortcoming of the 1991 estimates of stress intensity factors was for the case of through-wall circumferential cracks within the highly stressed lower knuckle of the tank. In the 1991 work, the lower knuckle was approximated by a cylindrical shell with an axial crack, with the shell radius set equal to the 30-cm (12-in.) radius of the lower knuckle. The stress in the cylindrical shell was assumed to be axisymmetric with the same through-wall bending stress as the local stress state at the knuckle location of interest.

Finite element calculations for cracked tank geometries were performed as part of the present work to address concerns for the accuracy and conservatism of the cylindrical shell approximation. These calculations were based on the finite element model shown by Figures 5.1 through 5.3. These figures indicate the meshing around the crack tip along with the applied loadings and boundary conditions. This model was implemented on the ANSYS finite element code using a curved, thin-shell element. Only a small radial segment of the tank was actually simulated, with symmetry conditions imposed on displacements along the radial edges of the segment. Calculations performed in this fashion actually addressed the physical situation of a tank with a regular array of cracks around the circumference of the tank (one crack per segment). Care was taken to ensure that the size of the segment was sufficiently large to minimize the interactions of adjacent cracks within the array.

The finite element model permitted through-wall cracks of different lengths to be embedded in the finite element mesh at prescribed angular locations around the radius of the lower knuckle. Calculated stresses in the uncracked knuckle are indicated in Figure 5.4. The detailed region around the crack tip displaying calculated crack opening displacements is shown by Figure 5.5.

The crack tip stress intensity factors were determined using the fracture mechanics capabilities of the ANSYS finite element computer program. A special macro was developed for ANSYS to permit the stress intensity factors for the through-wall bending component of stress to be calculated. In this bending stress calculation, the Poisson ratio factor of $(1 + \nu)/(3 + \nu)$ was applied to the ANSYS results (the ANSYS solutions were based on simplified thin-shell theory) to properly account for thick-shell behavior that plays a significant role in the immediate region of the crack tip. This adjustment permitted comparisons with cracked shell solutions presented by Rooke and Cartwright (1976).

Figure 5.1. Finite Element Model of Primary Tank Liner with Embedded Crack Within Lower Knuckle Region

Figure 5.2. Finite Element Model of Primary Tank Liner Showing Loading and Boundary Conditions

Figure 5.3. Finite Element Model of Primary Tank Liner Showing Mesh Detail at Tip of Embedded Crack

Crack at 45 Zipped

Figure 5.4. Calculated Meridional Stress in Lower Knuckle of Primary Liner of Tank

Figure 5.5. Calculated Crack Opening for Through Wall Crack in Lower Knuckle of Primary Tank Liner

Table 5.1. Summary of Calculation for Crack Tip Stress Intensity Factor for Through-Wall Cracks in Lower Knuckle of Primary Tank Liner

Parameter	Case 1	Case 2	Case 3	Case 4	Case 5
Angle from Bottom of Tank, Degrees	22.5	22.5	22.5	65.0	75.0
Total Crack Length, cm	30.5	15.2	61.0	30.5	30.5
Inner Surface Meridional Stress, MPa (uncracked solution)	69	69	69	-54	-16
Outer Surface Meridional Stress, MPa (uncracked solution)	-69	-69	-69	52	57
ANSYS - with ν term K_I - Inner Surface, $\text{MPa}\sqrt{\text{m}}$	15.9	3.5	20.5	0.8	-1.7
ANSYS - with ν term K_I - Outer Surface, $\text{MPa}\sqrt{\text{m}}$	6.0	-3.8	-12.8	-5.0	-4.6
ANSYS K_{II} , $\text{MPa}\sqrt{\text{m}}$	3.1	0.02	7.9	0.98	0.65
ANSYS K_{III} , $\text{MPa}\sqrt{\text{m}}$	12.4	5.7	20.5	3.5	1.6
ANSYS - Inner Surface $K_{\text{effective}} = \text{sqrt}(K_I^2 + K_{II}^2 + K_{III}^2)$, $\text{MPa}\sqrt{\text{m}}$	20.3	6.7	30.1	6.2	2.1
ANSYS - Outer Surface $K_{\text{effective}} = \text{sqrt}(K_I^2 + K_{II}^2 + K_{III}^2)$, $\text{MPa}\sqrt{\text{m}}$	14.2	6.9	25.4	3.7	4.9
Handbook - Inner Surface $K_{\text{effective}} = \text{Cylinder Solution}$ (with ν term), $\text{MPa}\sqrt{\text{m}}$	14.7	11.9	16.0	-11.2	-12.5
Handbook - Outer Surface $K_{\text{effective}} = \text{Cylinder Solution}$ (with ν term), $\text{MPa}\sqrt{\text{m}}$	-17.7	-13.1	-22.4	13.5	14.9

Table 5.1 summarizes numerical results from the finite element calculations, and also results of calculations using the cylindrical shell approximations of the Shurrab et al. (1991) report. A total of five crack geometries were addressed covering crack lengths from 15.24 to 61 cm (6.0 to 24.0 in.) and angular locations within the knuckle ranging from 22.5° to 75.0°. An unexpected result was the large contribution of mixed mode fracture for cracks in the knuckle region. The mode III transverse shear mode of crack tip displacement was particularly strong. This behavior was very significant for

the cracks at the 22.5° angle, which is a location that placed the crack relatively close to the bottom of the tank where displacements of the tank liner can be strongly affected by the contact with the supporting concrete. Evidently the edge of the crack near the tank bottom was restrained compared to the opposite edge of the crack, which was more free to displace in a characteristic bulging or "fish mouth" fashion.

The three individual contributions to the stress intensity factor (K_I , K_{II} , and K_{III}) were combined into an "effective stress intensity factor" using a root sum squares relationship as given in Broek (1989). The results of Table 5.1 were normalized with respect to both the applied stress level and the square root of crack length in the manner indicated on Figures 5.6 and 5.7. The parameter Q can be interpreted as a geometry factor that allows the results to be presented in the same format as used in Rooke and Cartwright (1976) for the cylinder solutions.

Both the finite element results and the handbook results for the cylinder geometry are shown in Figures 5.6 and 5.7. The detailed finite element results give higher levels of stress intensity factor for longer cracks and for cracks that are adjacent to the transition from the knuckle to the bottom of the tank. This finding is particularly significant because the maximum bending stresses occur at this location. Use of the cylinder solutions are therefore seen to be somewhat unconservative for this critical location. For other less critical locations, the cylinder solution approach is conservative.

The results of the finite element calculations as summarized by Figures 5.6 and 5.7 form the basis for a recommendation for estimating stress intensity factors in the lower knuckle region. A single bounding Q factor of 1.2 is recommended for estimating purposes. The recommended approach is to follow the procedure given in Rooke and Cartwright (1976) with the factors given in this reference replaced by a value corresponding to $Q = 1.2$. It is recognized that this simplified approach will overestimate stress intensity factors for short cracks and for cracks remote from the transition of the knuckle to the tank bottom. The finite element calculations are not sufficiently complete to permit a more precise approach. However, the factor of $Q = 1.2$ removes a source of unconservatism for evaluating cracks at the critical location of highest bending stresses in the lower knuckle region.

Figure 5.6. Calculated Crack Tip Stress Intensity Factor as Function of Crack Length for Through-Wall Cracks in Lower Knuckle of Primary Tank Liner

Figure 5.7. Calculated Crack Tip Stress Intensity Factor as Function of Angular Location for Through-Wall Cracks in Lower Knuckle of Primary Tank Liner

6.0 Elastic-Plastic Fracture Mechanics Methodology

This section describes the methods used to perform elastic-plastic fracture mechanics calculations. These calculations established the critical lengths for through-wall flaws that can grow in an unstable manner and result in failure of the inner tank. It should be noted that prior simplified calculations of unstable flaws (Shurrab et al. 1991) were based on linear-elastic fracture mechanics. The resulting critical flaw sizes were believed to be conservative because the calculations failed to consider the fact that large amounts of stable crack growth by ductile tearing can occur before conditions for unstable fracture are encountered.

The cracks of greatest concern in the 1991 work were vertical cracks [i.e., 15.24-cm (6-in.) long] in the wall of the tank at locations where there were substantial membrane hoop stresses in the range of 124 MPa (18 ksi). Critical crack lengths at other tank locations (i.e., lower knuckle region) were much greater than 15.24 cm (6 in.). The elastic-plastic calculations in this report have addressed only the vertical cracks in the tank wall, with other locations addressed by the conservative linear fracture mechanics approach. The present evaluations demonstrate the potential for significant increases in the calculated values of critical crack sizes when elastic-plastic calculations are performed as opposed to linear-elastic calculations. This outcome, however, requires materials and tank operating temperatures so as to ensure a fracture mode for the carbon steel tank steel outside of the ductile brittle temperature transition.

6.1 Failure Assessment Diagram Approach

Elastic-plastic fracture mechanics calculations were performed using the failure assessment diagram approach, which has been presented by Milne et al. (1986) as the British R6 method for assessment of the integrity of structures containing defects. The R6 method addresses crack growth by ductile tearing for the particular material and the particular J-resistance curve of interest, but performs the evaluation using assessment points calculated using linear-elastic stress intensity factors and limit loads for the plastic collapse of cracked structures.

The failure assessment diagram for Option 1 of the R6 approach is based on the following equation

$$\begin{aligned} K_r &= (1 - 0.14S_r^2) (0.3 + 0.7 \exp(-0.65S_r^6)) \text{ for } S_r < S_r^{\max} \\ K_r &= 0 \text{ for } S_r > S_r^{\max} \end{aligned} \quad (6.1)$$

In order to derive the diagram, the engineering values of yield strength and flow stress need to be known. The value for the cut-off $S_r^{\max}$ is defined as the ratio of flow stress to the yield stress.

For an internally pressurized cylinder, the limit load factor was calculated using the equation recommended by Milne et al. (1986)

$$S_r = \left(\frac{pR}{\sigma_y t} \right) \left(1 + \frac{0.4l^2}{Rt} \right)^{1/2} \quad (6.2)$$

where p = internal pressure
              R = cylinder radius
              t = wall thickness of cylinder
              l = length of through wall crack.

The parameter K_I was calculated from the elastic stress intensity factor for an axially cracked cylinder as given in Rooke and Cartwright (1976) using the equations

$$K_I = (G_m \pm G_b) K_0 \quad (6.3)$$

$$K_0 = \left[\frac{1 + \nu}{3 + \nu} \right] \sigma_m \sqrt{\pi a} \quad (6.4)$$

where ν = Poisson's ratio
              σ_m = Membrane hoop stress in cylinder
              $2a$ = Total crack length
              G_m, G_b = Factors given as plots in Rooke and Cartwright (1976)

The calculation of K_I requires that the stress intensity factor for a given amount of crack extension be divided by the fracture toughness for this extended crack length as determined from the J-resistance curve for the material of interest.

6.2 Results of Calculations

Appendix C provides details of the elastic-plastic fracture mechanics calculations and presents plots from a set of calculations. Parameters covered by these calculations were

Tank Liner Radius = 1143 cm (450 in.)

Tank Wall Thickness = 1.23 cm (0.485 in.)

Yield Strength = 221 MPa (32 ksi)

Flow Strength = 317 MPa (46 ksi)

Lengths of Through-Wall Cracks = 6.35 cm (2.5 in.)
                                                  12.7 cm (5 in.)
                                                  25.4 cm (10 in.)
                                                  38.1 cm (15 in.)
                                                  50.8 cm (20 in.)

63.5 cm (25 in.)
 76.2 cm (30 in.)
 88.9 cm (35 in.)
 101.6 cm (40 in.)
 114.3 cm (45 in.)
 127.0 cm (50 in.)
 139.7 cm (55 in.)
 152.4 cm (60 in.)

Primary Membrane Hoop Stress = 125 MPa (18.1 ksi)
 100 MPa (14.5 ksi)
 69 MPa (10.0 ksi)
 41 MPa (6.0 ksi)

Safety Factor on K_r = 1.0 and 2.77 .

Safety Factor on S_r = 1.0, 1.5, and 2.77

The following J-resistance curves were used:

- a) For 21°C (70°F) the curve from Battelle Columbus data labeled F49W-1 as shown in Figure 4.1 was applied. This curve was taken to bound the room temperature fracture response. An applied J-value of 175 KJ/m² (1000 in-lb/in²) marked the end of ductile tearing and the onset of low-energy cleavage fracture.
- b) For 54°C (130°F) the curve from Battelle Columbus data labeled A106 Class C pipe at 288°C (550°F) as shown in Figure 4.1 was applied. This curve was taken to represent the upper shelf toughness behavior at temperatures equal to or greater than 54°C (130°F). An applied J-value of 525 KJ/m² (3000 in-lb/in²) is attained at a ductile crack extension of 0.5 cm (0.20 in.).
- c) For 38°C (100°F) the curve from Battelle Columbus data labeled A106 Class C pipe at 288°C (550°F) as shown in Figure 4.1 was applied. For purposes of representing an intermediate temperature of 38°C (100°F), the ductile crack extension was assumed to convert to the cleavage mode at a crack extension of 1.14 mm (0.045 in.). This amount of stable crack extension corresponded to a fracture toughness value at 38°C (100°F) that was the average of the toughness values corresponding to curves 1 and 2.

Yield and ultimate strength values [221 MPa and 414 MPa (32 ksi and 60 ksi)] were taken from ASME Code tables for A-515 Grade 60 steel as a lower bound on strength levels for the various grades used for the double-shell tanks. The flow strength was taken as the average of the yield and ultimate strengths.

The wall thickness of 1.23 cm (0.485 in.) was the nominal thickness at the location of the maximum hoop stress level [125 MPa (18.1 ksi)]. The lower levels of hoop stress were taken to cover a range of locations and loading conditions that would have larger acceptable crack lengths than for the bounding 18.1 ksi condition.

Figure 6.1 is an example of results from the R6 failure assessment diagram. The individual curves correspond to particular values of through-wall crack lengths. Data points for these curves were calculated using a FORTRAN computer program that was written for this purpose. The trajectory of the "hooked" shaped curves results as different levels of stable crack extensions are considered. The important aspect of the plots is whether the trajectories extend inside the boundary of the diagram. Cracks are unstable if the entire trajectory remains outside the boundary of the diagram.

Figure 6.1 assumes a hoop stress of 125 MPa (18.1 ksi), the upper bound J-resistance curve, and applies no safety factors in the calculation of K_r or S_r . It is seen that through-wall crack lengths up to 76.2 cm (30 in.) give trajectories that fall inside the boundary. A longer crack of 88.9 cm (35 in.) gave a trajectory that was entirely outside the boundary, which indicates that the critical or unstable crack length is about 81.3 cm (32 in.).

In Section 7 of this report, other calculations as described in Appendix C are described and acceptable lengths of through-wall cracks are estimated. These estimated lengths for through-wall cracks incorporate appropriate safety factors, and address the effects of temperature and stress level.

Figure 6.1. Failure Assessment Diagram Indicating Critical Crack Lengths. Safety Factors of 1.0 on K_t and 1.0 on S_r . Highest Level of J-Resistance Curve. Hoop Stress of 125 MPa (18.1 ksi).

7.0 Acceptable Lengths for Through-Wall Cracks

This section describes the development of acceptance criteria for through-wall cracks in the inner liner of the double-shell tanks. The calculations focus on the governing (worst-case) crack configuration, which is an axial (vertical) crack in the relatively highly stressed wall of the inner liner. Through-wall cracks at other locations have also been addressed both in this report and in the previous study (Shurrab et al. 1991). To develop simple acceptance criteria tables, the elastic-plastic fracture mechanics evaluations for the axial crack have been applied to a number of vertical locations in the tank. Acceptance standards for circumferential (horizontal) cracks and for the highly stressed lower knuckle region of the tank are also addressed in this section of the report using conservative linear-elastic fracture mechanics calculations. Other locations and crack orientations having lower stress levels are addressed with continued application of the Shurrab et al. (1991) evaluations.

7.1 Safety Factor Considerations

Particular attention was given to appropriate safety factors in the calculations of acceptable flaw sizes for axial cracks in the tank wall, since the loading conditions of interest were sufficient to produce a primary hoop stress [125 MPa (18.1 ksi)] essentially equal to the code primary membrane (S_m) stress limit. It was evident that excess conservatism in the selection of safety factors could result in unreasonably small flaw sizes for the acceptance criteria. Nevertheless, care was taken to select safety factors that were conservative and consistent with practices in the ASME Section XI Code for evaluating flaws in pressure vessels and piping.

A safety factor of 2.77 was selected for use in the present work. This factor is slightly less than the usual factor of 3.0 for flaw evaluations, but is consistent with the ASME Section XI procedures for evaluating the acceptability of flaws in piping components. In application of the R6 diagram for flaw instability, the safety factor of 2.77 was applied only to calculations of the K_r parameter. For the S_r parameter, a smaller safety factor of 1.5 was applied rather than 2.77, due to the considerations discussed in the following paragraph.

Appendix C presents the result of using a safety factor of 2.77 for both K_r and S_r (Figures C.2 and C.6). It was found in these calculations that no crack length was acceptable (even a crack of zero length) if the safety factor of 2.77 was imposed on both K_r and S_r . This type of outcome from the R6 flaw evaluation diagram has been noted by others in applications of ASME Section XI flaw evaluation procedures. There has been no accepted strategy developed to avoid this unreasonable situation. In the strategy for the present report, the safety factor of 2.77 on S_r was replaced with a factor of 1.5. This avoided the situation of multiplying service stresses for the uncracked tank by a factor approaching 3.0, which produces resulting stress levels that exceed both the yield and flow strengths of the material.

The specific rationale for selecting the 1.5 safety factor for S_r is as follows. In assigning S_m values, the ASME Code procedure has been to restrict S_m to 1/3 of the ultimate strength and 2/3 of the material yield strength. This corresponds to safety factors of 3.0 and 1.5 on the two strength parameters. The factor 3.0 on ultimate strength is a margin on fracture, whereas the factor of 1.5 is a margin on gross plastic deformation that would result should the primary stress in the vessel exceed

the material yield strength. In calculating assessment points for the R6 instability diagram, the S_r axis addresses concerns for gross plastic deformation as a result of exceeding the limit load for the cracked structure. In the present calculations, the factor of 1.5 provides a margin against limit load failure, which is consistent with code stress limits based on considerations of yield strength.

7.2 Axial Through-Wall Cracks in Tank Wall

Previous fracture mechanics evaluations (Shurrab et al. 1991) showed that the most limiting flaw was an axial crack in the vertical wall of the inner liner. Since these evaluations were based on linear-elastic fracture mechanics, there has been concern that the calculated 15.24-cm (6-in.) acceptable crack length was overly conservative. Appendix C presents the results of an extensive set of elastic-plastic fracture mechanics calculations that were performed to address these concerns for excess conservatism.

Table 7.1 summarizes the results of the calculations as presented in Appendix C. The calculated crack lengths address two cases for fracture toughness. In the lower-temperature case, the fracture toughness was assumed to correspond to the transition temperature range for the ferritic steels of interest; whereas in the higher-temperature case, the fracture toughness was assumed to correspond to upper shelf temperature range. The flaw was assumed in both cases to be located at the highest stressed part of the tank wall, which is for location "H" at an elevation of about 444.5 cm (175 in.) above the bottom of the tank where the nominal wall thickness is 1.27 cm (0.5 in.).

The calculated values of critical crack lengths for instability (without any safety factor on loading) are given in Table 7.1 as 45.7 cm and 81.3 cm (18 in. and 32 in.) for the two assumed levels of fracture toughness. When the safety factor of 2.77 is applied to both the K_{Ic} and S_r parameters of the R6 failure assessment diagram, all crack lengths are unacceptable (including a crack length of zero). This problematic result occurs because the governing hoop stress of 125 MPa (18.1 ksi) when multiplied by a factor of 2.77 exceeds the both the yield and flow stresses of the tank material.

The other calculated values of acceptable crack lengths in Table 7.1 are based on safety factors of either 1.0 or 1.5 on S_r . These less conservative approaches give non-zero values for acceptable crack lengths. The safety factor of 1.0 corresponds to a linear elastic fracture mechanics analysis that does not address structural failure by the mode of plastic collapse. With the reduced safety factors, the calculated values of acceptable crack lengths range from 8.9 cm to 40.6 cm (3.5 in. to 16 in.), depending on the assumed toughness level and the level of hoop stress [125 and 100 MPa (18.1 and 14.5 ksi)].

Table 7.2 and Figure 7.1 summarize the effect of both temperature and applied hoop stress on the acceptable lengths for through-wall cracks. These results were generated from the results of Appendix C. The limiting case is that of a 8.9-cm (3.5-in.) long crack for the bounding stress level of 18.1 ksi and for a lowest service temperature of 21°C (70°F). This crack length is significantly less than the 30.5-cm (12-in.) acceptable crack length for deeper cracks ($50\% > a/t > 20\%$) proposed by the TSIP panel (TSIP 1994). The present fracture mechanics evaluation indicates some modification of the TSIP proposal (as described in Appendix B) for a 30.5-cm (12-in.) crack is needed to ensure compliance with Code-type approaches for flaw evaluations. However, the 30.5-cm

Table 7.1. Effect of Safety Factor on Acceptable Lengths of Through-Wall Cracks

	Toughness Characteristic of Material	
	Low Toughness Cleavage Fracture after Limited Ductile Crack Extension	High Toughness Fully Ductile J-Resistance Curve
Critical/Unstable Crack Length - Safety Factors = 1.0	45.7 cm (18 in.) (Figure C-1)	81.3 cm (32 in.) (Figure C-6)
Allowable Crack Length [for Maximum Hoop Stress = 125 MPa (18.1 ksi)] - Safety Factor on K_r = 2.77 - Safety Factor on S_r = 2.77	All Crack Lengths are Unacceptable by R6 Approach (Figure C-2)	All Crack Lengths are Unacceptable by R6 Approach (Figure C-7)
Allowable Crack Length [for Maximum Hoop Stress = 125 MPa (18.1 ksi)] - Safety Factor on K_r = 2.77 - Safety Factor on S_r = 1.00	12.7 cm (5 in.) (Figure C-3)	40.6 cm (16 in.) (Figure C-8)
Allowable Crack Length [for Maximum Hoop Stress = 125 MPa (18.1 ksi)] - Safety Factor on K_r = 2.77 - Safety Factor on S_r = 1.50	8.9 cm (3.5 in.) (Figure C-4)	22.9 cm (9 in.) (Figure C-9)
Allowable Crack Length [for Reduced Hoop Stress = 100 MPa (14.5 ksi)] - Safety Factor on K_r = 2.77 - Safety Factor on S_r = 1.50	16.5 cm (6.5 in.) (Figure C-5)	40.6 cm (16 in.) (Figure C-10)

(12-in.) flaw is acceptable for all but a limited number of flaw locations for tanks with operating temperatures at or above 54°C (130°F). Also the fill height for most tanks will be less than the bounding level of 1143 cm (450 in.) and the specific gravity of the stored waste may be less than 1.7. Figure 7.1 indicates that one or both of these factors (stress and temperature) can significantly increase the acceptable crack lengths such that in many cases the 30.5-cm (12-in.) limit of the TSIP proposal would be supported by the elastic-plastic fracture mechanics calculations of this report.

Table 7.2. Summary of Acceptable Sizes for Through-Wall Vertical (Axial) Cracks in Tank Wall as Established by Fracture Mechanics Calculations

Location	Wall Thickness [Hoop Stress]	Acceptable Length of Through-Wall Crack		
		21°C (70°F)	38°C (100°F)	54°C (130°F)
"F" Tank Wall	1.87 cm (0.735 in.) [114 MPa] [(16.6 ksi)]	12.7 cm (5.0 in.)	19 cm (7.5 in.)	33 cm (13.0 in.)
"G" Tank Wall	1.87 cm (0.735 in.) [117 MPa] [(16.9 ksi)]	11.43 cm (4.5 in.)	17.8 cm (7.0 in.)	29.21 cm (11.5 in.)
"H" Tank Wall	1.23 cm (0.485 in.) [125 MPa] [(18.1 ksi)]	8.9 cm (3.5 in.)	14 cm (5.5 in.)	22.9 cm (9.0 in.)
"I" Tank Wall	1.23 cm (0.485 in.) [106 MPa] [(15.4 ksi)]	15.24 cm (6.0 in.)	24.13 cm (9.5 in.)	38.1 cm (15.0 in.)
"J" Tank Wall	0.91 cm (0.360 in.) [51 MPa] [(7.4 ksi)]	45.7 cm (18.0 in.)	71.1 cm (28.0 in.)	122 cm (48.0 in.)

(1) Based on safety factor of 2.77 on K_r and 1.5 on S_r .

7.3 Circumferential Through-Wall Cracks in Lower Knuckle

Crack tip stress intensity factors for through-wall circumferential cracks in the highly stressed lower knuckle of the tank were addressed by finite element calculations described in Section 5 of this report. The stress intensity factor is calculated using the following equation.

Figure 7.1. Acceptable Crack Lengths for Axial Crack in Vertical Wall of Tank as a Function of Hoop Stress and Temperature for Safety Factors of 2.77 on K_t and 1.5 on S_t .

$$K = \left[\frac{1 + \nu}{3 + \nu} \right] Q \sigma_b \sqrt{\pi a} \quad (7.1)$$

- ν = Poisson's ratio
- Q = factor established by finite element calculations
- σ_b = bending stress at location of crack
- a = half crack length

Using a bounding value of $Q = 1.2$ from Figures 5.5 and 5.6, an allowable stress intensity factor of $68 \text{ MPa}\sqrt{\text{m}}$ ($62 \text{ ksi}\sqrt{\text{in.}}$) [$204 \text{ MPa}\sqrt{\text{m}}$ ($186 \text{ ksi}\sqrt{\text{in.}}$) fracture toughness with a safety factor of three applied], and a bending stress of $\sigma_b = 183 \text{ MPa}$ (26.5 ksi), the above equation was solved to obtain the value of $a = 19.8 \text{ cm}$ (7.8 in.). The total crack length [$2a \approx 40.6 \text{ cm}$ (16 in.)] is somewhat less than the crack length of 55.9 cm (22 in.) calculated in prior work (Shurrab et al. 1991).

7.4 Through-Wall Cracks at Other Locations

The earlier work (Shurrab et al. 1991) included calculations of allowable lengths for through-wall cracks at various locations for both the axial and circumferential orientations. The calculated lengths of the cracks were all relatively long [greater than 61 cm (24 in.)] due to the relatively low stress levels involved. Tables 7.3 and 7.4 give the results of the 1991 calculations. These tables have been revised only to reflect the current results for the cases of cracks in the tank wall (axial cracks at locations "F," "G," "H," "I," and "J") and in the lower knuckle region (circumferential crack at locations "D" and "E").

Table 7.3. Acceptable Lengths of Through-Wall Cracks in the Primary Tank for a Temperature of 21°C (70°F)

Location	Wall Thickness, cm (in.)	Hoop Stress, MPa (ksi)	Meridional Stress, MPa (ksi)	Acceptable Crack Lengths, cm (in.)	
				Axial Cracks, cm (in.)	Circumferential Cracks, cm (in.)
"A" Bottom Plate	1.23 (0.485)	36/32 (5.3/4.7)	30/24 (4.3/3.5)	> 61 (24)	> 61 (24)
"B" Bottom Plate	1.23 (0.485)	27/27 (3.9/3.9)	26/27 (3.8/3.9)	> 61 (24)	> 61 (24)
"C" Bottom Plate	1.23 (0.485)	27/43 (5.8/6.2)	45/49 (6.5/7.1)	> 61 (24)	61 (24)
"D" Lower Knuckle	2.18 (0.860)	31/7 (4.5/1.0)	183/-184 (26.4/-26.6)	> 61 (24)	40.6 (16)
"E" Lower Knuckle	2.18 (0.860)	32/6 (4.7/0.9)	90/-92 (13.0/-13.3)	> 61 (24)	40.6 (16)
"F" Tank Wall	1.87 (0.735)	99/114 (14.4/16.6)	-21/29 (-3.1/4.2)	12.7 (5)	> 182.9 (72)
"G" Tank Wall	1.87 (0.735)	113/116 (16.5/16.9)	-1/9 (-0.2/1.3)	11.4 (4.5)	> 182.9 (72)
"H" Tank Wall	1.23 (0.485)	125/125 (18.0/18.0)	4/8 (0.5/1.2)	8.9 (3.5)	> 182.9 (72)
"I" Tank Wall	1.23 (0.485)	106/106 (15.4/15.4)	6/6 (0.9/0.9)	15.2 (6)	> 182.9 (72)
"J" Tank Wall	0.9 (0.36)	49/51 (7.1/7.4)	6/12 (0.8/1.8)	45.7 (18)	> 182.9 (72)
"K" Upper Knuckle	0.9 (0.36)	-72/-87 (-10.5/-12.7)	27/-12 (3.9/-1.8)	> > 182.9 (72)	91.4 (36)
"L" Upper Knuckle	0.9 (0.36)	-54/-50 (-7.9/-7.2)	13/15 (1.8/2.1)	> > 182.9 (72)	> 127 (50)
"M" Dome Liner	0.9 (0.36)	6/4 (0.8/0.6)	14/20 (2.0/2.9)	> 182.9 (72)	127 (50)
"N" Dome Liner	1.23 (0.485)	25/19 (3.6/2.8)	30/17 (4.4/2.5)	> 60.9 (24)	> 60.9 (24)

For safety factor of 3.0 applied to fracture toughness.

Fracture toughness at 21°C (70°F) estimated as 204 MPa√m (186 ksi√in.)

Stresses designated as inside surface stress/outside surface stress.

Table 7.4. Acceptable Lengths of Through-Wall Cracks in the Primary Tank for a Temperature of 54°C (130°F)

Location	Wall Thickness, cm (in.)	Hoop Stress, MPa (ksi)	Meridional Stress, MPa (ksi)	Acceptable Crack Lengths, cm (in.)	
				Axial Cracks, cm (in.)	Circumferential Cracks, cm (in.)
"A" Bottom Plate	1.23 (0.485)	36/32 (5.3/4.7)	30/4 (4.3/3.5)	> 61 (24)	> 61 (24)
"B" Bottom Plate	1.23 (0.485)	27/27 (3.9/3.9)	26/27 (3.8/3.9)	> 61 (24)	> 61 (24)
"C" Bottom Plate	1.23 (0.485)	27/43 (5.8/6.2)	45/49 (6.5/7.1)	> 61 (24)	61 (24)
"D" Lower Knuckle	2.18 (0.860)	31/7 (4.5/1.0)	183/-184 (26.4/-26.6)	> 61 (24)	40.6 (16)
"E" Lower Knuckle	2.18 (0.860)	32/6 (4.7/0.9)	90/-92 (13.0/-13.3)	> 61 (24)	40.6 (16)
"F" Tank Wall	1.87 (0.735)	99/114 (14.4/16.6)	-21/29 (-3.1/4.2)	33 (13)	> 182.9 (72)
"G" Tank Wall	1.87 (0.735)	113/116 (16.5/16.9)	-1/9 (-0.2/1.3)	29.2 (11.5)	> 182.9 (72)
"H" Tank Wall	1.23 (0.485)	125/125 (18.0/18.0)	4/8 (0.5/1.2)	22.9 (9)	> 182.9 (72)
"I" Tank Wall	1.23 (0.485)	106/106 (15.4/15.4)	6/6 (0.9/0.9)	38.1 (15)	> 182.9 (72)
"J" Tank Wall	0.9 (0.36)	49/51 (7.1/7.4)	6/12 (0.8/1.8)	121.9 (48)	> 182.9 (72)
"K" Upper Knuckle	0.9 (0.36)	-72/-87 (-10.5/-12.7)	27/-12 (3.9/-1.8)	> > 182.9 (72)	91.4 (36)
"L" Upper Knuckle	0.9 (0.36)	-54/-50 (-7.9/-7.2)	13/15 (1.8/2.1)	> > 182.9 (72)	> 127 (50)
"M" Dome Liner	0.9 (0.36)	6/4 (0.8/0.6)	14/20 (2.0/2.9)	> 182.9 (72)	127 (50)
"N" Dome Liner	1.23 (0.485)	25/19 (3.6/2.8)	30/17 (4.4/2.5)	> 60.9 (24)	> 60.9 (24)

For safety factor of 3.0 applied to fracture toughness.

Fracture toughness at 54°C (130°F) estimated as 204 MPa√m (186 ksi√in.)

Stresses designated as inside surface stress/outside surface stress.

8.0 Acceptable Depths for Part-Through Surface Cracks

The growth of part-through surface cracks is addressed in this section by consideration of the mechanisms of stress corrosion cracking, fatigue crack growth, and ductile tearing. For the present evaluations, all cracks were assumed to be 30.5-cm (12-in.) long. Crack-tip stress intensity factors were calculated at representative tank wall locations of high stress, and were then compared with thresholds for the three mechanisms of crack growth.

8.1 Stress Intensity Factors for Surface Cracks

Crack-tip stress intensity factors were calculated for inner-surface cracks at representative locations of high stress (identified in the figures of Appendix A and as tabulated in Tables 8.1 through 8.4).

Table 8.1. Stress Intensity Factors for Inner-Surface Axial Cracks at Location "H" within the Tank Wall

Crack Depth	Stress Intensity Factor, MPa√m (ksi√in.)	
	Without Residual Stress	With Residual Stress
a/t = 20%	14.7 (13.4)	18.8 (17.1)
a/t = 30%	21.0 (19.1)	26.8 (24.4)
a/t = 50%	37.2 (33.9)	47.6 (43.3)
Hoop Stress = 125 MPa (18.1 ksi) Residual Stress = 34 MPa (5 ksi) Wall Thickness = 1.23 cm (0.485 in.) Crack Length = 30.5 (12 in.)		

**Table 8.2. Stress Intensity Factors for Inner-Surface Axial Cracks at
Location "G" within the Tank Wall**

Crack Depth	Stress Intensity Factor, MPa√m (ksi√in.)	
	Without Residual Stress	With Residual Stress
a/t = 20%	16.5 (15.0)	21.4 (19.5)
a/t = 30%	22.3 (20.3)	29.1 (26.5)
a/t = 50%	38.6 (35.1)	50.2 (45.7)
Hoop Stress = 114 MPa (16.47 ksi) Residual Stress = 34 MPa (5 ksi) Wall Thickness = 1.87 cm (0.735 in.) Crack Length = 30.5 (12 in.)		

**Table 8.3. Stress Intensity Factors for Inner-Surface Circumferential Cracks at
Location "D" within the Lower Knuckle**

Crack Depth	Stress Intensity Factor, MPa√m (ksi√in.)	
	Without Residual Stress	With Residual Stress
a/t = 10%	15.7 (14.3)	19.2 (17.5)
a/t = 20%	21.4 (19.5)	26.8 (24.4)
a/t = 50%	24.9 (22.7)	38.0 (34.6)
Hoop Stress = 183 MPa (26.5 ksi) Residual Stress = 34 MPa (5 ksi) Wall Thickness = 2.18 cm (0.860 in.) Crack Length = 40.6 (16 in.)		

Table 8.4. Stress Intensity Factors for Inner-Surface Circumferential Cracks at Location "C" within the Tank Bottom Plate

Crack Depth	Stress Intensity Factor, MPa√m (ksi√in.)	
	Without Residual Stress	With Residual Stress
a/t = 20%	5.7 (5.2)	9.9 (9.0)
a/t = 40%	15.6 (14.2)	19.8 (18.0)
a/t = 50%	14.5 (13.2)	25.1 (22.8)
Hoop Stress = 49 MPa (7.1 ksi) Residual Stress = 34 MPa (5 ksi) Wall Thickness = 1.23 cm (0.485 in.) Crack Length = 30.5 (12 in.)		

The calculations of stress intensity factors were based on handbook solutions (Tada, Paris, and Irwin 1985) for long surface flaws in flat plates. The reduced levels of stress intensity factors for finite length cracks versus long (infinite) surface cracks were estimated using the approach described in Simonen et al. (1986). These reduction factors for evaluating finite length cracks were based on the work of Newman and Raju (1981). In each case, the crack had a semi-elliptical shape and the calculated values of stress intensity factor corresponded to the point of maximum crack depth.

Locations "H" in the tank wall and "D" in the lower knuckle were selected as the locations with the highest levels of bending stress and membrane stress, respectively. Location "G" in the tank wall has a relatively high level of membrane hoop stress [114 MPa (16.47 ksi)], along with a plate thickness [1.87 cm (0.735 inch)] that is thicker than at location "H." With the increased plate thickness, there is a potential for a greater crack-tip stress intensity factor given that the flaw depth in each case is a given fraction of wall thickness.

Location "C" within the bottom plate has a stress level [49 MPa (7.1 ksi)], which is substantially less than for the critical locations within the tank wall and lower knuckle. Nevertheless, location "C" was of interest because it bounds the stress levels for all the other less critical crack locations and orientations.

The assumed residual stress level of 34 MPa (5 ksi) was the same level as used in Shurrab et al. (1991). This stress was included as a conservative assumption to account for possible welding residual stresses that remain after stress relief of the tank.

8.2 Assessment of Stress Corrosion Cracking

Nitrate stress corrosion cracking of the mild steel tank materials is not expected to occur because 1) DSTs were stress relieved, and 2) the stored wastes contain inhibitors as protection against cracking. Such cracking has occurred in DSTs at the Savannah River site, where the tanks had not been stress relieved and where there was a lack of effective inhibitors. In these cases, the cracks were transverse to the welds and grew from the welds into the base metal before arresting. There has been no evidence of stress corrosion cracking in Hanford DSTs nor is such cracking expected. Nevertheless, due to possible uncertainties with the effectiveness of inhibitors and with the effectiveness of stress relief, stress corrosion cracking has been made a consideration for the inservice inspection of the tanks, and for the development of flaw acceptance criteria.

If stress corrosion cracking does occur, these cracks can grow at significant rates. Shurrah et al. (1991) cited data from Donovan (1977) for an estimated growth rate of 1.05×10^{-9} m/s. More recent evaluations of data by Blackburn (1995) indicate that 1.05×10^{-9} m/s is representative of average growth rates rather than of upper-bound growth rates. Bounding growth rates have been estimated by Blackburn to be 1.5×10^{-8} m/s. For this rate, the time needed for a crack to grow through a 1.27-cm (0.5-in.) tank wall is about 10 days. Therefore, once conditions for stress corrosion cracking occur, cracks are expected to grow through the wall of the tank in a relatively short time period.

Given the rapid crack growth rates, the strategy for tank integrity must be to preclude conditions for crack growth. Data on nitrate cracking as interpreted by Blackburn (1995) indicate that cracks do not grow if the crack-tip stress intensity factor is less than some threshold level. Shurrah et al. (1991) cited data from Donovan (1977) for a threshold stress intensity factor of $32 \text{ MPa}\sqrt{\text{m}}$ ($29 \text{ ksi}\sqrt{\text{in.}}$). The more recent evaluations by Blackburn (1995) indicate lower-bound thresholds in the range of $22\text{--}24 \text{ MPa}\sqrt{\text{m}}$ ($20\text{--}22 \text{ ksi}\sqrt{\text{in.}}$). For purposes of the present evaluation, $22 \text{ MPa}\sqrt{\text{m}}$ ($20 \text{ ksi}\sqrt{\text{in.}}$) was adopted as the criterion for precluding stress corrosion cracking.

Tables 8.1 through 8.4 of stress intensity factors for part-through inner-surface cracks indicate the allowable crack depths of Table 8.5 that will preclude stress corrosion cracking. Table 8.6 gives similar results for acceptable depths of axial cracks at several locations in the vertical wall of the tank. For purposes of reference, Table 8.6 gives the results at these same locations for the acceptable lengths of through-wall cracks as given previously in Table 7.2.

The stress intensity factors for crack depths $a/t = 50\%$ at locations "H," "G," and "D" are significantly greater than the thresholds needed for stress corrosion cracking. Cracks of smaller depths ($a/t = 20\%$ as have been recommended for flaw acceptance criteria) have stress intensity factors that are below the threshold level for stress corrosion cracking. The one exception is for the highly stressed lower knuckle region, where the acceptable crack depths are about 15% of the 2.18-cm (0.860-in.) wall thickness of the lower knuckle.

It is concluded that it is unlikely that any inner-surface cracks of $a/t = 20\%$ or less will grow by stress corrosion cracking, particularly with the use of inhibitors and stress relief for the DSTs. There could be cases where the inhibitors prove to be less effective than expected. In these cases, there would only be a small probability of crack growth for the $a/t = 20\%$ crack. The present calculations indicate that such growth would occur only if the crack growth threshold for the material

Table 8.5. Acceptable Flaw Depths to Preclude Flaw Growth by the Mechanism of Stress Corrosion Cracking

Flaw Location/Orientation	Acceptable Flaw Depth to Preclude Stress Corrosion Cracking
Location "H" Axial Crack in Tank Wall	$a/t = 23.8\%$
Location "G" Axial Crack in Tank Wall	$a/t = 20.8\%$
Location "D" Circumferential Crack in Lower Knuckle	$a/t = 13.5\%$
Location "C" Circumferential Crack in Bottom Plate	$a/t = 44.2\%$

approaches the lower bound 22 to 24 MPa/ $\sqrt{m}$ (20 to 22 ksi/ $\sqrt{in.}$) range, and if the conservative stress levels actually exist at the specific location of the preexisting surface crack. It is more likely that a random preexisting crack will be at a location or at an orientation having lower stress levels. It should also be noted that the present calculations of applied stress intensity factors have assumed bounding loading conditions for both the fill height and the specific gravity of the waste, and have assumed a relatively long [30.5- cm (12-in.)] surface flaw.

8.3 Assessment of Fatigue Crack Growth

An evaluation was performed to show that the amount of crack growth by the mechanism of fatigue will be minimal, because only a small number of stress cycles is expected. Fatigue evaluations based on the stress intensity factors listed in the above tables for locations "H," "G," and "D" were performed. A deep crack with $a/t = 50\%$ was assumed to be present at the worst-case location "G" of the tank wall. This case corresponds to a vertical crack with the highest calculated value of applied stress intensity factor for an $a/t = 50\%$ crack. It was conservatively assumed that each stress cycle corresponded to a complete fill and removal of all waste from the tank, which gives a cyclic stress intensity factor of $\Delta K = 35.1$ ksi/ $\sqrt{in.}$ A crack growth rate was estimated using the ASME Section XI curve for carbon steels assuming accelerated rates for an aggressive water environment and a high R ratio. These conservative assumptions gave an estimated crack growth of 6.3×10^{-4} cm (2.5×10^{-4} in.) per cycle. The calculated number of cycles needed for a modest growth of 10% of the wall thickness was about 300 cycles. This number of cycles is well above the anticipated usage of any DST. For the smaller $a/t = 20\%$ flaw, the corresponding number of cycles (location "D" governs for this flaw depth) is about 1100 cycles. Again no significant crack growth is predicted.

Table 8.6. Summary of Acceptable Sizes for Part-Through Vertical (Axial) Cracks in Tank Wall
as Established by Fracture Mechanics Calculations

Location	Wall Thickness [Hoop Stress]	Acceptable Depth Based on Threshold for Growth of Stress Corrosion Cracks ⁽¹⁾	Acceptable Length of Through-Wall Crack Based on Unstable Crack Extension		
			21°C (70°F)	38°C (100°F)	54°C (130°F)
"F" Tank Wall	1.87 cm (0.735 in.) [114 MPa] [(16.6 ksi)]	$a/t = 20.7\%$	12.7 cm (5.0 in.)	19 cm (7.5 in.)	33 cm (13.0 in.)
"G" Tank Wall	1.87 cm (0.735 in.) [117 MPa] [(16.9 ksi)]	$a/t = 20.8\%$	11.43 cm (4.5 in.)	17.8 cm (7.0 in.)	29.21 cm (11.5 in.)
"H" Tank Wall	1.23 cm (0.485 in.) [125 MPa] [(18.1 ksi)]	$a/t = 23.8\%$	8.9 cm (3.5 in.)	14 cm (5.5 in.)	22.9 cm (9.0 in.)
"I" Tank Wall	1.23 cm (0.485 in.) [106 MPa] [(15.4 ksi)]	$a/t = 27.6\%$	15.24 cm (6.0 in.)	24.13 cm (9.5 in.)	38.1 cm (15.0 in.)
"J" Tank Wall	0.91 cm (0.360 in.) [51 MPa] [(7.4 ksi)]	$a/t = 48.2\%$	45.7 cm (18.0 in.)	71.1 cm (28.0 in.)	122 cm (48.0 in.)

- (1) Based on a 22 MPa $\sqrt{m}$ (20 ksi $\sqrt{in.}$) threshold crack-tip stress intensity factor for stress corrosion cracking. Inner-surface crack length of 30.5 cm (12-in.) was assumed.

8.4 Assessment of Ductile Tearing

An evaluation of part-through-wall cracks has been performed to support the conclusion that crack growth by ductile tearing will not occur. It was established that the calculated levels of applied stress intensity factors as tabulated in the above tables were found to be much less than the levels needed to initiate ductile tearing.

Data presented in Section 4 indicates that the growth of part-through-wall cracks will be governed by an upper shelf ductile (high toughness) tearing fracture mode. A transition temperature fracture behavior (i.e., mode conversion to low energy cleavage fracture as may be relevant to through-wall cracks) will not be a concern for part-through-wall flaws for the plate thicknesses relevant to tank construction. The maximum calculated stress intensity factors for crack depths of $a/t = 50\%$ are less than $50.2 \text{ MPa}\sqrt{\text{m}}$ ($45.7 \text{ ksi}\sqrt{\text{in.}}$); whereas, the fracture toughness data cited in Section 4 indicate that the initiation of ductile crack extension requires levels of at least $132 \text{ MPa}\sqrt{\text{m}}$ ($120 \text{ ksi}\sqrt{\text{in.}}$). Substantial margins therefore exist relative to the initiation of ductile crack extension.

9.0 Acceptance Criteria for Crack-Like Flaws

The fracture mechanics calculations of this report have established the lengths and depths of cracks that have the potential to grow by various mechanisms including ductile tearing, stress corrosion cracking, and fatigue. These results provide the technical basis for developing a simple and comprehensive set of tables of acceptance criteria for any crack-like flaw detected during ultrasonic inspection. This section of the report concludes with a recommended set of such tables, provides a review of approaches used by others to develop tables for similar applications, defines an overall strategy for the present double-shell tank application, and discusses the option of performing detailed fracture mechanics calculations for cases of detected flaws that exceed the conservative limits of the recommended set of tables.

9.1 Review of Acceptance Criteria for Savannah River Reactor Tanks

Acceptance criteria for ultrasonic indications have been developed for the Savannah River reactor tanks (Daugherty 1990, Adamonis et al. 1989, and Begley and Daugherty 1989). The technical basis for these criteria and the resulting acceptable flaw sizes were reviewed as part of the present work as guidance in establishing acceptance criteria for the DSTs.

Critical crack lengths for through-wall flaws in the Savannah River reactor tanks were calculated using elastic-plastic fracture mechanics. The calculated length for an axial flaw in the cylindrical part of the tank for instability (no safety factor on pressure loading) was 147.3 cm (58 in.), and the corresponding ASME-allowable crack length (safety factor of 3.0 on pressure loading) was 63.5 cm (25 in.). The flaw acceptance criteria further reduced this length by an arbitrary factor of 2.0, and made an allowance for 6.35 cm (2.5 in.) of crack growth between inspections. The resulting final value for acceptable crack length was set at 25.4 cm (10 in.).

In the Savannah River work, all flaws with depths less than 20% of the wall were considered acceptable regardless of length. Flaws greater than 20% of the wall were acceptable for flaw lengths less than 25.4 cm (10 in.). Flaws greater than 25.4 cm (10 in.) in length could still be accepted on the basis of detailed fracture mechanics calculations. These detailed calculations must use a safety factor of 3.0 on pressure.

The present evaluations of flaws in DST inner liners were reviewed in the context of the Savannah River criteria. It was expected that critical flaw lengths in the double-shell tanks would be significantly smaller than those for the Savannah River reactor tanks. The governing hoop stress in the DST is about 125 MPa (18.1 ksi) versus 38.5 MPa (5.58 ksi) for the reactor tanks. The material for the reactor tanks is stainless steel versus carbon steel for the Hanford tanks. Given the high toughness for stainless steels and the much lower hoop stress, the calculated critical flaw length for the reactor tanks was 147.3 cm (58-in.) versus critical lengths ranging from 45.7 cm to 81.3 cm (18 in. to 32 in.) for the Hanford tanks. This range in the calculated crack lengths corresponds to different assumptions regarding the effect of the ductile-to-brittle transition temperature on the fracture toughness of the carbon steel tank materials.

The Savannah River work provides useful guidance for the present work on DST acceptance criteria. However, the high-toughness stainless steel materials and the low levels of hoop stress permitted a relatively high level of conservatism in the Savannah River flaw evaluations, with little penalty in terms of unreasonably small flaw sizes for the flaw acceptance criteria. Such levels of conservatism have not been used in the present application, because the resulting sizes of rejectable flaws could be judged to be unreasonably small. Furthermore, the consequences of a leak or rupture of the waste tanks are less, so additional conservatism of this case is not warranted.

9.2 Review of Recommendations of Tank Structural Integrity Panel

The Tank Structural Integrity Panel (TSIP 1994) has provided guidance for tank inspection, including recommendations for flaw acceptance criteria for cracks, wall thinning, and pitting. Tables in Appendix B summarize the recommendations of the panel.

The recommendations for flaw acceptance criteria in the TSIP report appear to be based on engineering judgement with evidence of influence by the acceptance criteria developed for the Savannah River reactor tanks. In the present report, we have sought to follow the guidance in the TSIP report, while developing a technical basis for those recommendations that depart from the TSIP report.

The TSIP recommendations parallel the Savannah River work with all cracks less than 20% of the wall thickness being acceptable without regard to crack length. Deeper cracks up to 50% of the wall thickness are acceptable if the lengths of these flaws are less than 30.5 cm (12 in.). The same criteria are specified for all regions of the tank including the high-stress regions of the vertical wall and the lower knuckle.

The TSIP recommendations also address wall thinning. Wall thinning up to 20% is acceptable without regard to the size of the thinned area. Pitting up to 50% of the wall is also acceptable. The same thinning and pitting criteria are specified for the various regions of the tank including the tank wall, lower knuckle, and bottom plates.

9.3 Option for Detailed Fracture Mechanics Evaluation

The acceptance standards as proposed in this report are in the format of simple tables that permit relatively small indications found by inservice inspection to be accepted without a need for detailed fracture mechanics calculations. However, there may be occasions when crack sizes exceed the sizes given in the proposed tables. In developing the present criteria, it has been assumed that detailed fracture mechanics analysis can be performed in order to justify the acceptance of larger cracks at specific locations. These more detailed calculations can address the potentially lower stress levels for the specific crack location and the operating stresses and temperature for the tank of interest. Factors such as the waste material density and the fill level for the tank can significantly reduce the stress levels in the tank from the worst-case condition assumed for the present bounding calculations. Also the actual temperatures that govern the fracture toughness of the material may be higher and thus at more favorable levels than assumed in the development of the generic acceptance criteria.

9.4 Strategy for Flaw Acceptance Tables

The fracture mechanics evaluations of this report indicate a wide range of acceptable flaw depths and lengths depending both on where the flaw is located (e.g., bottom plate or tank wall), and on the orientation of the flaw (i.e., axial or circumferential). The objective of this section of the report is to bring together the results of the various calculations in order to generalize the results into a simple set of tables and criteria. These tables address those flaws that can be classified as cracks as opposed to other forms of degradation such as wall thinning and pitting. Section 10 of this report addresses those flaws that can be classified as local wall thinning and pitting.

The fracture mechanics evaluations show that the only two modes of crack growth of concern are 1) unstable lengthwise growth of through-wall cracks by ductile tearing and/or cleavage fracture, and 2) rapid growth of part-through cracks at the inner surface by stress corrosion cracking. Axial cracks located in the vertical wall of the tank liner are of particular concern both for unstable lengthwise growth and for growth by stress corrosion cracking. The other major concern is for circumferential cracks in the lower knuckle region, for which growth by the mode of stress corrosion cracking is the major factor. Cracks at other locations and orientations are relatively benign, and can be addressed by a common set of acceptance criteria.

In the interest of developing a simple set of flaw acceptance criteria, cracks are categorized by discrete depths ($a/t = 10\%$, 20% , 40% and 50%) and by discrete crack lengths [10.2-, 30.5-, 40.6-, and 61-cm (4-, 12-, 16-, and 24-in.)]. The recommended acceptance criteria have been built around the following bounding assumptions on acceptable and unacceptable flaw sizes:

- a) Inner-surface cracks with depths of $a/t < 10\%$ are acceptable under all conditions without regard to the length of the flaw, the flaw location, or the flaw orientation. This stipulation is consistent with the detailed fracture mechanics calculations of this report, because there were no cases of flaws of depth $a/t = 10\%$ for which the calculated stress intensity factor exceeded the threshold level for stress corrosion cracking (20 ksi $\sqrt{\text{in.}}$). The current recommendation for $a/t < 10\%$ is somewhat more restrictive than the 20% level proposed by the Tank Structural Integrity Panel (1994) because of concerns for stress corrosion crack growth at highly stressed tank locations.
- b) Buried and outer-surface cracks with depths of $a/t < 20\%$ are acceptable under all conditions without regard to the length of the flaw, the flaw location, or the flaw orientation. This stipulation is the same as proposed by the Tank Structural Integrity Panel (1994) and is consistent with the fracture mechanics evaluations for long cracks, which showed significant margins against growth of part-through cracks by any of the crack growth mechanisms of concern.
- c) All cracks with depths $a/t > 50\%$ are unacceptable. This stipulation is the same as proposed by the Tank Structural Integrity Panel (1994). The 50% limit is based on somewhat arbitrary considerations that cracks of this extreme depth are unlikely to be encountered and should in any case be subject to a detailed fracture mechanics evaluation.

- d) Cracks with depths $10\% < a/t < 50\%$ can be accepted or rejected on a case-by-case basis by applying the tables of flaw acceptance criteria that address the following factors:
- length of the flaw
  - location of the flaw within tank
  - position of the flaw within tank wall (inner surface, outer surface, or buried)
  - orientation of the flaw
- e) Any unacceptable crack can be evaluated by detailed fracture mechanics calculations, and can be accepted on the basis of meeting criteria for margins against crack extension. The detailed fracture mechanics calculations should apply the same assumptions, criteria, and margins as used in this present report; but the evaluation may be based on the stress level for the actual location of the flaw and for stresses and temperatures relevant the particular tank of interest.

9.5 Recommended Flaw Acceptance Tables for Cracks

The recommended acceptance criteria for cracks in the inner liner of double-shell tanks are given by Tables 9.1, 9.2, and 9.3.

Table 9.1 addresses all flaw locations and flaw orientations except for the two high-stress locations corresponding to axial flaws in the vertical tank wall, and to circumferential flaws in the lower knuckle. The fracture mechanics evaluation for circumferential cracks at location "C" within the tank bottom plate was used to bound the evaluations for all the lower stress locations in the tank. Flaw lengths up to 61 cm (24 in.) and flaw depths up to 50% of the wall thickness are acceptable for the lower stresses at location "C." Because these flaws are relatively large, further refinement of the tables to address lower stresses at other locations was unwarranted. It should be noted that inner-surface flaws up to $a/t = 40\%$ are acceptable at the lower stress locations without exceeding thresholds for flaw growth by stress corrosion cracking.

Table 9.2 addresses the specific case of circumferential flaws in the lower knuckle. With the high levels of bending stress in the knuckle, the depth of inner-surface flaws is limited to $a/t < 15\%$

Table 9.1. Acceptable Sizes for Axial and Circumferential Cracks - Excluding 1) Axial Cracks in Vertical Tank Wall, and 2) Circumferential Cracks in the Lower Knuckle

Flaw Length	Acceptable Flaw Depth	
	Inner Surface Flaws	Buried and Outer Surface Flaws
Length > 61 cm (24 in.)	< 10% t	< 20% t
Length < 61 cm (24 in.)	< 40% t	< 50% t

Table 9.2. Acceptable Sizes for Circumferential Cracks in the Lower Knuckle

Flaw Length	Acceptable Flaw Depth	
	Inner Surface Flaws	Buried and Outer Surface Flaws
Length > 40.6 cm (16 in.)	< 10% t	< 20% t
Length < 40.6 cm (16 in.)	< 15% t	< 40% t

to preclude flaw growth by stress corrosion cracking. On the other hand, crack lengths up to 40.6 cm (16 in.) can be accepted, because the high levels of bending stress do not have a potential to cause growth of through-wall cracks by unstable ductile tearing.

Table 9.3 addresses the specific case of axial flaws in the vertical tank wall. Because relatively short through-wall flaws of this type can grow by unstable ductile tearing, Table 9.3 has been developed to address the effects of the tank operating temperature on critical flaw sizes. At the lower-bound tank wall temperature of 21°C (70°F), the acceptable flaw length is limited to 8.9 cm (3.5 in.). At a more typical operating temperature of 54°C (130°F), the acceptable flaw length increases to 22.9 cm (9.0 in.), which approaches the 30.5-cm (12-in.) length proposed by the Tank Structural Integrity Panel (1994).

Table 9.3. Acceptable Sizes for Axial Cracks in Vertical Tank Wall

Temperature	Flaw Length	Acceptable Flaw Depth	
		Inner Surface Flaws	Buried and Outer Surface Flaws
> 21°C (70°F)	Length > 9 cm (3.5 in.)	< 10% t	< 40% t
> 21°C (70°F)	Length < 9 cm (3.5 in.)	< 20% t	< 50% t
> 38°C (100°F)	Length > 14 cm (5.5 in.)	< 10% t	< 40% t
> 38°C (100°F)	Length < 14 cm (5.5 in.)	< 20% t	< 50% t
> 54°C (130°F)	Length > 23 cm (9.0 in.)	< 10% t	< 40% t
> 54°C (130°F)	Length < 23 cm (9.0 in.)	< 20% t	< 50% t

10.0 Acceptance Standards for Wall Thinning

While this report focuses on crack-like defects, evaluations were also performed to establish acceptable levels of tank wall degradation in the form of wall thinning and pitting. This effort addressed the applicability of existing ASME Section XI criteria as given in Code Case N-480 (ASME 1990). The detailed technical basis for the wall thinning criteria of the Code Case are documented in Gerber et al. (1988). Criteria developed for pitting of carbon steel piping at the Savannah River K Reactor (Mertz, Lam, and Awadalla, 1993) were also reviewed for applicability. Following the review of the technical basis, a set of acceptance criteria for both wall thinning and pitting are recommended at the conclusion of this section of the report.

10.1 Three Criteria for Acceptable Wall Thinning

While Code Case N-480 was developed for pipe wall thinning, the technical bases were judged to be generally applicable to wall thinning in the cylindrical vertical wall of a tank. Wall thinning can be accepted by Code Case N-480 on the bases of the following three considerations:

1. Measured wall thicknesses of 0.875 times the nominal thickness are acceptable. This consideration in Code Case N-480 addresses the wall thickness variations in piping that fall within fabrication tolerances. While dimensional tolerances for the plate materials of the tank will be tighter than for piping, it is still appropriate to assume that a 12.5% reduction in wall thickness will have an acceptable impact on structural integrity.
2. Measured wall thicknesses less than the nominal thickness are acceptable, provided that the remaining wall is greater than the Code-minimum wall thickness. This consideration addresses the common situation where the specified wall thickness is greater than that needed to achieve Code margins on stress levels.
3. Measured wall thicknesses less than the Code-minimum wall thickness are acceptable, if the region of wall thinning is localized to the dimensions prescribed in Code Case N-480.

Calculations were performed as part of this study for some specific cases of wall thickness, and stress levels relevant to double-shell tanks. These results are described below to provide an indication of the levels of local wall thinning that can be accepted at representative locations.

10.2 Methods for Evaluating Local Wall Thinning

Figure 10.1 defines the parameters that are used in Code Case N-480, and also in the present evaluations to characterize local wall thinning in DSTs. The vertical extent of the wall thinning is defined as $L_m(a)$ and the circumferential extent as $L_m(t)$. These dimensions define the region over which the wall has been thinned to a thickness less than the Code-minimum wall thickness. Only that portion of the thinned wall (but not portions of the wall with thickness greater than the Code-minimum wall), is included in establishing the dimensions $L_m(a)$ and $L_m(t)$.

Figure 10.1. Wall Thinning within Vertical Wall of Tank Inner Liner Showing Dimensions Defining Region of Thinning

- Case 1 - In this case the thinning extends only a small distance around the circumference of the tank in the form of a vertical band. The maximum dimension in the circumferential direction is limited to $L_m(t) < \sqrt{Rt_{min}}$, where R is the radius of the tank inner liner and t_{min} is the minimum wall thickness at the location needed to maintain the stress (hoop stress) to the Code-allowable stress levels. The maximum vertical dimension of this wall thinning is calculated using the method of Code Case N-480.
- Case 2 - In this case the thinning may extend entirely around the circumference of the tank in the form of a horizontal ring. The maximum vertical dimension of this wall thinning is calculated using the method of Code Case N-480.

These limiting cases were applied in example calculations for two locations in the tank. The first was location "J" near the top of the tank where the nominal wall thickness is 0.95 cm (3/8 in.). This location is a place where wall thinning might be expected because of the liquid vapor interface.

These limiting cases were applied in example calculations for two locations in the tank. The first was location "J" near the top of the tank where the nominal wall thickness is 0.95 cm (3/8 in.). This location is a place where wall thinning might be expected because of the liquid vapor interface. The hoop stress [49 MPa (7.1 ksi)] at location "J" is substantially below the Code-allowable level, and it was therefore expected that substantial thinning would be acceptable.

The second case addressed was for location "H," which is at a somewhat lower level in the tank where the hoop stress has little or no margin compared to the Code-allowable stress. The nominal wall thickness at location "H" is 1.27 cm (0.5 in.), and the calculated hoop stress is 125 MPa (18.1 ksi). Given the relatively high stress at this location, it was expected that only a rather limited amount of wall thinning would be acceptable.

The example wall thinning calculations for locations "J" and "H" were performed for the bounding stress levels calculated by Giller (1991). Since liquid levels and liquid densities could often be less severe than assumed in these bounding stress calculations, the example calculations also addressed allowable wall thinning for potentially lower levels of hoop stress.

In future work the methodology of Code Case N-480 could be used to perform calculations for other tank locations and for tank-specific values of liquid densities and liquid fill levels. Since the results as given below are based on bounding stress levels, the indicated wall thinning limits can be applied in a bounding fashion for any tank. Should inservice inspections detect significant wall thinning, further detailed evaluations using Code Case N-480 would be warranted.

10.3 Example Calculations for Wall Thinning at Location "J"

Location "J" is near the top of the tank where wall thinning might be expected because of the adjacent liquid vapor interface. The nominal wall thickness at location "J" is 0.95 cm (3/8 in.). The hoop stress [49 MPa (7.1 ksi)] is substantially below the Code-allowable stress [about 125 MPa (18 ksi)]. It was therefore expected that a substantial amount of wall thinning would be acceptable. It should be noted that the Giller (1991) stress analysis used a wall thickness of 0.91 cm (0.360 in.), which evidently included a corrosion allowance of 0.04 cm (0.015 in.).

- Case 1 - Figure 10.2 addresses the Case 1 type of wall thinning, which corresponds to a thinned wall that extends only a limited extent around the circumference of the tank [20.6 cm (8.1 in.) or less at location "J"]. Given the limited circumferential dimension, larger reductions in wall thickness can be accepted as compared to the smaller reductions permitted for Case 2 as indicated by Figure 10.3. For example, a measured wall thickness of 0.25 cm (0.10 in.) can extend a vertical distance of about 63.5 cm (25 in.) compared to only 20.3 cm (8 in.) for the situation addressed by Figure 10.3.
- Case 2 - Figure 10.3 addresses the Case 2 type of wall thinning, which corresponds to a thinned wall that extends entirely around the circumference of the tank, but extends only a finite distance in the vertical direction. A measured wall thickness of 2.22 cm (0.875 in.) of the nominal wall thickness is also acceptable [i.e., $2.22 \times 0.95 = 0.83$ cm ($0.875 \times 0.375 = 0.328$ in.)]. Furthermore, the stress at location "J" is relatively low, which means that the Code-minimum wall thickness is only 0.37 cm (0.145 in.). Therefore, this level of reduced

Vertical Extent of Wall Thinning, $L_m(a)$, meter

Vertical Extent of Wall Thinning, $L_m(a)$, inch

Figure 10.2. Allowable Wall Thickness for Case 1 (Thinning Extending Partially Around Tank Circumference) at Location "j" within Vertical Wall of Tank Inner Liner

Figure 10.3. Allowable Wall Thickness for Case 2 (Thinning Extending Around Full Tank Circumference) at Location "J" within Vertical Wall of Tank Inner Liner

1

wall thicknesses is acceptable without regard for the vertical extent of the thinning. A thickness less than 0.37 cm (0.145 in.) can be acceptable only if the inservice inspection provides data to show that the thinning is sufficiently localized. For example, Figure 10.3 indicates that a measured wall thickness of 0.3 cm (0.120 in.) requires that the vertical extent of the wall thinning be less than 50.8 cm (20 in.). For the relatively low level of hoop stress of 49 MPa (7.1 ksi), the acceptable wall thicknesses at location "J" can become as small as about 0.13 cm (0.05 in.) and still be acceptable by Code Case N-480, provided that this minimum thickness extends only about 7.6 cm (3 in.) in the vertical direction.

10.4 Example Calculations for Wall Thinning at Location "H"

Location "H" has the highest level of calculated hoop stress [125 MPa (18.1 ksi)] and provides a bounding condition for addressing wall thinning for other locations. The nominal wall thickness is 1.27 cm (0.5 in.) at location "H." The Giller (1991) stress analysis used a wall thickness of 1.23 cm (0.485 in.), which evidently included a corrosion allowance of 0.04 cm (0.015 in.). Comparisons of the 125 MPa (18.1 ksi) hoop stress with ASME Code-allowable stresses has indicated that 1.23 cm (0.485 in.) can be assumed to be essentially equal to the Code-minimal wall thickness for location "H" [i.e., $t_{\min} = 1.23 \text{ cm (0.485 in.)}$].

- Case 1 - Figure 10.4 addresses the Case 1 type of wall thinning, which corresponds to a thinned wall that extends only a limited extent around the circumference of the tank [37.6 cm (14.8 in.) or less at location "H"]. Given this limited circumferential dimension, relatively large reductions in wall thickness can be accepted compared to the smaller reductions permitted by Case 2 (Figure 10.2). For example, a measured wall thickness of 0.9 cm (0.35 in.) can extend a vertical distance of about 89 cm (35 in.) compared to only 25.4 cm (10 in.) for the situation addressed by Figure 10.5.
- Case 2 - Figure 10.5 addresses Case 2 type wall thinning at location "H," which corresponds to a thinned wall that extends entirely around the circumference of the tank, but extends only a finite distance in the vertical direction. The curves of Figure 10.5 have also included the Code Case acceptance of a measured wall thickness of 2.22 cm (0.875 in.) of the nominal thickness. Therefore at location "H," a reduced thickness of 1.11 cm (0.4375 in.) is acceptable regardless of the vertical extent of thinning. A thickness less than 1.11 cm (0.4375 in.) can be accepted only if the inservice inspection indicates that the thinning is sufficiently localized. For example, Figure 10.5 shows that a measured wall thickness of 0.9 cm (0.35 in.) requires that the vertical extent of the wall thinning be less than 25.4 cm (10 in.). For the bounding hoop stress of 125 MPa (18.1 ksi), the reduced wall thicknesses at location "H" can even be as small as about 0.38 cm (0.15 in.) and still be acceptable by Code Case N-480. However, this thickness can extend only about 7.62 cm (3 in.) over the vertical direction.

10.5 Review of Recommendations of Tank Structural Integrity Panel

The Tank Structural Integrity Panel (1994) has provided guidance for tank inspection, including recommendations for acceptance criteria that address wall thinning and pitting. The tables in Appendix B summarize the recommendations of the panel.

Vertical Extent of Wall Thinning, $L_m(a)$, meter

Figure 10.4. Allowable Wall Thickness for Case 1 (Thinning Extending Partially Around Tank Circumference) at Location "H" within Vertical Wall of Tank Inner Liner

Vertical Extent of Wall Thinning, $L_m(a)$, meter

Vertical Extent of Wall Thinning, $L_m(a)$, inch

Figure 10.5. Allowable Wall Thickness for Case 2 (Thinning Extending Around Full Tank Circumference) at Location "H" within Vertical Wall of Tank Inner Liner

As with the acceptance criteria for crack-like defects, the recommendations for acceptance of wall thinning and pitting in the TSIP report appear to be based on engineering judgement. In the present report, we have sought to follow the guidance of the TSIP report, except for high-stress locations. At these locations, the present evaluations indicate a need for more restrictive criteria than recommended in the TSIP report.

The TSIP recommendations can be summarized as follows. Thinning of the original wall thickness up to metal loss of $a/t = 20\%$ is permitted at any locations. This includes specific reference to the liquid-vapor interface, the liquid-sludge interface, the external surface of the primary tank, and the bottom of the tank. There are no stated restrictions on the vertical or horizontal extent of the thinned area. The same thinning criteria are specified for all regions of the tank.

The TSIP recommendations accept pits up to a depth of $a/t = 50\%$ at any location with particular reference to the liquid-vapor interface, the liquid-sludge interface, and the bottom of the tank. There is no statement whether the pits must be isolated, or if arrays of closely spaced pits of 50% depth are also permitted. There are also no stated restrictions regarding the overall acceptable size of the pitted area.

10.6 Option for Detailed Evaluations

The proposed acceptance criteria for wall thinning and pitting are in the format of simple tables that permit wall thinning and pitting to be accepted without a need for detailed calculations. These tables were developed to address the highest stressed locations, and are intended to provide conservative limits on wall thinning and pitting. It was beyond the scope of the present work to develop tables to address all potential situations of wall thinning and/or pitting. More detailed evaluations should be performed if future tank inspections measure wall degradation in excess of the limits of the tables of the acceptance criteria given below. Such evaluations would be focused on specific locations in the tank and on particular morphologies of degradation. It was not possible in the present study to anticipate the specific situations that may be of future concern.

10.7 Recommended Acceptance Criteria for Wall Thinning (Including Pitting)

Recommended acceptance criteria for wall thinning and pitting are given by Tables 10.1 and 10.2. These tables were intended to follow the overall recommendations of the Tank Structural Integrity Panel (Appendix B), while providing criteria that address some specific concerns for the location and extent of degradation. Wall thinning was evaluated following the guidance of ASME Section XI Code Case N-480 and Gerber et al. (1988). Pitting was addressed on the basis of Mertz, Lam, and Awadalla (1993).

- Wall Thinning - Table 10.1 addresses wall thinning that extends around the entire circumference. The lower stressed regions of the bottom plates permit wall thinning of depth $a/t = 20\%$ consistent with the TSIP recommendations. For the more highly stressed vertical wall of the tank, a depth of $a/t = 20\%$ is permitted (by application of Figure 10.5) only if the vertical extent of such thinning is less than 45.7 cm (18 in.). Otherwise the $a/t = 12.5\%$ provision of

Code Case N-480 applies. In the high-stress region of the lower knuckle, the 12.5% provision of Code Case N-480 was also applied. While it is likely that somewhat greater levels of thinning could be permitted, no structural mechanics evaluations were available to justify such less conservative limits for thinning in the knuckle region.

Table 10.1. Acceptable Depths for Wall Thinning Extending Around Entire Circumference

Location	Vertical Extent of Wall Thinning	Acceptable Depth of Thinning
Bottom Plates	N/A	$< 20\% t$
Lower Knuckle	N/A	$< 12.5\% t$
Vertical Tank Wall	$> 45.7 \text{ cm (18 in.)}$	$< 12.5\% t$
	$< 45.7 \text{ cm (18 in.)}$	$< 20\% t$

Table 10.2. Acceptable Depths for Wall Pitting

Type of Pitting	Spacing of Pits Ratio of Center-to-Center Spacing to Pit Diameter	Acceptable Depth of Pitting
Isolated Pits	> 4.0	$< 50\% t$
	> 2.0	$< 25\% t$
	> 1.0	$< 12.5\% t$
Arrays of Pits (cases where center-to-center spacing cannot be demonstrated to be greater than 1.0)	N/A	Use criteria for wall thinning by enveloping of extent and depth of pitted region

- **Pitting** - Table 10.2 addresses pitting of the tank wall. The approach of Mertz, Lam, and Awadalla (1993) was applied to relate allowable pit depths to the spacing between pits. The approach considers the loss of net cross-sectional area of the wall due to the pits. Thus, deeper pits are permitted if the pits are more widely spaced, such that the net loss of cross section is equivalent.

The acceptance criteria of Table 10.2 were developed by consideration of the most highly stressed locations of the vertical tank wall and these criteria were conservatively specified for all locations. Pit depths up to the $a/t = 50\%$ limit of the TSIP recommendations are permitted only if the pits are clearly isolated and widely spaced within the limits stated in Table 10.2. Otherwise the allowable depths are reduced. Pit depths of $a/t = 12.5\%$ are permitted without regard to spacing criteria by extension of the approach of Code Case N-480. If arrays of pits cannot be characterized as being isolated pits, Table 10.2 states that the array should be enveloped by a boundary and then treated as an equivalent situation of wall thinning using the criteria of Table 10.1.

11.0 Expected Flaws in Tank Welds

This section describes estimates of the numbers, sizes, and locations of flaws that should be expected in the welds of the inner liner of the double-shell tanks. These estimates were not used directly in the development of the flaw acceptance criteria of this report. Rather, the estimates were used to indicate whether the flaw sizes specified by the criteria will or will not lead to unjustified evaluations or repairs of the flaws that are typical of the expected population of flaws in welded steel construction.

The present estimates address only the flaws that would have existed since the time of tank fabrication, and do not address other flaws that may have initiated and/or grown during the service history of the tanks. In general, fabrication flaws are either flaws that were undetected by inspection at the time of construction, or detected flaws that were too small to require repair by the repair requirements that applied to the construction. It is important to recognize that an inservice inspection can and will detect fabrication flaws. The flaw acceptance criteria for inservice inspection provide a basis to accept such flaws and thereby avoid the consequences of unneeded repairs.

The estimates as described here were derived from results of a weld simulation model developed by Chapman (1993) in the United Kingdom. This weld simulation model makes extensive use of information on the types, sizes, and frequencies of flaws reported by experienced engineers responsible for welding, nondestructive evaluation, and quality assurance.

Table 11.1 gives the estimated numbers of flaws of various depths that would exist in the inspected length of welds in one waste tank. For the present purposes, it was assumed that the tank inspections are performed through two 61-cm (24-in.) diameter vertical risers, and that this permits inspection of two of the eight vertical welds in each tank. It was also assumed that the inspection addresses about 10% of the total length of horizontal welds. The total inspected length of weld per tank was thus estimated to be about 45.7 m (150 ft.).

The results from Chapman were for welds in ferritic steel pipe with a wall thickness of about 2.54 cm (1 in.) and a diameter of about 61 cm (2 ft.). It was assumed that the numbers of flaws per unit length of pipe weld was the same as the number of flaws per unit length weld in the tank. Table 11.1 was generated on this basis. Two categories of flaws are indicated in Table 11.1. The inner surface flaws are of greatest concern, because such fabrication flaws would have the potential to grow by stress corrosion cracking. The second category listed in Table 11.1 addresses all flaws including buried flaws and outer surface flaws. These flaws are of little concern because they are unlikely to grow for the stresses and service environments of interest.

Table 11.1 lists the estimated probabilities that the inspected weld will have a flaw larger than the sizes defined in the acceptance criteria (i.e., $a/t = 20\%$). Most flaws will not be inner-surface flaws, with less than 1% of the total number of flaws being in this category. The results for both the manual metal arc and the submerged arc welds indicate that there should be less than a 1% probability for an inner-surface flaw with $a/t > 20\%$ within the inspected length of weld in a given tank. If all the weld length (both inspected and uninspected) is addressed, the probability would still be less than 10%. However, if all of the welds in all of the 28 double-shell tanks are considered, it is expected that there will be about one inner-surface flaw with depth $a/t > 20\%$.

Table 11.1. Expected Number of Flaws in Welds of Each Inspected Tank

	Number of Flaws in Inspected Welds of One Tank	
	Inner Surface Flaws	All Flaws
Manual Metal Arc Weld		
a/t > 10%	0.0043	44.00
a/t > 25%	0.0014	4.00
a/t > 50%	0.0000	0.23
Submerged Arc Weld		
a/t > 10%	0.0069	0.79
a/t > 25%	0.0023	0.23
a/t > 50%	0.0011	0.015

In conclusion, it appears that a flaw depth of $a/t > 20\%$ for inner-surface flaws should provide a workable basis for an acceptance criteria, because it is unlikely that there will be any benign fabrication flaws greater than this depth within the length of inspected welds in a tank. It is more likely that a buried flaw in the depth range of $a/t = 25\%$ to 50% will be detected. Such flaws are not expected to grow by stress corrosion cracking. Unless they are very long and in the most highly stressed welds, such flaws should be acceptable from the standpoint of unstable ductile fracture.

12.0 Conclusions

This report provides recommendations and technical bases for acceptance criteria for flaw indications detected during ultrasonic inspection of inner liners of the DSTs. Three types of indications are addressed - crack-like flaws, wall thinning, and pitting. In establishing acceptable flaw sizes, the evaluations have taken into consideration the potential for crack growth by the mechanisms of ductile tearing, fatigue, and stress corrosion cracking. The recommended acceptance criteria are intended to be simple to apply using a set of tables giving acceptable flaw sizes. The tables are sufficiently conservative to bound the results of the fracture mechanics calculations and to be applicable to all double-shell tanks.

In those cases that a particular flaw exceeds the size permitted by the tables, it is proposed that additional criteria permit more detailed and less conservative evaluations to address specific conditions of stress levels, operating temperature, flaw location, and material properties. In those cases that a flaw exceeds the size permitted by the tables, it is proposed that detailed evaluations be performed.

It is believed that in most cases degradation expected to be encountered during inservice inspections can be accepted on the basis of the simplified and general-purpose acceptance criteria as given by Tables E.1 through E.5. A review of published data on the numbers and sizes of welding defects is presented in this report, and it is concluded that cracks exceeding the sizes given by the flaw acceptance criteria are unlikely to be found in the tank welds.

While there are tank-to-tank differences between the specific grades of low-carbon steels and details of the welding processes, it was concluded for the present purposes that the various grades of tank materials can be treated as falling within a single scatter band of fracture properties for low-carbon structural steels. For these steels, it was concluded that tank operating temperatures in the 21°C (70°F) range are not sufficiently high to completely ensure ductile upper shelf fracture by ductile tearing rather than by brittle cleavage fracture. Accordingly, the elastic-plastic fracture mechanics calculations were based on tearing resistance curves that included a conversion of the fracture mode to low-energy brittle cleavage fracture following a relatively small amount of stable crack growth.

Finite element calculations for cracks in the tank lower knuckle were performed to address concerns for the accuracy and conservatism of the previous estimates based on cylindrical shell approximations. The contribution of the mode III transverse shear mode of crack-tip displacement was found to be significant. Application of a factor of 1.2 to the previous method of estimating stress intensity factors was adopted to remove a source of unconservatism in evaluating cracks located in the highly stressed lower knuckle.

Elastic-plastic fracture mechanics calculations were performed using the failure assessment diagram approach of the British R6 method for assessment of the integrity of structures containing defects. Particular attention was given to appropriate safety factors for the calculations of acceptable sizes of axial cracks in the tank wall. It was established that excess conservatisms in the selection of safety factors could result in unreasonably small flaw sizes for the acceptance criteria. Care was taken to select safety factors that were conservative and consistent with practices in the ASME Section

XI Code. On this basis in application of the R6 diagram, a safety factor of 2.77 was applied in calculations of the K_I parameter, with a factor of 1.5 applied for calculation of the S_r parameter.

The smallest calculated values for critical crack lengths (without any safety factor on loading) were for axial cracks in the vertical tank wall, where the calculated lengths ranged from 45.7 cm to 81.3 cm (18 in. to 32 in.) for the assumed range of temperature-dependent fracture toughness. With the application of safety factors, the calculated values of acceptable crack lengths at the most highly stressed part of the tank wall ranged from 8.9 cm to 22.9 cm (3.5 in. to 9 in.).

The growth of part-through-surface cracks is addressed by consideration of the mechanisms of stress corrosion cracking, fatigue crack growth, and ductile tearing. Crack-tip stress intensity factors were calculated at representative tank wall locations of high stress and were then compared with thresholds for the three mechanisms of crack growth. A residual stress level of 34 MPa (5 ksi) was assumed as a conservative assumption. A lower bound threshold of $22 \text{ MPa}\sqrt{\text{m}}$ ($20 \text{ ksi}\sqrt{\text{in.}}$) was adopted as the criterion for precluding stress corrosion cracking. It is concluded that it is very unlikely that any inner-surface cracks of $a/t = 20\%$ or less will grow by stress corrosion cracking, particularly with the use of inhibitors and stress relief for the DSTs. No significant crack growth is predicted for part-through-wall flaws by the mechanisms of fatigue or ductile tearing.

Acceptance criteria for ultrasonic indications as developed for the Savannah River reactor tanks and as proposed by the Tank Structural Integrity Panel were reviewed. These prior efforts provided useful guidance for the present work on DST acceptance criteria. However, the lower toughness levels for the ferritic steel DST materials and the high levels of hoop stress in the DSTs both contributed to selected reductions in acceptable crack sizes as compared to the sizes proposed in the prior Savannah River and TSIP efforts.

Evaluations were performed to establish acceptable levels of tank wall degradation in the form of wall thinning and pitting. Wall thinning was addressed by the application of the existing ASME Section XI criteria as given in Code Case N-480. Pitting was addressed using the criteria developed for pitting of carbon steel piping at the Savannah River K Reactor. The acceptance criteria for thinning and pitting were developed to provide a simple and conservative approach, and were not intended to address the wide range of possible morphologies for wall degradation. Future work can, as needed, address specific patterns of thinning and/or pitting as identified by the results of inservice inspections.

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Appendix A

Tank Configuration and Stresses

Appendix A

Tank Configuration and Stresses

Figures A.1 through A.4 have been extracted from a prior document (Shurrah et al. 1991) on tank structural integrity. These figures provide details of tank dimensions and calculated stress levels. Flaw acceptance criteria of this report are based in the calculated stress levels of Figures A.3 and A.4 as reported in Giller (1991). These stress levels were assumed to bound the expected stress levels in the population of double-shell tanks.

Upper dome is ellipse of major/and minor diameters of 80 ft and 30 ft.

Figure A.1. Dimensions of the Primary Tank

Figure A.2. Wall Thickness in the Primary Tank (in.)

Key

Inner surface/outer surface

79109187.9

Figure A.3. Hoop Stresses (psi) in the Primary Tank

Key
Inner surface/outer surface

Figure A.4. Axial (Meridional) Stresses (psi) in the Primary Tank

Appendix B

Recommendations of Tank Structural Integrity Panel

Appendix B

Recommendations of Tank Structural Integrity Panel

Table B.1 is extracted from a draft document prepared in 1994 by the Tank Structural Integrity Panel titled "Guidelines for Development of Structural Integrity programs for DOE High-Level Waste Storage Tanks" (Draft for Review Purposes Only). This table outlines a recommended inservice inspection program and proposes acceptance levels for flaws detected during inspection. These recommendations were used to guide the development of acceptance criteria as described in the present report. The recommendations of the present report generally follow those in the draft report from the Tank Structural Integrity Panel, except where the detailed evaluations indicated that the criteria failed to provide sufficient margins. In some cases, the detailed evaluations provided a basis for relaxation of the acceptance criteria.

Table B.1. Examinations of Carbon or Low-Alloy and Austenitic Stainless Steel or High-Alloy Tank Containing High-Level Waste

Region Examined	Examination Requirements	Examination Methods	Acceptance Levels	Extent of Examination	Frequency of Examination
Liquid-vapor interface	± one foot of interface	Volumetric (0° UT)	Pits (< 50%t)	5% of interface length of each tank to be examined*	Each inspection interval (divided into two periods)
Liquid-sludge interface, if such exists	± one foot of interface	Volumetric (UT) from outer surface	Pits (< 50%t) Cracks (< 50%t)*** (< 20%t)** Gross corrosion (< 20%t)	5% of interface length of each tank to be examined	Each inspection interval
Lower knuckle of primary tank	Upper weld	Volumetric	Cracks (< 20%t)** (< 50%t)***	5% of length divided into two or more segments, if accessible	Each inspection interval
Lower knuckle of primary tank	Predicted maximum stress region of base metal plus lower weld if accessible	Volumetric	Cracks (< 20%t)** (< 50%t)***	5% divided between knuckle base metal and lower weld if accessible; otherwise 5% of knuckle divided into two or more segments	Each inspection interval
External surface of primary tank if accessible, and internal surface of secondary tank if such exists	Overall scan of accessible regions	Remote visual	Any signs of degradation must be evaluated	All accessible regions	At least once each inspection interval

Table B.1. Examinations of Carbon or Low-Alloy and Austenitic Stainless Steel or High-Alloy Tank Containing High-Level Waste (continued)

Region Examined	Examination Requirements	Examination Methods	Acceptance Levels	Extent of Examination	Frequency of Examination
External surface of primary tank if accessible	Below nominal vapor-liquid interface	Volumetric (0°) UT	Wall thinning (<20%t)	Each inspection interval	Each inspection interval
Vapor region at top of primary tank	Confirm VT with PT or UT if attack is found	Remote visual	Evidence of attack should be evaluated	Remote scan of vapor region	Each inspection interval
Plate making up bottom of tank if accessible	"Best effort" NDE examination	Volumetric	Cracking (<20%t)** (<50%t)*** Thinning (<20%t) Pitting (<50%t)	Primarily for new tanks designed for accessibility; however, limited scans should be conducted if feasible	Each inspection interval
Overall scan of internal surface	When a tank is essentially empty	Remote visual	Evidence of degradation should be evaluated	General scan of inside of primary tank	When a tank is empty

* Tank population to be examined is 10% of tanks, but not less than one; alternatively, the population examined may be greater than 10% with a comparable reduction in the amount examined in each tank, provided the totals are the same as for the 10% population.

** <20%t for cracking applies with flaw lengths $\geq$ one foot.

*** <50%t for cracking applies with flaw lengths < one foot with lower bound lengths about 1.27 cm (0.5 in.).

The inspection interval is 10 years; the inspection period is approximately 5 years.

Appendix C

Elastic-Plastic Fracture Mechanics Calculations

Appendix C

Elastic-Plastic Fracture Mechanics Calculations

This appendix documents details of the elastic-plastic fracture mechanics calculations and presents plots of a set of calculations for the stability of through-wall axial cracks in the vertical wall of the inner liner of the double-shell waste storage tanks. These calculations were performed using the R6 method as described in Section 6 of this report. Parameters covered by these calculations were

Tank Liner Radius = 1143 cm (450 in.)

Tank Wall Thickness = 1.23 cm (0.485 in.)

Yield Strength = 32 ksi

Flow Strength = 46 ksi

Lengths of Through-Wall Cracks = 6.35 cm (2.5 in.)
12.7 cm (5 in.)
25.4 cm (10 in.)
38.1 cm (15 in.)
50.8 cm (20 in.)
63.5 cm (25 in.)
76.2 cm (30 in.)
88.9 cm (35 in.)
101.6 cm (40 in.)
114.3 cm (45 in.)
127.0 cm (50 in.)
139.7 cm (55 in.)
152.4 cm (60 in.)

Primary Membrane Hoop Stress = 125 MPa (18.1 ksi)
100 MPa (14.5 ksi)
69 MPa (10.0 ksi)
41 MPa (6.0 ksi)

Safety Factor on K_r = 1.0 and 2.77

Safety Factor on S_r = 1.0, 1.5, and 2.77

J-resistance curves:

- a) For 21°C (70°F) the curve from Battelle Columbus data labeled F49W-1 as shown in Figure 4.1 was applied. This curve was taken to bound the room temperature fracture

response. An applied J-value of 175 KJ/m² (1000 in-lb/in²) marked the end of ductile tearing and the onset of low-energy cleavage fracture.

- b) For 54°C (130°F) the curve from Battelle Columbus data labeled A106 Class C pipe at 288°C (550°F) as shown in Figure 4.1 was applied. This curve was taken to represent the upper shelf toughness behavior at temperatures equal to or greater than 54°C (130°F). An applied J-value of 525 KJ/m² (3000 in-lb/in²) is attained at a ductile crack extension of 0.5 cm (0.20 in.).
- c) For 38°C (100°F) the curve from Battelle Columbus data labeled A106 Class C pipe at 288°C (550°F) as shown in Figure 4.1 was applied. For purposes of representing an intermediate temperature of 38°C (100°F), the ductile crack extension was assumed to convert to the cleavage mode at a crack extension of 1.14 mm (0.045 in.). This amount of stable crack extension corresponded to a fracture toughness value at 38°C (100°F) that was the average of the toughness values corresponding to curves 1 and 2.

Yield and ultimate strength values [221 MPa and 414 MPa (32 ksi and 60 ksi)] were taken from ASME Code tables for A-515 Grade 60 steel as a lower bound on strength levels for the various grades used for the double-shell tanks. The flow strength was taken as the average of the yield and ultimate strengths.

The wall thickness of 1.23 cm (0.485 in.) was the nominal thickness at the location of the maximum hoop stress level [125 MPa (18.1 ksi)]. The lower levels of hoop stress were taken to cover a range of locations and loading conditions that would have larger acceptable crack lengths than for the bounding 125 MPa (18.1 ksi) condition. Such stress conditions would address:

- a) Other vertical locations in the tank with lower levels of hoop stress.
- b) Situations where wall thickness is known to be greater than the minimum wall (with corrosion allowance) used in the stress analysis.
- c) Lower stress levels due to tank fill height and fluid density being less than the conservative values assumed in the stress analyses.

The safety factor of 1.0 was used for estimating the lengths of cracks that will actually become unstable by ductile tearing or by cleavage following some limited stable growth by ductile tearing. The safety factor of 2.77 was based on the use of this factor in ASME Section XI for evaluations of flaws in stainless steel and ferritic steel piping. As discussed in Section 7.1 of the present report, the use of a safety factor on load for the calculation of both the K_r and S_r parameters of the R6 analysis was believed to introduce excessive conservatism into the evaluation. For this reason, flaw acceptance criteria were based on a reduced safety factor of 1.5 applied to the S_r parameter, but with the factor of 2.77 retained for the K_r parameter.

Figures C.1 through C.18 provide the results of the R6 flaw evaluations. These diagrams indicate the stability of through-wall cracks of different lengths (with total crack defined as $2a_0$). The following summarizes the information on this collection of diagrams.

- Figures C.1 through C.4 These plots all address the condition of maximum hoop stress [125 MPa (18.1 ksi)] and the lower bound on the J-resistance curve [cleavage fracture at $J = 175 \text{ KJ/m}^2$ (1,000 in-lb/in²)]. The four curves address various safety factors ranging from 1.0 to 2.77.
- Figure C.5 This plot assumes the same toughness as the previous set of figures but assumes a somewhat lower level of hoop stress of 100 MPa (14.5 ksi) [80% of the maximum of 100 MPa (18.1 ksi)]. The safety factors were the values recommended in the Section 7.1 of this report (2.77 on K_r and 1.5 on S_r).
- Figures C.6 through C.10 These plots cover the same parameters as the previous plots (Figures A.1 through A.5) except that the upper bound J-resistance curve has been used to address the situation where the ductile tearing occurs without conversion to low-energy cleavage fracture.
- Figures C.11 through C.12 These plots assume the intermediate level of material toughness with hoop stress levels of 125 MPa (18.1 ksi) and 100 MPa (14.5 ksi). The safety factors were the values recommended in the Section 7.1 of this report (2.77 on K_r and 1.5 on S_r).
- Figures C.13 through C.15 These plots address lower levels of hoop stress [69 MPa and 41 MPa (10 ksi and 6 ksi)] for the three levels of material toughness. The safety factors were the values recommended in the Section 7.1 of this report (2.77 on K_r and 1.5 on S_r).
- Figures C.13 through C.18 These plots address lower levels of hoop stress [69 MPa and 41 MPa (10 ksi and 6 ksi)] for the three levels of material toughness. The safety factors were the values recommended in the Section 7.1 of this report (2.77 on K_r and 1.5 on S_r).

Figure C.1. Failure Assessment Diagram Indicating Critical Crack Lengths. Safety Factors of 1.0 on K_I and 1.0 on S_r . Lowest Level of J-Resistance Curve. Hoop Stress of 125 MPa (18.1 ksi).

Figure C.2. Failure Assessment Diagram Indicating Acceptable Crack Lengths. Safety Factors of 2.77 on K_I and 2.77 on S_r . Lowest Level of J-Resistance Curve. Hoop Stress of 125 MPa (18.1 ksi).

Figure C.3. Failure Assessment Diagram Indicating Acceptable Crack Lengths. Safety Factors of 2.77 on K_r and 1.0 on S_r . Lowest Level of J-Resistance Curve. Hoop Stress of 125 MPa (18.1 ksi).

Figure C.4. Failure Assessment Diagram Indicating Acceptable Crack Lengths. Safety Factors of 2.77 on K_r and 1.50 on S_r . Lowest Level of J-Resistance Curve. Hoop Stress of 125 MPa (18.1 ksi).

Figure C.5. Failure Assessment Diagram Indicating Acceptable Crack Lengths. Safety Factors of 2.77 on K_r and 1.5 on S_r . Lowest Level of J-Resistance Curve. Hoop Stress of 100 MPa (14.5 ksi).

Figure C.6. Failure Assessment Diagram Indicating Critical Crack Lengths. Safety Factors of 1.0 on K_r and 1.0 on S_r . Highest Level of J-Resistance Curve. Hoop Stress of 125 MPa (18.1 ksi).

Figure C.7. Failure Assessment Diagram Indicating Acceptable Crack Lengths. Safety Factors of 2.77 on K_r and 2.77 on S_r . Highest Level of J-Resistance Curve. Hoop Stress of 125 MPa (18.1 ksi).

Figure C.8. Failure Assessment Diagram Indicating Acceptable Crack Lengths. Safety Factors of 2.77 on K_r and 1.0 on S_r . Highest Level of J-Resistance Curve. Hoop Stress of 125 MPa (18.1 ksi).

Figure C.9. Failure Assessment Diagram Indicating Acceptable Crack Lengths. Safety Factors of 2.77 on K_r and 1.5 on S_r . Highest Level of J-Resistance Curve. Hoop Stress of 125 MPa (18.1 ksi).

Figure C.10. Failure Assessment Diagram Indicating Acceptable Crack Lengths. Safety Factors of 2.77 on K_r and 1.5 on S_r . Highest Level of J-Resistance Curve. Hoop Stress of 100 MPa (14.5 ksi).

Figure C.11. Failure Assessment Diagram Indicating Acceptable Crack Lengths. Safety Factors of 2.77 on K_r and 1.5 on S_r . Intermediate Level of J-Resistance Curve. Hoop Stress of 125 MPa (18.1 ksi).

Figure C.12. Failure Assessment Diagram Indicating Acceptable Crack Lengths. Safety Factors of 2.77 on K_r and 1.5 on S_r . Intermediate Level of J-Resistance Curve. Hoop Stress of 100 MPa (14.5 ksi).

Figure C.13. Failure Assessment Diagram Indicating Acceptable Crack Lengths. Safety Factors of 2.77 on K_r and 1.5 on S_r . Acceptable Level of J-Resistance Curve. Hoop Stress of 69 MPa (10.0 ksi).

Figure C.14. Failure Assessment Diagram Indicating Acceptable Crack Lengths. Safety Factors of 2.77 on K_r and 2.77 on S_r . Intermediate Level of J-Resistance Curve. Hoop Stress of 69 MPa (10.0 ksi).

Figure C.15. Failure Assessment Diagram Indicating Acceptable Crack Lengths. Safety Factors of 2.77 on K_r and 1.5 on S_r . Highest Level of J-Resistance Curve. Hoop Stress of 69 MPa (10.0 ksi).

Figure C.16. Failure Assessment Diagram Indicating Acceptable Crack Lengths. Safety Factors of 2.77 on K_r and 1.5 on S_r . Lowest Level of J-Resistance Curve. Hoop Stress of 41 MPa (6.0 ksi).

Figure C.17. Failure Assessment Diagram Indicating Acceptable Crack Lengths. Safety Factors of 2.77 on K_I and 1.5 on S_r . Intermediate Level of J-Resistance Curve. Hoop Stress of 41 MPa (6.0 ksi).

Figure C.18. Failure Assessment Diagram Indicating Acceptable Crack Lengths. Safety Factors of 2.77 on K_I and 1.5 on S_r . Highest Level of J-Resistance Curve. Hoop Stress of 41 MPa (6.0 ksi).